A Modular Numerical Model for Stirling Engines and Single-Phase Thermodynamic Machines

by

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ABSTRACT

A numerical model and software interface for the design and modelling of Stirling engines was presented. This model was developed to suit low-temperature Stirling engines, those that run at source temperature of less than 150 °C and run at speeds where temporarily developed losses become significant. The work had three objectives. The first was to create a combined mechanical and thermodynamic model to solve dynamic problems. The second objective was to provide graphical feedback during creation of the geometry and reviewing of a solution. The third objective was to test the model against experimental data taken from a low-temperature gamma-type engine and compare the model against another numerical code.

The resulting model, called the modular single-phase model or MSPM, incorporated a uniform pressure assumption which was used to solve the instantaneous flow rates in a one-dimensional network of pipes. The flow network is generated automatically from arbitrary arrangements of cylindrical or annular extrusions created by the user, within which the solid heat conduction is solved in 2-dimensions. Angular position dependent deformations are driven by the mechanical system, which responded to the forces generated by the gas system. This scheme transferred impulses from the gas network after short increments, which then defined the dynamics next increment. To capture flow losses pressure drops are approximated from gas velocities and the modified pressures are used to calculate the mechanism response.

The software itself presents the user with graphical feedback like that found in CAD software. This makes it possible to generate informative animations of the moving boundaries of an engine. These animations carry forward into the output of the code, presenting temperature, pressure, turbulence, heat flow, flow direction and pressure drop in spatially relevant positions on the virtual engine cross-section. The user can also place sensors, reuse previous simulation data, and run batch tests and optimize engine geometry using the software.

When the uncalibrated model was compared against experimental results featuring an in-lab engine running at 0.56 to 2.26 Hz, this numerical code developed a maximum discrepancy of 43.1% with an average deviation from the experimental results of 30.6%. An exploratory calibration of the effects of compression was conducted drawing on conclusions from the initial

tests, resulting in an overall improvement of the accuracy to an average of 21.9%. The final discrepancy is largely systematic, possibly correctable with reasonable adjustments to the automatically generated convection and friction terms. A sensitivity study of the properties related to heat transfer and friction was presented at two different speeds, the results indicated that the most substantial and predictable effector of power was the convection coefficient. Flow friction became a larger contributed at higher speeds. The code was then compared against SAGE, the numerical code of choice, with 5 tests at 16.7 Hz and 50 bar and with source temperatures ranging from 150 °C to 750 °C. Over these tests MSPM produced a maximum error of 59.1% and an average deviation of 33.5%. When compared against a second patch of in-lab produced SAGE results at slow speeds the two models diverged, it was concluded that the two models featured very different flow loss characteristics at low speeds among a variety of other differences. In a final experiment the optimal design of a beta type Stirling engine was obtained using the geometrical optimization tool within MSPM the results and design process of the beta type engine was presented.

PREFACE

This thesis is an original work by Steven Middleton. Aspects of this research have been published in the following conference publications:

Middleton, S. and Nobes, D.S. (2018) "Dynamic Modelling of Low Temperature Stirling Engines", *18th ISEC International Stirling Engine Conference*, Tainan, Taiwan, Sept 19-21, 2018

Middleton, S. and Nobes, D.S. (2019) "Modular one-dimensional simulation tool for oscillating flow and thermal networks in Stirling engines", *4th Thermal and Fluids Engineering Conference*, Las Vegas, United States of America, April 14-17, 2019

Middleton, S. and Nobes, D.S. (2021) "Approximations for use in cycling thermodynamic systems: Applications for Stirling engines", *Proceedings of the CSME International Congress*, Charlottetown, Canada, June 27-30, 2021

The author also contributed to the following publications that did not contribute directly to this Thesis:

Stumpf, C.J.A, Middleton, S. and Nobes, D.S. (2017) "Heat Transfer in Oscillating Fluid Flow Through Parallel Flat Plate Channel Heat Exchangers", *Okanagan Fluid Dynamics Meeting*, Kelowna, British Columbia, Canada, Aug 22-23, 2017

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Roman Alphabet Variables

Symbol	Description	Unit
A	Area	m^2
C	Conduction coefficient	W / K
c	Constant used in calculation	Various
C_D	Constant of turbulent dissipation. In tubes $= 0.08$.	-
c_p	Specific heat under constant pressure.	J / kg / K
c_T	Heat capacity of solid	J / kg / K
c_v	Specific heat under constant volume.	J / kg / K
d	Diameter	m
d_h	Hydraulic Diameter in the volume element $= 4V/S_{solid}$, as a face element $= 4A_{fc}/Perimeter_{fc}$	M
$\dot{E}_{ext}$	Power, entering a space, derived from a source that is assumed to be not strongly connected to the upcoming change in velocity, such as conduction or compression.	W
$\dot{E}_{flow}$	Power, entering a region from a different region. Based on energy required to push gas into a space of a given pressure.	W
$\dot{E}_{kin}, \dot{E}_{pot}, \dot{E}_{int}$	Kinetic, Potential, Internal changes in energy.	W
$\dot{E}_{shaft}$	Power as measured at the output drive shaft of the engine.	W
f	Frequency	Hz
$f(\dots)$	Function of …	Various
$F_{shear}, F_{velocity}$	Coefficient on angular speed producing instantaneous linear velocity. For shearing rate and linear velocity of face respectively.	m / rad
g	Gravitational constant $= 9.81\ m/s^2$	m / s
h	Convection coefficient.	W / m^2 / K
I	Moment of Inertia	kg m^2
k	Thermal conductivity.	W / m / K
K	Minor loss coefficient	-
L, l	Length, linear or characteristic.	m
m	Mass.	kg
$\dot{m}$	Mass change or mass exchange.	kg / s
N_f	Darcy Friction factor	-
N_{Fo}	Fourier Number $= \alpha_t . \delta/\Delta x^2$	-
N_k	Streamwise thermal conductivity factor.	-
N_{Nu}	Nusselt number $= D_h . h/k$	-
N_{Pe}	Pechlet Number $= N_{Re} . N_{Pr}$	-

N_{Re}	Reynolds number $=U.D_h.\rho/\mu$	-
$N_{Re_{laminar}}$	Upper limit Reynold's number for a flow to be considered laminar. $= 1{,}700$	-
N_{Va}	Valensi number $= \rho\omega d_h^2/\mu$	-`
N_{West}	West Number $= (W_s/P.V_{swept}f)(T_H - T_L/T_H - T_L)$	-
P	Pressure	Pa
$\dot{Q}$	Heat Transfer by conduction and convection into control volume.	W
R	Thermal resistance	K / W
r	Radius	m
r_c	Compression ratio	-
R_{spec}	Specific Gas Constant is equal to the $= R_{univ}/M$	J / kg / K
S	Perimeter of a face or area.	m
$\dot{S}$	Entropy generation rate.	-
T	Temperature, Torque applied by engine load	K, N m
t	Time, measured from start.	s
u, U	Specific internal energy, total internal energy	J / kg
U	Velocity, considered the average over the face.	m / s
V	Volume	m^3
$\dot{V}$	Change in volume or flow rate.	m^3 / s
$\hat{v}$	Specific volume	m^3 / kg
W	Work	J
w	Weight for interpolation with values between 0 and 1	-
$\dot{W}_b$	Instantaneous energy extracted from moving the boundary of the control volume.	W
x, y	Scalar position relative to an origin.	m
y	Sign of face, when used with respect to node i, and face $i \rightarrow j$, the sign is negative because the natural flow is out of node i.	-
z	Vertical position	m

Greek Alphabet Variables

Symbol	Description	Unit
α_t	Thermal diffusivity $= k.\rho/c_p$	m / s
B	Ratio of Areas	-
β	Porosity	-
δ	Small increment in time, often associated with the length of a timestep.	s
θ	Angular Position	rad
θ_{inc}	Angular Increment, over which cycle is divided. Also represents mechanism acceleration lag.	rad
K	Turbulent kinetic energy	J
κ	Specific Turbulent kinetic energy	J / kg
μ	Dynamic Viscosity	Pa s
ρ	Density	kg / m^3
т	Turbulence weighting factor, value of zero denotes laminar flow, value of 1 denotes fully turbulent flow.	-
ω	Angular Speed	rad / s

Subscripts

Symbol	Description
0	Measured at start of local period of consideration.
avg	Arithmetically averaged over the entire cycle.
c, k, r, h, e	Referring to compression, cooler, regenerator, heat and expansion spaces respectively.
$cond$	Associated with conduction or convection
$cycle$	Accumulated over the entire cycle.
$dead$	Dead volume, Eulerian volume that doesn't change its temperature though matter may flow through it.
DP, PP	Displacer Piston, Power Piston
eff	Not a true measurement but the composite value after the initial is modified by an external, not fully modelled effect.
fc	Associated with a face, an interface between two spaces.
gen	Internally produced.
H	High, often referring to source property.
i, j, nd	Indices referring to separate spaces or nodes.
$i \rightarrow fc, fc \rightarrow i, i \rightarrow j, \ldots$	Referring to a delta up to an interface from the center point of a space.
ij	Arithmetic mean of space i and space j properties.
in, out	Into system/space, out of system/space.
L	Low, often referring to sink property.
$load$	Refers to load on drive shaft
$loop$	A property characteristic of a fully connected loop of cells
n	Iteration subscript, indicating current and next value.
o, i, max, min	Outside and Inside, or alternatively farther or closer to the datum, often used for bounds of a shape.
$perp, para, th, g, f, tube, s, c, w, wth$	Perpendicular, parallel, fin thickness, gap between features, fin or fin space, spacing or separation, channel, feature width, wall thickness.
$region$	Bulk property of a region, which is an interconnected zone of gas such as a engine volume. Either the sum or a uniform constant.
$shaft$	Measured at the output shaft of the engine.
$swept$	Quantity forced to enter heat exchange components
$t, t + \delta$	Current time, next time after timestep δ
up	Quantity is taken from the space upwind of the current feature.

CHAPTER 1. INTRODUCTION

The following chapter outlines background information and the motivation for investigating Stirling engines in the low-temperature regime. Relevant literature on the topic of numerical modeling of Stirling engines will also be discussed. This chapter concludes with a summary of objectives and thesis structure.

1.1 Project Background

1.1.1 General Background

The research conducted at the University of Alberta's Dynamic Thermal Energy Conversion Laboratory (DTECL), is focused, as of the writing of this thesis, on investigating the operation of Stirling engines with reservoirs at temperatures between 100 °C and ambient (5°C). Such engines are informally classified as low-temperature difference Stirling engines (LTDSE).

Heat sources that produce such low-grade heat streams in high amounts include: industrial waste heat and geothermal heat, with geothermal being a focus of DTECL. Waste heat, in a study by Stricker et al [1], accounts for 70% of the energy used in Canadian industries. With regards to geothermal energy: Banks and Harris [2] estimated that a total of 6,100 MW of thermal energy potential in their studied region (an area of Alberta South of Grand Prairie, West of Edmonton and North West of Calgary). In their study, the highest potential sources (those with source temperature above 120 °C) provide a total up to 712 MW of electrical power which could be reliably gathered over 30 years with existing technology [2]. In addition to these findings, the prolific oil and gas activity throughout Alberta has generated around 170,000 orphaned wells, which represent 37% of all wells in Alberta [3]. Given these numbers, there is a likelihood that many of these may have favorable downhole temperatures. With the high upfront cost of geothermal development, this offers an important jumpstart to both geothermal investigation and capacity installment. Despite this, no active examples of geothermal power generation exist in Canada, with the first example to come online in Saskatchewan at the end of 2021 [4].

There are relatively few competing technologies designed for such temperature conditions. Among them is the organic Rankine cycle (ORC), Kalina cycle and thermoelectric technologies [5]. The ORC, is a relative to the steam Rankine used for high-temperature applications. It has been very successful globally with 250 MW in electrical generating capacity as of 2015, with roughly 40% of that capacity generated from geothermal sources [6]. The Kalina cycle has the potential for higher efficiency [7] than the ORC and improved cycle control. However, it is a proprietary technology with increased complexity, scale, and corrosion than an ORC [5]. Thermoelectric technologies offer simplicity given their solid-state nature, but often have poor efficiencies with state of the art thermoelectric technologies achieving only 12% [5] of the Carnot limit and the vast majority achieving less than 10% of Carnot [8], in the low-temperature regime.

Stirling engines are closed cycle, externally heated, reciprocating engines that utilizes a chemically inert working gas [9] such as hydrogen, helium or air and are made of common structural materials such as steel, polymers and aluminium. Stirling engines offer the additional benefit of being able to increase in power density through pressurization while containing no valves, pumps or turbines. This attribute makes them relatively simpler on an individual basis than competing fluid-based technologies. At larger scales, engines would be coupled together, and the resulting modularity may improve the ability of a generator to provide more consistent power.

1.1.2 Research Activities in DTECL

Stirling engines are a relatively insignificant player in the global low-temperature energy market. It is the objective of the DTECL group to investigate whether this is a valid oversight. Research began with Speer [10] who modified an existing mathematical model, the SIMPLE model by Urieli and Berchowitz [11] to include a host of additional losses. This was used to predict experimental results from a modified 90-degree gamma engine converted from a high temperature solar application to work with low temperatures. The conclusions determined that the error of the SIMPLE model increased substantially at lower temperatures (on the order of 150%) and speeds and established that low temperature engines required different geometry and additional investment in loss prevention. Stumpf [12] optimized the operating parameters of a large diameter low-temperature gamma type engine for maximum shaft power. In doing so established a means of predicting the optimal compression ratio based on the temperature ratio. Stumpf [12] also found

that the West number for well designed low temperature engines rested around 0.21, lower than the expected value for high temperature engines equal to 0.25, indicating that performance expectations are different for low-temperature engines. Miller [13] investigated the effect of flywheel size on transient and steady-state performance. Miller [13] also investigated improvement avenues for the modified model from Speer [10] with regards to low temperature machines, the studies conducted showed that the model was less accurate for low-temperature regimes. The suggestions were to include leakage into the model parameters and include a more sophisticated mechanical power loss calculation and gas spring losses. Michaud [14] performed an experimental optimization study on a low temperature alpha type engine. Though the engine failed to run due to poor heat conduction and higher mechanical losses optimal crank angle was determined by driving the engine with a motor.

The reason's why Michaud's engine [14] failed to run had not been predicted by the SIMPLE model even after modification by Speer [10], where it still predicted 5 Watts of power. This was a consistent finding through all the projects that existing models at the time performed poorly when estimating low-temperature scenarios. For Speer [10] the modelling error increased dramatically at low-temperature due to ignored losses, losses which Miller [13] identified as gas spring hysteresis leakage and mechanical losses. Additionally, feedback from colleges indicates that user error in encoding the engine behaviour into a numerical model is one of the most challenging aspects of engine modelling using such models.

1.1.3 Project Goals

Given the work that has been completed at the University of Alberta, a new numerical model was required. The model, would satisfy the following constraints:

1. It will be designed in the low temperature context, including features that are important to low temperature engines, these will be discussed in further sub-sections.
2. The new model will be validated against experimental data as well as an existing commercially available numerical code known as SAGE.
3. It will assist in the design of new engines, by allowing the incorporation and assessment of geometrical features in a physical realizable arrangement. This will be realized through a

solid modelling interface. Which, given its visual nature, will be simple and intuitive to learn, a benefit, given the user-base is regularly changing.

1.2 Stirling Engines

1.2.1 History

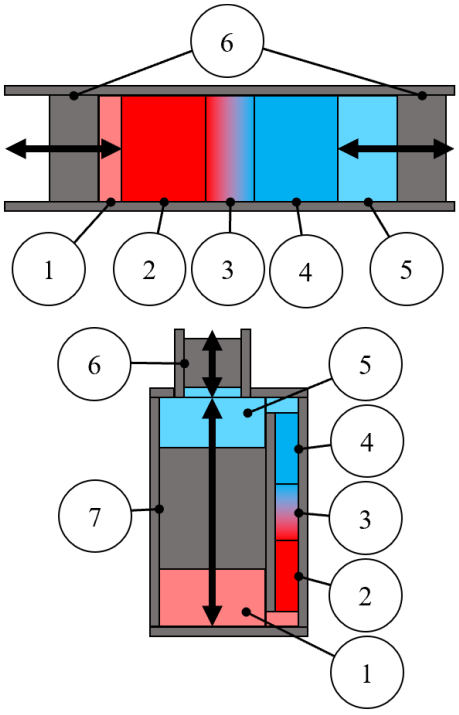
The Stirling engine, often called a hot air engine, as stated in the 1816 patent [15] was invented by Rev. Robert Stirling as an industrial prime mover in the early days of the steam engine. Though its introduction was proceeded by other air engines by more than a century, the addition of the economizer, made the Stirling engine a much more efficient invention for the time. This economizer, now termed a regenerator [16], is an internal thermal mass built to store thermal energy for a later point in the cycle. In addition to its efficiency, Stirling engines were noted as safer and quieter but ultimately had poorer economic efficiency [17]. Eventually Steam engines became more efficient and safer and Stirling engines became low-power domestic engines before being overshadowed again by electric motors [17]. The Stirling engine remerged as a quiet alternative to internal combustion for military radio sets by Philips [9], their research forms the basis of what is known today, but ultimately Philips only made financial success with reverse Stirling cycle cryo-coolers. Today, Stirling engines quietly power submarines [18], domestic combined heat and power systems [19], and high efficiency concentrated solar power systems [20]. Further detail into the history of Stirling Engines is discussed by Lloyd [21].

1.2.2 Stirling Engine Principles

Stirling engines fall under the category of heat engines, a group of processes that generate usable energy from the heat transfer from high to low temperatures. The principles of design and operation of Stirling engines are described in detail by West [22], as well as through preceding thesis: [12], [13], [10] and [14]. The principles are also summarized in brief below.

1.2.2.1 Fundamental Components

There are several fundamental components of a Stirling engine, which for the purpose of clarity are displayed in Figure 1.1 for both an alpha (top) as well as a gamma type (bottom) engine.



(1) **Expansion Space** – The variable volume zone that when expanding facilitates the bulk heating of the gas.
(2) **Heater** – The group of surfaces that facilitate the heating of the gas. These surfaces may be within the expansion space or have their own separate zone.
(3) **Regenerator** – A set of surfaces and material volume that store a thermal gradient between the heater and cooler, which preheats and precools the gas before entering the opposite exchanger.
(4) **Cooler** – The group of surfaces that facilitate the cooling of the gas. These surfaces may be within the compression space or have their own separate zone.
(5) **Compression Space** – The variable volume zone that when expanding facilitates the bulk cooling of the gas.
(6) **Power Piston** – A piston which separates the engine and a volume outside of the engine. This piston changes the volume of the engine and extracts work.
(7) **Displacer Piston** – A piston which divides the expansion and compression space. The displacer's function is to facilitate the movement of gas between the expansion and compression space.

Figure 1.1: Fundamental components of Stirling engines: (top) alpha type engine, (bottom) gamma/beta type engine

1.2.2.2 Ideal Stirling Cycle

All the possible configurations of a Stirling engine are an attempt to mimic the ideal Stirling cycle, while satisfying specific constrains and minimizing losses within their intended application. These configurations are reviewed in greater detail by West [22] as well as Martini [23]. A summary, in the form of a gamma type engine, is also provided here.

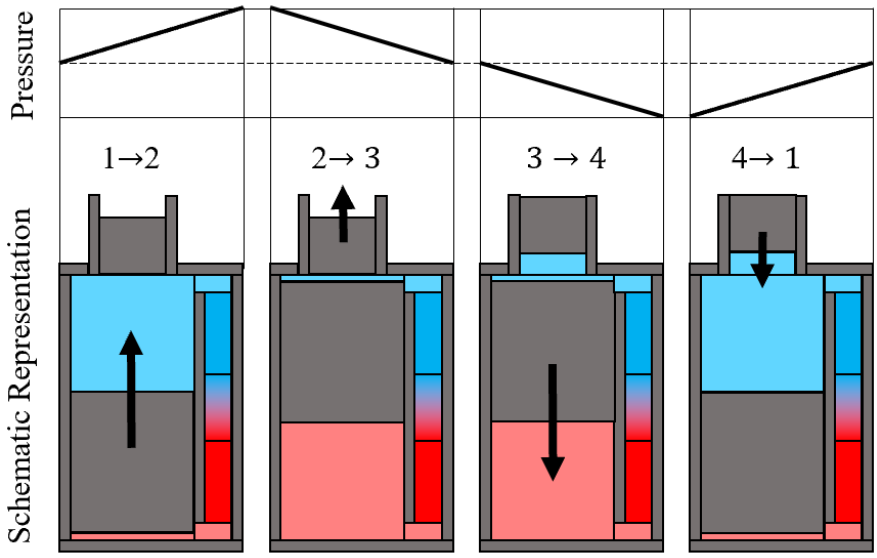


Figure 1.2: The 4 phases of the ideal Stirling engine cycle: arrows represent a motion that is occurring during the phase. Components are defined in Figure 1.1.

Figure 1.2 schematically illustrates the 4 motions of the ideal Stirling cycle, which appear also in Figure 1.3 as well as in following subsections. Figure 1.3 represents a different style of representation, known in the literature as an indicator diagram. A typical indicator diagram plots engine pressure against internal volume. The line color represents average engine internal temperature, the horizontal dashed line represents the average pressure of the buffer space – the space around the engine which imparts pressure on the backside of the power piston – and the shaded region represents the total sum of work produced by the engine during a single cycle.

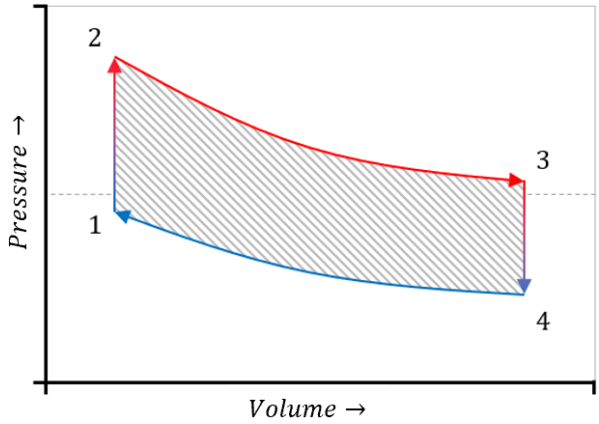


Figure 1.3: Ideal Stirling engine cycle in a pressure-volume diagram form

The 4 steps of the ideal Stirling cycle outlined in Figure 1.3 are (1-2) isochoric heat addition, (2-3) isothermal expansion (3-4) isochoric heat removal and (4-1) isothermal compression. These steps are described in detail in the following subsections.

1.2.2.2.1. (1-2) Isochoric Heat Addition

The gas is pushed, by the displacer piston, from a mostly cold state to a mostly hot state. During this stage, heat is added through the heat exchange surfaces into the gas. This produces a net increase in the pressure of the engine and occurs while the volume is smallest.

1.2.2.2.2. (2-3) Isothermal Expansion

Energy, in the form of boundary work, is extracted by the expansion of the engine volume via the power piston. Simultaneously, the thermal sources add thermal energy to compensate for expansion cooling, thus maintaining an isothermal environment.

1.2.2.2.3. (3-4) Isochoric Heat Removal

The gas is pushed, by the displacer piston, from a mostly hot state to a mostly cool state. During this stage, heat is discharged through the heat exchange surfaces from the gas. This produces a net decrease in the pressure of the engine and occurs while the volume is largest.

1.2.2.2.4. (4-1) Isothermal Compression

Energy, in the form of boundary work, is added through the compression of the engine volume via the power piston. Simultaneously, the thermal sources remove energy to compensate for compression heating, thus maintaining an isothermal environment.

1.2.2.3 Methods of Idealization

Every idealized heat engine follows Carnot's principle [24], which postulates that a heat engine is most efficient when all of its processes are reversible. A reversible process indicates that it happens in a way that requires the same amount of energy to accomplish a task as it does to undo it. Alternatively, the reversible process does not produce entropy, which is a representation of a loss of potential. There are two idealized thermal models, isothermal [25] and adiabatic [11], which enable the ideal Stirling cycle to achieve its maximal efficiency. These two models establish that heat transfer occurs always over a temperature difference of exactly zero. This negligible temperature difference is important for heat transfer to be reversible, as entropy generation is

proportional to the difference in the inverses of temperatures by the following formula, from Clausius [26]:

$$\dot{S} = \dot{Q}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{1}$$

where: $\dot{S}$: Entropy generation.

$\dot{Q}$: Thermal energy flux between temperature sources.

T_1, T_2: Temperatures, measured at two positions.

Notably, at higher temperatures a larger temperature difference can be utilized for the same entropy generation rate due to the asymptotic nature of the inversed temperatures.

The analysis and derivation of these models are described in detail along side the SIMPLE model [11]. The two models are quite similar; however, the adiabatic model allows the temperatures to swing in the compression and expansion spaces according to compression heating and cooling. Conversely, the isothermal model maintains a constant temperature in those spaces. This is illustrated in Figure 1.4 and Figure 1.5 below.

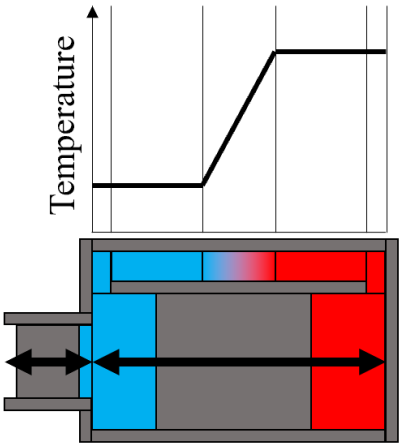


Figure 1.4: Illustration of the isothermal idealization

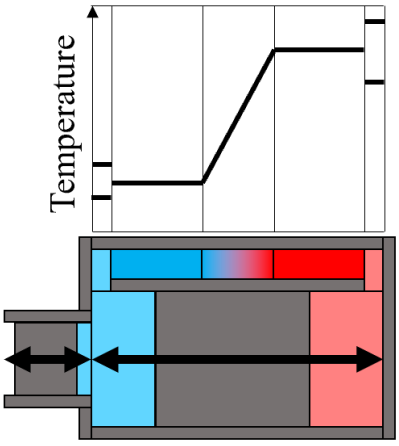


Figure 1.5: Illustration of the adiabatic idealization

The isothermal idealization shown in Figure 1.4 is discussed by Urieli [11] and introduced by Gustav Schmidt [25] in 1871. This analytical simplification describes an engine in which the temperature in all spaces remain static. Thus, all temperature change occurs during the flow

through the regenerator and all other heat exchange occurs at a temperature difference of zero. Notably, the compression and expansion spaces are kept consistently at the temperature of their respective heat exchangers. Such an engine would exist only in a slowly cycling engine with heated cylinder spaces and a perfectly effective regenerator.

The adiabatic idealization as shown in Figure 1.5 was introduced by Urieli [11] and serves as an alternative to the ideal isothermal model. This model implies that heat transfer only occurs within the boundaries of the heater, cooler and regenerator. The only variation between this and the isothermal model is that the expansion and cooling spaces can oscillate according to compression cooling and heating without heat transfer to the walls. The regenerator and heat exchangers are perfectly effective, and thus all heat transfer pathways are kept at a temperature difference of zero despite the discontinuities. Urieli argued that this modification was more realistic for quickly rotating engines.

1.2.3 The Real Stirling Cycle

The following subsections discuss the idea of a realistic Stirling engine, an engine that diverges from the impractical ideal cycle.

1.2.3.1 Continuous Volume Variations

Real systems use real mechanisms to move the boundaries of the engine. Kinematic engines utilize slider cranks, yokes, rockers or wobble plates [9], which form motions derived from the sum of several sinusoids, while the resonant free-piston engines use springs, forming near sinusoidal motions. This is a divergence from the discontinuous motion prescribed by the ideal cycle. The effect of these smoothed motions can be seen in Figure 1.6 below, the discontinuous ideal indicator diagram is shown as the dashed outline.

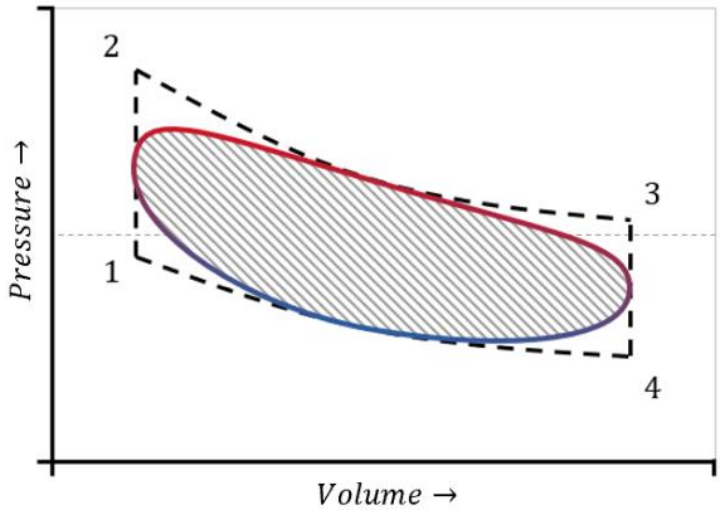


Figure 1.6: Pressure-volume diagram of an engine with a sinusoidal volume variation compared against one with idealized motions

Note that the area of the curve is smaller than the ideal case for the same volume and temperature bounds, indicating that the simple act of changing the motion of pistons relative to pressure extremes results in lower engine power. Commonly, mechanisms are selected to maximize the lifetime of the engine, with more specialized mechanisms being avoided for reasons of balancing, design risk or manufacturing complexity [9]. Thus, with Stirling engines there is a drive to produce a mechanism that is both mechanically efficient, produces good motion to maximize the indicated power and offers good control over the phasing of the engine pistons. Senft [27] discusses the mechanical efficiency and design of Stirling engines to great length and produced a series of efficient low-temperature engines. Hargreaves [9], documents the long history of Phillip's Stirling engine technology which includes a variety of tested and successful mechanical configurations.

1.2.3.2 Imperfect Thermal Control

The ideal Stirling engine cycle is highly temperature-controlled, energy is assumed to transmit only between the gas and the surfaces designed for heat transfer and it does so perfectly without the solid surface changing temperature. In real systems, deviations from this ideal thermal assumption always result in a loss of output energy. The following sub-sections outline how these deviations come about. Losses in this area affect the indicator diagram by reducing the temperature bounds, which has the effect of moving the isothermal/adiabatic lines closer together. This is shown in Figure 1.7.

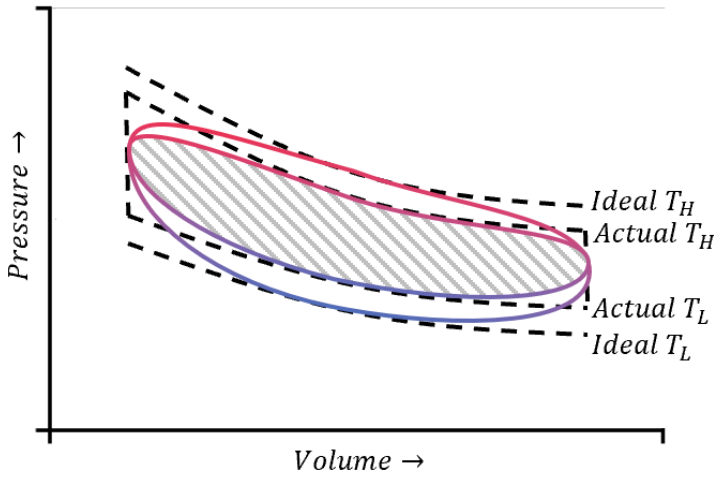


Figure 1.7: Effect of thermal losses on the pressure-volume (indicator) diagram.

1.2.3.2.1. Conduction Loss

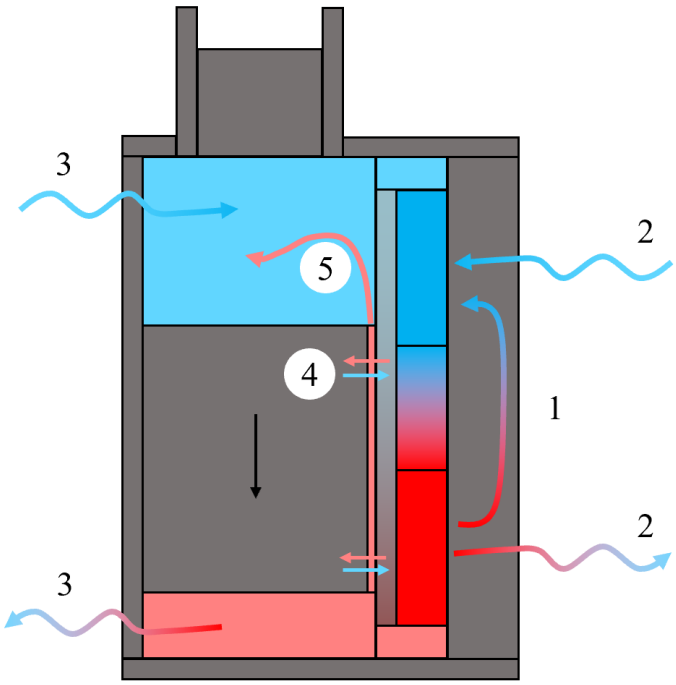


Figure 1.8: Thermal energy pathways in a Stirling engine

Conduction losses emerge from the conduction of energy through the solid structures of the engine, which has several primary forms as shown in Figure 1.8. All of these are facilitated by the combination of conduction, convection, and radiation. As all conduction between two bodies

produces a loss in exergy it is important that conduction is minimized as much as possible, thus heat transfers beyond the heat exchangers is a drain on the resulting power or efficiency.

1) Direct conduction between the hot and cold sources which simply results in that energy bypassing the heat engine entirely. [9]
2) Conduction from the hot or cold exchanger through the walls to the surroundings, this energy never engages in the cycle but is a loss component of engine systems.
3) Conduction from the interior of the engine to the exterior at ambient temperatures, which represents energy entering the cycle, but exiting partway through the cycle.
4) Conduction supported by motion, often referred to as the shuttle loss [22], is where a moving element, primarily a piston, carries with it a temperature gradient that is closely exposed to a wall of a different or offset temperature gradient. Usually, this is reduced by introducing a very long piston and/or modifying the gap between it and the wall. [22]
5) Heat transfer from the mixing of two gas streams of different temperatures. This happens when gas from two separate spaces by-passes the heat exchangers, through a seal, or the annular gap. This loss reduces the amount of heat transfer, due to a diminishing of total flow-through, at the same time it reduces the maximum temperatures of both spaces by mixing of hot with cold streams and vis-versa.

All these losses will result in a reduction of the temperature extremes and therefore pressure extremes of the engine.

1.2.3.2.2. Non-Ideal Heat Exchanger

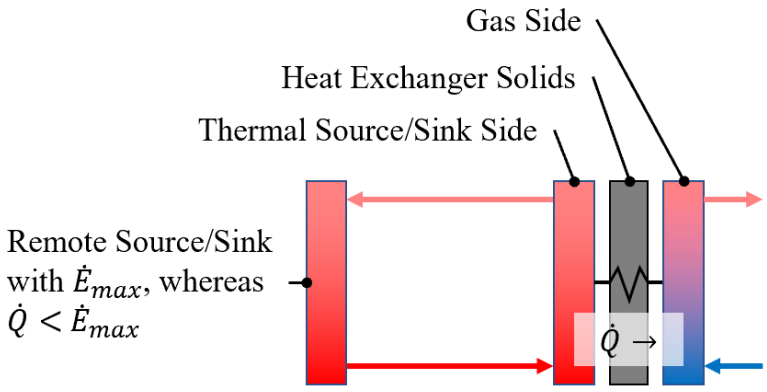


Figure 1.9: Thermal energy pathway through a heat exchanger

Heat exchange through a heat exchanger relies on 4 regimes, seen in Figure 1.9. For the purposes of this discussion, let us refer to the exchanger as a source, as the same principles apply

to thermal sinks. First of which, is the ability of the source to provide the exchanger with heat. This value $\dot{E}_{max}$ could be limited by external factors such as rate of fuel injection, fluid flow rate and heat capacity, solar irradiance, or any number of other factors. Exceeding or even approaching this limiting rate may result in a drop in source temperatures. Secondly, there is a loss associated with convection between the source fluid and the heat exchanger geometry. Thirdly, is the conduction of the heat through the solid structure of the heat exchanger. Finally, the convection of the heat from the solid surfaces into the gas. Increasing the resistance of any of these or lowering the potential of the source result in lower gas temperature and thus lower power.

1.2.3.3 Gas Friction

Friction is experienced by the gas as it flows through the geometry of a Stirling engine. The energy required to overcome this friction must be taken from the flywheel. These losses are generated via two main sources. The primary source is flow along the main gas path, where flow encounters the heat exchangers and regenerator and any fittings along the way. The second source called pumping loss [16] is generated from the compression and expansion of gases which causes the fluid to get pumped in and out of every crevasse of the engine, this is most noticeable in tight components such as the annulus of the displacer. The effect of both of these flow losses is detected by the mechanism as a shift in the pressure experienced at the piston faces. The net effect of this disturbance always reduces the overall area of the pressure volume diagram by an amount equal to the loss in energy.

1.2.3.4 Mechanical Friction

Friction, which exists in the sliding or rolling surfaces and seals of a mechanical devices, can absorb a significant portion of the work produced by the engine. This topic is discussed in depth by Senft [27] and often this loss can be as large as 5 to 15% of the output of engine [23]. These losses are dependent on several factors, including engine speed, mechanism weight, balancing, piston loading in both axial and perpendicular directions. Mechanical losses generally have a strong relationship with machine lifetime as friction or imbalances in the engine cause surface wear and fatigue, respectively. Mechanical losses are involved in the transport of energy to and from the engine, the quantity of energy that re-enters the engine to assist in completing the compression or expansion of the cycle can be directly calculated from the indicator diagram and

occurs anytime a piston goes against its pressure regime. The study of this phenomenon, called forced work, was pioneered by Senft [27] and is discussed in detail in the preceding theses [10], [12], [13], and [14].

1.2.3.5 Compressibility

At higher speeds, gases compress up against accelerating surfaces, slightly changing the experienced pressures. This results in higher pressures when compressing and a higher vacuum when expanding. The study of this particular effect was pioneered by Petrescu et al [28]. Additionally, the density variations caused by pressure losses can cause variations in the local properties of heat transfer, and flow friction.

1.2.4 What is important for low-temperature engine?

There is no strict definition of what constitutes a low-temperature engine. In the context of this lab it is taken as having a hot side temperature of less than 150 °C. The cold side is ambient, as opposed to engines which use cryogenic sources. The essence of a low temperature, or low temperature ratio engine can be effectively by the following flowchart.

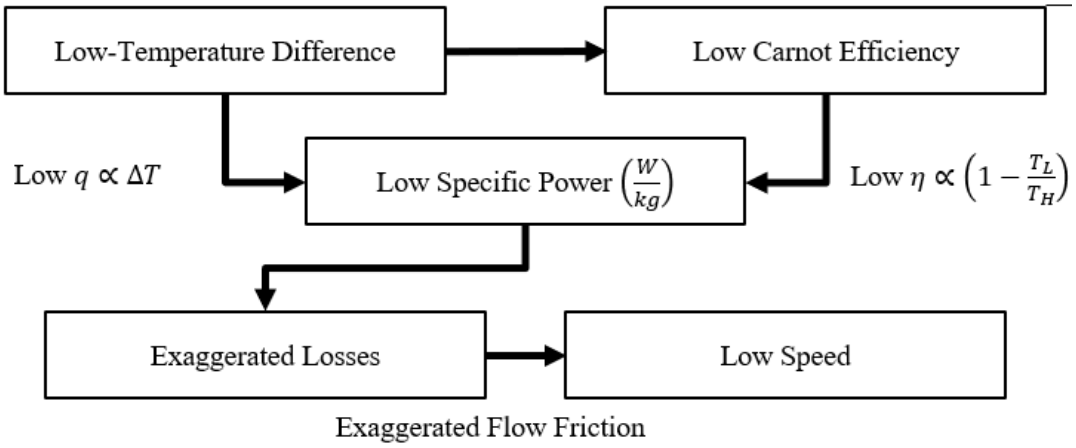


Figure 1.10: Thermodynamic consequences for of low temperature (ratio) engines

The following are consistent with DTECL's low-temperature laboratory engines.

1. Low-temperature engines run slower than high-temperature engines.
2. Low-temperature engines have lower power density than high-temperature engines.

A non-dimensional number that is often used to represent the power of an engine is the West number (N_{Wes}). In theory, this number allows for the direct comparison between engines of any design with each other. This non-dimensional number, which is the ratio of actual output power to a representation of ideal power, was introduced by West [22] and makes use of the fact that power is proportional to charge pressure, the volume of gas that changes temperature and the engine frequency. The West number is defined as:

$$N_{West} = \frac{\dot{E}_{shaft}}{P_{avg}.V_{swept}.f_{engine}} \frac{T_H + T_L}{T_H - T_L} \tag{2}$$

where: $\dot{E}_{shaft}$: Power as measured at the output shaft of the engine

P_{avg}: Mean, internal pressure in the engine over the cycle.

V_{swept}: Swept volume of the expansion space.

f_{engine}: Running frequency of the engine, at which $\dot{E}_{shaft}$ was measured.

T_H: Source temperature

T_L: Sink temperature

1.2.4.1 Pressure Leakage

The energy loss between a sinusoidally varying pressure region and a constant pressure region over one cycle is equal to the integration of the instantaneous energy loss over the cycle period described by:

$$E_{leak,cycle} = \oint \dot{E}_{leak}.dt = \oint F(P_1 - P_2).dt$$
$$E_{leak,cycle} = C\frac{1}{f_{engine}} \tag{3}$$

where: $E_{leak,cycle}$: Sum of energy lost to a leak over one complete cycle

$\dot{E}_{leak}$: Instantaneous energy lost to a leak.

$F(\dots)$: The leak function, which prescribes the amount of energy lost to the leak (proportional to the mass which crosses it) as a function of the pressure difference. Importantly, this function is ideally independent of time.

C: A constant with respect to time. This occurs because $F(\dots)$ is independent of time, therefore the integral is equal to the integral of $F(\dots)$ over the range of P values which are governed by angular position. Therefore, time will simply serve as a scaling factor on the magnitude on $E_{leak,cycle}$, as angular speed simply defines the slope of angle vs time.

This results in an energy loss which is inversely proportional to cycle time. With regards to engine speed, a slow engine will accrue more power loss per cycle than a fast cycle. With regards to engine size, given that a leak may be in some way related to engine size, for the same power output a low-temperature engine will have a larger power loss due to leakage.

1.2.4.2 Heat Exchange

As sink temperatures are normally ambient temperatures given its accessibility, low-temperature engines are limited by the Carnot efficiency as: $\eta = 1 - T_L/T_H$. Low-temperature engines are further disadvantaged by the proportional relationship between heat transfer and temperature difference. Meaning that low-temperature engines require larger heat exchanger surface areas to maintain an adequate temperature ratio, which ultimately balances friction losses against power gains from better temperatures. Low-temperature engines are often limited by heat exchange. Therefore, this requires a more detailed look into heat exchangers for such engines.

The construction of the West number [22] provides the greatest illustration of the effect of temperature on Stirling engines. Specifically, the form of the derivative of shaft power with response to rising source temperatures:

$$\frac{\partial \dot{E}_{shaft}}{\partial T_H} = 2N_{West}.P_{avg}.V_{swept}.f_{engine}\frac{T_C}{(T_H + T_C)^2} \tag{4}$$

The increase in power is approximately dependent on the inverse of source temperature squared, such that at low-temperatures improvements in source temperature will lead to substantial increases in power, while at higher temperatures, there is little incentive to improve gas

temperatures. This will incentivize low-temperature engines to invest more into heat exchange than high temperature engines, even at the increase in flow losses or dead volume.

1.2.4.3 Conduction Losses

Thermal conduction is a temporally developing loss found in Stirling engines, this loss has two attributes associated with it: gas spring hysteresis (GSH) and wall conduction, which are innately tied together. GSH has been well studied by the Stirling engine community and in general, all equations for its loss rate follow some variation of the following form [29]:

$$\dot{E}_{GSH} \propto \gamma^{n}.(\gamma-1)^{2-n}\sqrt{\pi.k.f_{engine}.P_{avg}.T_{avg}}\left(\frac{\Delta V}{V_{avg}}\right)^{2} A \tag{5}$$

where: γ: The ratio of specific heats = c_p/c_v

n: Exponent, varies depending on approximation [29].

k: Thermal conductivity of gas

T_{avg}: Average temperature of engine interior space

ΔV: Difference between maximum engine volume to minimum engine volume.

A: Surface area over which loss takes place.

If the properties of angular speed, surface area and temperature are isolated the following equation is found.

$$\dot{E}_{GSH} \propto A\sqrt{\omega.T_{avg}} \tag{6}$$

As a note, area is approximately proportional to volume to the 2/3rd power. According to the scaling rules of Organ [30] the equivalent speed of a larger engine scales with volume to the negative 1/3rd power. Combining these into a single equation gives:

$$\dot{E}_{GSH} \propto V^{\frac{2}{3}} \sqrt{\frac{1}{V^{\frac{1}{3}}}.T_{avg}} \propto \sqrt{V.T_{avg}} \tag{7}$$

According to the West number, power is directly proportional to size, speed and exponentially related to temperature. Thus, the GSH loss may be less of a burden at high speed and temperature ratios. And larger engines will experience a lower GSH loss due to having a diminishing surface area to volume ratio. A large low-temperature engine may have lower GSH than a small high-temperature engine, but the resulting loss is likely to be a larger proportion of power in the low-temperature Stirling engine due to the strong dependence of power on temperature difference.

The second attribute of thermal conduction losses is conduction through the solid containment of the Stirling engine volume. This energy exchange pathway, governed by Fourier's law, is constant in time but linearly proportional to the difference in temperature extremes.

$$\dot{E}_{Conduction} \propto \frac{A}{L}.\Delta T.dt$$

Where:

$$A \propto V^{\frac{2}{3}}, \qquad L \propto V^{\frac{1}{3}}, \qquad dt \propto V^{-\frac{1}{3}} \text{ [30]} \tag{8}$$

Thus:

$$\frac{V^{\frac{2}{3}}}{V^{\frac{1}{3}}}\frac{\Delta T}{V^{\frac{1}{3}}} \propto \Delta T$$

With regards to engine size this loss will be constant at equivalent speeds, as defined by Organ [30]. The larger engine runs slower but will generate power proportional to $V^{\frac{2}{3}}$ with the same conduction loss as the smaller engine. With regards to engine speed, a slower engine has longer time to develop this loss, thus allowing it to consume a greater proportion of power. Because power output increases faster with respect to temperature difference than this loss, a high proportion of power will be taken up by conduction losses in low-temperature engines.

1.2.4.4 Viscous Friction

Viscous friction loss, or pressure loss, is a function of flow geometry, gas viscosity and gas velocities. With regards to speed, the viscous friction loss is, in turbulent cases, dependent on velocity squared according to the Darcy-Weisbeck equation [31] for pipe-flow. The viscosity of the gas, which generally increases with temperature, will increase the pressure losses. This will be seen to a much less extent than velocity as its effect is only seen in the friction factor (f) calculation via (in the pipe flow case) the Colebrook-White equation [32]. The dependence of friction on viscosity varies from linear in the laminar regime to a negligible effect in the fully turbulent regime, where turbulent dissipation overshadows molecular dissipation.

With regards to geometry, an engine that is scaled to be 2 times larger in all dimensions will have flow paths that are 2 times longer with cross-sections that are 4 times higher, hydraulic diameters are 2 times larger and volumetric flow rates that are 8 times larger. This results in 2 times larger flow velocities. Larger scales also effect the surface finish, in theory an equivalent surface finish could be obtained, which would allow a large engine to approach that of a smooth pipe. Inserting these modified dimensions into the Darcy-Weisbeck equation [31]:

$$\Delta P = \frac{f.\rho.L}{2D_h}\left(\frac{\dot{V}}{A}\right)^2 = \frac{f.\rho}{2}\frac{(2L)}{(2D_h)}\left(\frac{8\dot{V}}{4A}\right)^2 = f.4\left(\frac{\Delta P}{f}\right)_{1x} \tag{9}$$

where: ΔP: Pressure drop over flow path

f: Darcy friction factor: defined as the Colebrook-White equation [32]:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\epsilon}{3.7D_h} + \frac{2.51}{N_{RE}\sqrt{f}}\right)$$

$N_{Re} = \frac{\rho.D_h.U}{\mu} = \frac{\rho}{\mu}(2D_h)(2U) = 4N_{Re,1x}$

$\frac{\epsilon}{D_h} = \frac{\epsilon}{2D_h}$, thus roughness is halved.

ρ: Fluid density

L: Streamwise length of flow path

D_h: Hydraulic diameter

$\dot{V}$: Volumetric flow rate

This results in a pressure drop that is roughly the same in the laminar case (as the 4's cancels out and roughness is neglected), and in the fully turbulent case is between 2 to 4 times larger for the large engine, since roughness is – at best – linearly related to the friction factor. Based on the West number, energy produced per cycle increases linearly with volume, so a large engine will have 8 times as much power, but between 8 to 32 times as much flow losses when running at the same speeds. Therefore, low-temperature engines must run at low-speeds to minimize these increased flow losses, caused by their larger sizes. This is further enforced by the more constrictive heat exchangers found in such devices. This is also confirmed by Organ [30], who's scaling laws declare that the speed of the engine will scale with volume to the 1/3rd, or in our case here should be halved, corresponding exactly to a 1:1 increase in cycle energy with flow losses.

An alternative to running at lower speeds is to increase the cross-sectional area of the heat exchangers vs its length. This, in theory offers nearly the same temperature change (if the flow is laminar, and therefore having a constant Nusselt number) but can run into problems with preferential flow the lower the pressure drop gets, additionally it may be geometrically challenging to design a high cross-section heat exchanger that does not introduce significant amounts of dead volume from distribution geometry.

1.2.4.5 Mechanical Losses

Kinematic mechanisms, driven by a rotating drive, which are discussed in detail in CHAPTER 2 result in forces on the drive shaft that follow the following structure:

$$F = A(\theta).\alpha + B(\theta).\omega^2 + G(\theta) + E(\theta).F_p \tag{10}$$

where: $A(\theta)$: Coefficient on angular acceleration (α), represents the system inertia as a function of angular position (θ)

$B(\theta)$: Coefficient on angular velocity squared (ω^2), represents internal inertia as a function of angular position (θ)

$G(\theta)$: Gravitation force, as a function of angular position (θ)

$E(\theta)$: Coefficient on piston force (F_p), which represents how the piston force, when translated through the mechanism produces a load on the drive shaft.

With most engines the value of angular acceleration (α) is small, the value of angular velocity squared (ω^2) increases internal and external loads as a function of engine speed squared. With a larger and slower engine, loads from the piston ($E(\theta).F_p$) and static loads from gravity will dominate. Friction is often taken as linearly proportional to the normal force [33] (as in Coulomb friction), or rolling resistance such as in dry ball bearings, lubrication depends on both normal force and speeds, and often the friction coefficient decreases with speed as lubrication films even out. In addition, at high speeds lower viscosity lubricants are required [34] and many high-speed Stirling engines utilize bearings that at high enough speeds utilize none contact gas bearings [21] with very little friction or wear.

A high-speed engine will have larger internal loads due to the internal inertia term, which may result in larger friction losses, however such an engine may reduce these loads with lower friction components. Such an engine will require a lighter flywheel and suffer from lower static loadings which would reduce friction further through leaner component design. Low-speed engines require larger flywheels but suffer less from internal inertia forces, however they have to be designed for larger static loads. Low-temperature engines could be the clear loser, with heavier components, thicker lubricants and a power density that is exponentially less than their high-temperature cousins.

1.2.5 Summary of Stirling Engines

In summary, while the ideal Stirling cycle provides the highest power per cycle, it is also impossible to accomplish. Therefore, designers must be able to manage the losses that appear as part of the practical modifications to the ideal cycle. The accurate modelling of these phenomena is particularly important for low-temperature engines, which as shown in section 1.2.4 suffer to a greater proportion in every loss category identified with the exception of inertia losses. Often the first step in loss identification is numerical modelling of the engine, which is the topic of the following section.

1.3 Modeling Techniques

There are many modeling tools developed specifically for Stirling engines or related machines. The complexity, and variety of tasks that Stirling engines have been applied to has forced the

creation of many specific models. Many have significant simplifications for the sake of computational efficiency which limit the scope of applicability of those models. Several advanced models are commercially available [35]–[37], which are outlined below and many models are described in the literature. Few are publicly available to the author's knowledge, as a result, this list is not all-encompassing, and many models and their implementation are only partially described in the literature.

Stirling engine models are classified by their order, a classification scheme introduced by Martini [23] in their "Stirling Engine Design Manual" of 1978. It is important to note that most models have been designed for a high-temperature context and that although many models may work under low-temperature conditions, the selection of correlations and factors common in lower-order models becomes a challenge [10].

1.3.1 1st Order Models

The most basic requirement for a model to be 1st order is that it produces closed-form solutions. What is meant by this is that the power can be determined explicitly through an equation, with often little more than the source and sink temperatures. Generally, they are recommended only for those who wish to begin investigating the possibility of a Stirling engine [23].

1.3.1.1 Efficiency Prediction

The most basic of 1st Order models described by Martini [23] is described by multiplying the Carnot efficiency by a series of efficiencies that represent different major losses:

$$\eta_{eff} = \left(1 - \frac{T_L}{T_H}\right).\eta_C.\eta_H.\eta_M.\eta_A \tag{11}$$

where: T_H, T_L: Hot (source) and Cold (sink) gas temperatures.

η_C: Carnot Efficiency, ratio of indicated efficiency to Carnot Efficiency, includes all gas and thermal internal losses. Often = $0.65 \rightarrow 0.75$, but can be as high as 0.80.

η_H: Heater Efficiency, a measure of how efficiency the heating element deliverers heat to the engine. Often related to a burner, but can be related to a heat delivery system. Often = $0.85 \rightarrow 0.95$

η_M: Mechanical Efficiency, related to the reduction of energy from the indicated power to the shaft power. Often = $0.85 \rightarrow 0.95$

η_A: Represents the power loss due to the driving of auxiliary systems, such as pumps, valves and instrumentation. Often = 0.95

This is multiplied by the input thermal power to form the expected power. Though useful, if estimating the power output in a well understood design space, this sort of model offers little to the designer for parametrization.

1.3.1.2 West Number

Introduced in the previous section, the West number [22] (N_{West}) is a non-dimensional number that represents the performance of a Stirling engine as is defined as:

$$\dot{E}_{shaft} = N_{West}.P_{avg}.V_{swept}.f_{engine}\frac{T_H - T_L}{T_H + T_L} \tag{12}$$

where: $\dot{E}_{shaft}$: Power as measured at output shaft of engine, after all engine specific losses.

P_{avg}: Average internal pressure of engine, averaged over both space and time.

V_{swept}: Volume of gas pushed through (in one direction) the exchangers.

f_{engine}: Engine (cycle per second) frequency at which $\dot{E}_{shaft}$ is measured.

T_H: Temperature of source, or average temperature in expansion space.

T_L: Temperature of sink, or average temperature of compression space.

The normal range of West numbers is around 0.25 [22]; a number that was obtained from a variety of high temperature high-performance engines. The power can be predicted by rearrangement. The West number establishes a baseline given that an engine is well designed it

should provide output power proportional to the macroscopic properties. However, it offers no key information on what exactly an engine, well designed for its conditions, should look like.

1.3.1.3 Schmidt Model

The Schmidt model is a semi-ideal analytical model, created by Gustav Schmidt in 1871 [25], that takes advantage of several assumptions about Stirling Engines. The Schmidt model offers greater insight into parametrization, of importance is the influence of piston motions on the indicated power. Due to its relative information density, it is the basis on which many 2nd and 3rd order models are constructed. As such it will be outlined in detail in the following pages, as outlined by Walker [38]. The isothermal simplification was classically used in this model that includes the following assumptions:

1. Perfect Regenerator:
    a. While within the regenerator the gas and regenerator material are the same temperature.
    b. The Regenerator temperature is constant in time.
    c. The Regenerator temperature follows a linear trend from the hot to the cold side.
2. The pressure is the same throughout the engine.
3. The working gas is ideal and therefore follows the equation of state: $P.V = R_{spec}.T$
4. There is no leakage internally or with the surroundings.
5. The piston motion and therefore the volume variations are perfectly sinusoidal in time.
6. Heat exchangers are uniform temperatures both spatially and temporally.
7. The cylinder wall and piston temperatures are constant.
8. There is perfect mixing in the expansion and compression volumes.
9. The temperature of the dead volume is constant.
10. The speed of the machine is constant.
11. Flow conditions are steady state.
12. The expansion and compression spaces are assumed to be isothermal.

Starting from assumption 4, the constant total mass is equal to the mass of all the gas spaces within the engine for every point in the cycle. The total mass (M) is the sum of masses (m) in individual components as:

$$M = m_{compression} + m_{cooler} + m_{regenerator} + m_{heater} + m_{expansion}$$
$$M = m_c + m_k + m_r + m_h + m_e \quad (13)$$

where: M: Total mass

m: Mass of the contents of individual components

By substituting mass with its equivalents within the ideal gas law and applying assumptions 2 and 3:

$$M.R_{spec} = P.\left(\frac{V_c + V_k}{T_L} + \frac{V_r}{T_r} + \frac{V_h + V_e}{T_H}\right) \quad (14)$$

where: R_{spec}: Specific gas constant of the gas inside the engine.

P: Pressure inside of engine (considered uniform, cycle position dependent)

V: Instantaneous volume of individual component

T: Average temperature of whole gas contents of individual component

By assumption 1, a linear temperature profile must exist in the regenerator:

$$T(x) = \frac{(T_H - T_L).x}{L_r} + T_L \quad (15)$$

where: L_r: Length, in flow direction, of regenerator.

x: Distance, in flow direction, from cold heat exchanger.

To calculate the mass of the regenerator, the temperature profile can be substituted in to give:

$$m_r = \int_0^{V_r} \rho(x).dV_r = \frac{V_r.P}{R_{spec}} \int_0^{L_r} \frac{1}{\frac{(T_H - T_L).x}{L_r} + T_L} dx \quad (16)$$

where: ρ: Local gas density, is a function of P, R_{spec} and $T(x)$

This reduces to:

$$m_r = \frac{V_r . P . \ln\left(\frac{T_H}{T_L}\right)}{R_{spec} . (T_H - T_L)} \tag{17}$$

which gives the temperature for the regenerator as:

$$T_r = \frac{(T_H - T_L)}{\ln\left(\frac{T_H}{T_L}\right)} \tag{18}$$

This can also give the pressure of the engine volume as:

$$P = \frac{M . R_{spec}}{\frac{V_c + V_k}{T_L} + \frac{V_r . \ln\left(\frac{T_H}{T_L}\right)}{T_H - T_L} + \frac{V_h + V_e}{T_H}} \tag{19}$$

The work done by a single cycle (W_{cycle}) is simply:

$$W_{cycle} = \oint P . \left(\frac{dV_c}{d\theta} + \frac{dV_e}{d\theta}\right) . d\theta \tag{20}$$

where: θ: Cycle angular position, from which V_c and V_e are both derived.

The volume variations as a function of θ are different for each of the 3 classical engine configurations but given a sinusoidal pattern the integral above may be solved simply by hand. The final work may then be multiplied by the cycles per second to get the work at any running speed. Using numerical integration, the above equations can be solved for non-sinusoidal motions as well which allows the model to generally applicable. However, based on the discussions in section 1.2.3, the isothermal idealization present in the Schmitt model make it a poor predictor of actual engine performance.

1.3.2 2nd Order Models

Second-Order models are simulations that are based upon or are closed-form solutions. According to Martini [23], 2nd Order models start with a 1st Order model, and then degrade the resulting power output by losses that are decoupled from the engine cycle. 2nd Order models often apply empirical correlations for these losses which can be subjected to calibration. However, they generally do not considered loss dependencies and often require expert knowledge to apply the correct correlations [23]. This makes accuracy susceptible to a case-by-case basis. Like 1st order models, speed is an input to these models, making them incapable of determining speed as an output or modelling dynamic speed scenarios. Due to their uncoupled nature, 2nd Order models are only capable of converging towards a steady state solution and the user must consult the produced engine curves when determining the engine speed for a given loaded condition. The following details the main 2nd order models discussed in the literature.

1.3.2.1 Urieli & Berchowitz

The SIMPLE model – so called as it is a simplification of the actual non-steady flow heat exchange – was derived by Urieli and Berchowitz in their 1984 publication [16]. The scheme was originally written in Fortran, but updated to MATLAB [39] and hosted online by Urieli [11]. This software used the ideal adiabatic model assumption and integrates into the solution the non-ideal performance of the heat exchanger sections. The model assumes quasi-steady assumption of friction and heat exchange through the heat exchangers. This model is decoupled from losses not associated with non-ideal heat exchanger or regenerator performance. The base model by default subtracts regenerator wall leakage and pumping losses from the power output. The model was expanded by Speer [10] to include a host of recognized Stirling engine losses as decoupled subtractors.

1.3.2.2 Babaelahi & Sayyaadi

The SIMPLE model [16] was expanded in 2014 by Babaelahi and Sayyaadi [40]. The authors included heat absorbed and rejected by the displacer piston and mass leakage between the engine and buffer spaces in addition to using different equation forms for representing pressure. Additional decoupled losses included finite speed losses, mechanical friction, and the longitudinal conduction along the regenerator wall. The study predicted the power and efficiency of the high-

temperature 3kW GPU-3 Stirling engine by General Motors with at least 5 times as much accuracy compared to the original SIMPLE model and better than the state of the art of equivalent models at the time.

Babaelahi and Sayyaadi [41] developed a new model in 2015, called the polytropic analysis of Stirling engine with various losses or PSVL. The model takes into consideration that Stirling engines are a continuously varying polytropic process. The author's devised a method for determining polytropic indexes for each working space as a function of crank angle. The method also introduces 3 categories of loss considerations. The first of which was direct partial differential equation representation for polytropic heat transfer, gas leakage and shuttle effect. The second, including non-ideal heat transfer, pressure drops which applied their corrections to the temperatures between each iteration. The third category involves losses that don't affect the temperature distribution and were therefore subtracted from the power afterward. The polytropic index is derived from properties and used in heat conduction for each increment of the cycle, the model is iterated until the index forms a continuous loop. The model proved to be more accurate than the author's previous models.

1.3.2.3 Commercial Codes

One of two commercially available 2nd order models: SNAP pro by Altman [37] is a model implemented within the MS Excel environment for straight forward user modification. By default, an engine parameter set can be optimized via a genetic algorithm. SNAP Pro is based on the work of various researchers including Martini [23], Berchowitz's linear analysis [42] for free-piston analysis and includes losses due to forced work from Senft [27].

The second commercially available software, PROSA 2 by Thomas [36] is implemented in a self-contained program with a detailed parametrization scheme with simplex optimization. The author also developed a 3rd order model that allows for speed variations and non-sinusoidal piston variations, but further documentation for either model could not be found.

1.3.3 3rd Order Models

According to Martini [23], third-order models divide the working volume into distinct volumes and the basic equations are solved using numerical methods. This, as opposed to the 2nd order

assumption, allows interdependent processes to affect one another. The field was pioneered by Finkelstein [43], who developed the first nodal analysis, who's work is updated by the models discussed below. These models are regarded as more accurate than 2nd order models in general, in particular a 3rd order model will have greater accuracy when exploring a new design space, but may be comparable to a 2nd order model in a well-defined space [23]. Due to their sensitivity to such features and higher general accuracy, they are often used in the later stages of engine design and as part of optimization studies.

In addition to greater generality, 3rd Order models offer outputs that cannot be measured experimentally or by lower order models. Temperature is notoriously difficult to measure reliably due to response times, whereas the 3rd Order model defines the instantaneous values. Depending on the solution scheme, dynamic solutions may also be available which can detect phenomena such as staling after a change in load and even allow initial design of engine control systems before a physical prototype is even made.

1.3.3.1 SAGE

Possibly the most well known commercially available 3rd Order model for Stirling engines is SAGE, developed by Gedeon [35]. This modular model, which is well documented, creates discretized networks of nodes, that are solved using the harmonic assumption. The harmonic assumption, which represents cyclic values as a Fourier series, is largely accurate for a wide variety of Stirling engine designs and very computationally efficient because parameters are defined as a series of phases and magnitudes as opposed to individual timestamped values. SAGE has been used for both low-temperature [44] and high-temperature Stirling engine designs [45]. A detailed discussion of this model can be found in Gedeon [35], as well as Hoegel [45]. SAGE features high performance, but through communication with users within the University of Alberta, it is noted to have a high learning curve and has difficulty converging in unique circumstances. In addition, SAGE is unable to support dynamic scenarios [35] due to the nature of the harmonic solver. Regardless, this model was studied extensively during the development of the current model presented later in this thesis.

1.3.3.2 Nlog Thermodynamic Analysis Code

The Nlog thermodynamic analysis code is a 1D control volume code. The model was created by researchers investigating neural-network-based performance prediction [46] and was even modified to support dynamic scenarios [47]. Given a set of detailed parameters, Nlog solves the equations of mass, momentum, and energy for each volume in the engine. The model ignores solid-conduction effects and instead has two wall types: An isothermal wall type, i.e., temperature remains constant and a regenerative wall type, i.e., net heat transfer to its control volume is zero over the cycle. It is not well documented to the authors knowledge and may be difficult to configure to engine types.

1.3.3.3 Anderson

Anderson et al [48], from the Technical University of Denmark, developed a modular model for research usage using the MusSim framework, which the author also developed. The author studied the effect of the regenerator's thermal response within the cycle and found that handling it dynamically introduced a relatively substantial change in calculated engine power. Anderson's model is constructed out of modular groups much like SAGE's implementation but in the incremental form, making it capable of deriving dynamic scenarios given that the mechanism dynamics are provided. However, this model is not publicly available to the authors knowledge and little information could be found on its implementation.

1.3.4 Higher-Order Models

Models that consider flow to be a one-dimensional phenomenon often have increased error when the engine is not symmetric about its axis. Discretizing gas space in a 2nd dimension is generally what changes a 3rd Order model into a higher-order model. Substantially more computationally expensive, this form of engine modeling is generally very accurate, but the approach is currently too slow for any but final engine design and optimization. Two groups have made advances in this level of modeling, researchers at the University of Northumbria [49] and researchers at NASA [50].

1.4 Chapter Conclusions

There is a great opportunity for alternative energy generation through recovery of low-temperature energy source. These include: waste heat which accounts for up to 70% of all energy used in Canadian industries [1] and geothermal energy. The energy recoverable from these processes, which are limited by thermodynamics to between 2-4% in most cases still amounts to significant energies. Geothermal energy has potential [2], but is completely untapped by existing technologies in Canada. It is the goal of DTECL to investigate Stirling engines as potential contributor to utilizing these energy sources.

Work is being conducted in this area, but a major weakness of the investigation is the models that are being used, which are inaccurate [10], [13], [14], particularly at low-temperatures and are difficult or inextensible in usage. A significant weakness in all the models presented is either being too specific or opaque, as in 1st and 2nd Order models. Or being inaccessible to new users such as with many 3rd Order models.

1.5 Thesis Goals

The goals of this thesis are as follows.

To develop a numerical model to

1. Simulate low-temperature engines. This entails a model that focuses on heat transfer, flow friction, leakage and allows detailed definition of the mechanism with its internal friction. To improve computational efficiency, loss modes such as radiation, fluid inertia and acoustics will be ignored.
2. Produce results that are validated against an experimental laboratory engine, analytical experiments and results from SAGE, an accessible and well validated numerical code.

In addition, the software will

1. Allow a user to construct a full working model of arbitrary geometry using a graphical user interface.
2. Present the model geometry in an intuitive and visual manner.
3. Provide the user with tools to record data of interest and interpret results.

The goal of the remainder of this thesis is to devise an implementation of the above goals in MATLAB [39] and test its ability to accurately model Stirling engines within the low-temperature context.

1.6 Thesis Outline

CHAPTER 2 documents the development process for the structure of the software and the problems that need to be solved using the model.

CHAPTER 3 documents the core mathematical and numerical processes.

CHAPTER 4 documents the implementation of the discretization and numerical solving.

CHAPTER 5 documents the algorithms used to enhance the convergence of the model.

CHAPTER 6 documents important information on how to use the software module, as well as the importance of model outputs.

CHAPTER 7 documents the tests used to verify the performance of the model.

CHAPTER 8 concludes the thesis with an assessment of the project goals.

Further information for each of these chapters as well as the entire project code can be found in the Appendices.

CHAPTER 2. SYSTEM DEVELOPMENT AND ARCHITECTURE

2.1 Development

The following sections outline the type of problem that this model targets. This begins with defining the processes that go on within an engine and then abstracting those phenomenon and features into components that can be added by the user. Based on the discussion in section 1.2, a low-temperature engine's power is limited to a great extent by its losses. These losses stem from poor heat conduction within heat exchangers, problems with heat control in other volumes, pressure leakage, flow friction and mechanical friction. These losses are all interconnected, poorer heat transfer into the engine, also reduces the loss of that energy to the wall. Internal to external leaks or even leaks between different areas of the engine effect heat transfer and flow friction through changing gas flow rates. Flow friction effects the force on the piston and thus the mechanism losses.

2.1.1 The Gas Medium

The best way to model these losses is to model the physical system that produces these losses. The extreme of this is to build physical prototypes. Outside of that the most conservative approach is to use CFD or 4^{th} Order models which attempt to model all the physics with as little assumptions as possible. A further compromise then exists by assuming that the flow is 1-dimensional, which reduces the number of calculations but increases the complexity of each of them. This complexity thankfully is very well studied as it reduces the Stirling engine into a dynamic pipe network problem. Having modelled the gas inside the engine as a pipe network, albeit a cyclically changing one, the viscous friction, leaks and the gas side of heat conduction can be relatively easily solved using empirical correlations to match the encountered flow geometry and conditions.

2.1.2 Uniform Pressure

Stirling engines rely on the compressibility of their contents to function; therefore, the gas must be modelled as compressible. This leads to a problem though, as the low-temperature Stirling engines generally don't operate at speeds that would require properly modelled acoustics, a

phenomenon which requires that the timestep is restricted by the speed of sound and not the speed of the gas. Practitioners have come up with ways of modelling the acoustic component implicitly [51], which avoids this restriction, but the assumption is made here is that acoustics has a negligible impact on the operation of the low-temperature Stirling engine. One way of modelling this is to assume, as in the Schmidt model, that the pressure is uniform throughout the engine. Friction losses can still be approximated as required by using the flow rates, but without compressibility, the gas speed – not the speed of sound – contributes to the timestep. This is thoroughly discussed in CHAPTER 3.

2.1.3 The Solid Medium

The next problem exists when solving the solid medium, solid conduction problems are simple compared to their gas counterparts, the equations are linear, and the conduction does not appreciably change with temperature within reasonable bounds. Therefore, it is easy to model thermal conduction in the solid body of the engine as a 2D or 3D network, provided that an engine is reducible to such a form. This will allow the system to naturally arrive at conduction losses without resorting to empirical formulas or surface idealizations.

2.1.4 The Mechanical System

The last component of development is the mechanical system. At this stage, for simplicity, only kinematic mechanisms will be studied. Thus, the volume of the piston cylinder spaces is solely dependent on the angular position. The gas spaces, in return, provide a force on the piston itself; composed of many individual pressures and shears. This force is translated through the mechanism, which uses the equation form introduced in section 1.2.4.5 to output a set of normal forces and torques. The normal forces are used to generate losses on the drive shaft. The torque, minus losses, feeds into the flywheel, generating an acceleration of the system.

The inclusion of a mechanism was important, as it was desired that the software could model dynamic scenarios. This would differentiate it from previous works such as SAGE [35] most of which are optimized for solving steady-state solutions. This restriction is often justified due to the fact that the majority of operating conditions Stirling engines will be connected to a reliable supply of thermal energy and therefore run at steady-state. However, permitting dynamic speed allows

MSPM to, in the future, support the design of control schemes for Stirling engine power systems. It allows the designer to properly size flywheels, which are required to be large for slowly rotating devices due to the inclusion of the ω^2 term in rotational kinetic energy. Additionally, it can prediction of conditions required for successful start-up of Stirling engines and predict stalling behavior from changes in load, which are hypothesized to occur due to the thermal distribution changes for different operating speeds.

2.1.5 Gas and Mechanism Relationship

The gas and mechanical systems are intimately linked, the question is then how to solve these two systems together. In normal Stirling engine operation, the mechanical system does not change speed very much over a cycle. The solution then is to break up the cycle into periods of time where the speeds are precomputed, this would allow the mechanical system to change speed and is due to the fact that the actual acceleration lags the force generated by the gas. A depiction of this can be seen in Figure 2.1. It is important to note that the lag can be reduced to be as small as desired by increasing the number of increments per cycle.

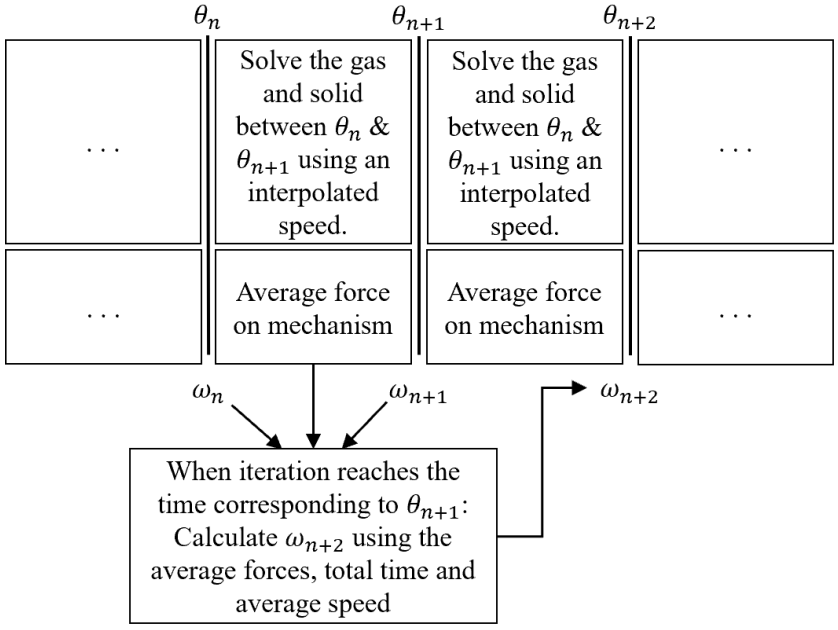


Figure 2.1: Gas/solid system and mechanical system interaction loop

2.1.6 Axial Symmetry

The design of Stirling engines revolves around the shape of its pistons, which make up the bulk of its internal space. Extra space in a Stirling engine not swept by the pistons, called dead volume, reduces the pressure swing and therefore the power of the engine. As a result, areas that are not pistons are compact and conform to the engine. Since pistons are round, based on manufacturing techniques used in the manufacture of both the bore and the piston head, Stirling engines are very commonly symmetric about a single axis or at the very least symmetric about multiple axis connected by round pipes. Round pipes due to the minimization of perimeter per cross-section as well as pressure resilience are also optimal. In addition, asymmetry in a Stirling engine leads to preferential flow, which makes them less efficient. All these factors enforce that a well-designed Stirling engine aught to be axially symmetric. Additionally, this restricts the solid modelling to only 2 dimensions which improves the readability of the model construction and reduces the computational complexity.

2.1.7 First Elements

The preceding discussion leads to a virtual engine that is composed of groups of cylindrical or annular elements. These elements are called bodies. A graphical depiction of this can be found in Figure 2.2.

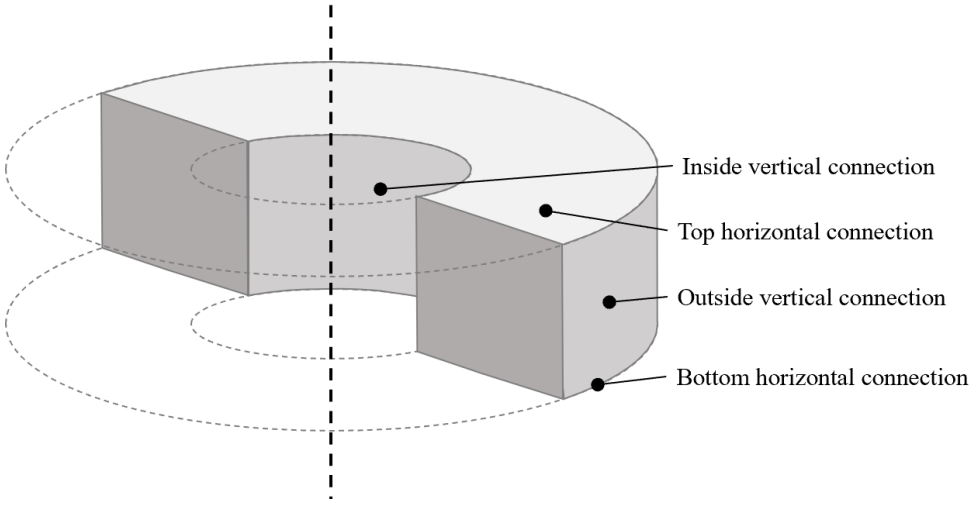


Figure 2.2: A body and member connections. In cylindrical elements, the inside vertical connection may be reduced to a single line at the axis.

These bodies have rectangular cross-sections when cut by a plane coincident with the center axis. This restriction, while it limits the variation in geometry that can be modelled, drastically reduces the complexity and handled cases from a programming perspective. A rectangle is characterized by having 4 sides at right angles to each other, thus sides can only be cylindrical shells or planes perpendicular to the center axis. As blocks of material in a Stirling engine are packed together, it makes sense that these surfaces – called connections – rather than the blocks themselves contain the dimension information, represented either a radius or distance along the axis. This trait prevents blocks from overlapping, except for the case where the interface moves enough to give an affected body a negative volume.

2.1.8 Further Abstraction

Often Stirling engines are not wholly axially symmetric. Gamma engines are classic examples as characterized by power pistons that are not inline with their displacer pistons. This then requires that to model these aspects, at least in a visually interpretable manner, that the ability to have multiple sets of these elements; lying upon potentially different axis is required. These sets will be called groups and allow the user to visually arrange the engine. With elements now separated in this manner, the only way to connect them would be to artificially produce a connection between a body in one group, to a body in another group, this component is called a bridge. Several additional components such as the leak, custom minor loss coefficient and non-connection also connect, modify, or disconnect two remote bodies in their own way. All these components will be discussed in greater detail further into this chapter.

Some structures such as those found in regenerators or heat exchangers are too small or complex to be modelled at the body level. Instead, it leads to an additional component called a matrix. This matrix component will be added to a body, modifying it by introducing representations of the fine geometry. These modifications will be such that interactions during simulation approximate the macroscopic behaviour of the structure.

2.1.9 The Name

All models need a name. This software and the solving system that is contained within is intended to solve the thermodynamics and losses of Stirling engines. As will be seen later in the

following sub-sections and CHAPTER 3 the model is a modular structure that is intended to solve single phase problems that have cyclically varying motions. Thus, from now on, the model is called MSPM or Modular Single-Phase Model, as it does not have to be restricted to just Stirling engines. The term modular refers to the fact that the network that is solved is formed from blocks representing components such as bodies of solid material, flow channels, heat exchangers or open volumes which change shape. These modules can be arranged into arbitrary arrangements, which the software converts into a network, and solves for pressure, temperature and mass.

2.1.10 Final Structure

Figure 2.3 represents the final hierarchical map of the different components of a definition file. These components – bodies, connections, groups, and bridges – contain the bulk geometrical information as well as the information and functionality needed to discretize themselves. These linking lines do not represent the programming concept of inheritance, but rather which objects contain references to other objects.

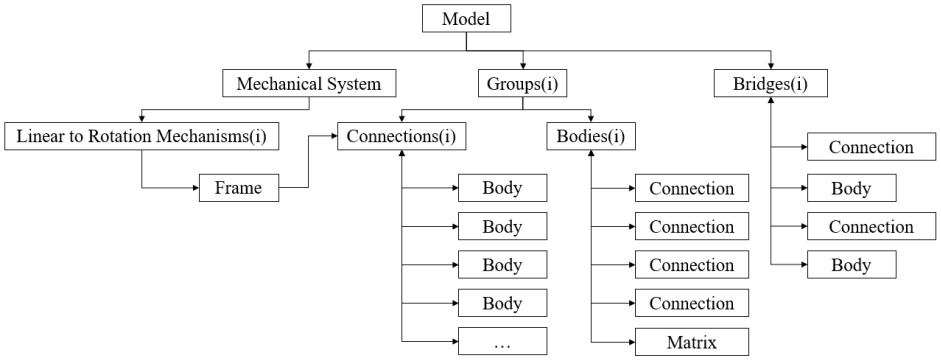


Figure 2.3: A flow chart of the system architecture

The core element, a class called model – so called as it is a representation of the physical model of an engine – includes a single mechanical system which links to multiple linear to rotational mechanisms (such as slider crank mechanisms). Each linear to rotational mechanism provides a motion profile, here called a frame. The model can contain multiple groups, which are collections of bodies which lie around the same rotational axis. Each of these bodies contains a reference to 4 connections. Those connections that are oriented perpendicular to the normal axis can also reference a frame and in turn are able to move in accordance with that frame using their current

position as the datum. In gas bodies a representation of an internal structure, here called a matrix, can be added.

The next sub-sections, for the purposes of terminology, will discuss the numerical elements followed by a section on the macroscopic features.

2.2 Finite Elements

Finite elements represent small sections of the engine, within which the properties are assumed to be constant. The smaller these elements are, the more the modelled system reflects the continuum of the real world. Following subsections will define the finite elements that play important roles in the creation of the mesh.

2.2.1 Nodes

A node represents a small element of matter. The shape of gas nodes may evolve in response to the motion of engine components, solid nodes - though incompressible - may translate through space, for example as a part of piston assemblies. There are 4 variants of nodes as outlined in the following sub-sections:

2.2.1.1 Common Properties

Volume (V) – The total volume of the node: $V = \pi(r_o^2 - r_i^2)/(y_o - y_i)$

Internal Energy (u) – The specific internal energy of the node, this property is initially determined as a function of the initial temperature, but later defines the temperature.

Temperature (T) – The temperature of the node

2.2.1.2 Gas

Mass (m) – The total amount of mass in the node, initial mass is derived from the set pressure, temperature, and volume: $m = VP/R_{spec}T$

Pressure (P) – The pressure of the gas node

Turbulence (τ) – If the node is of constant volume, this value is the weighting factor between laminar and fully turbulent. For variable volume nodes, it is a representation of the specific turbulent kinetic energy, which is the amount of oscillatory kinetic energy for each unit mass.

Hydraulic Diameter (d_h) – Geometry and orientation dependent

Radial Flow	Annular Flow	Cylindrical Flow
$2(y_{max} - y_{min})$	$2(r_{max} - r_{min})$	$2r_{max}$

Nusselt Number Function ($F_{N_{Nu}}(N_{Re})$ or $F_{N_{Nu}}(N_{Re}, N_{Pr})$) – Geometry and orientation dependent as:

Radial Flow	Annular Flow	Cylindrical Flow
	Laminar	
3.66	Inner: $4.4438.\left(\frac{r_o}{r_i}\right)^{-0.43}$ Outer: $4.6961.\left(\frac{r_o}{r_i}\right)^{0.0548}$	3.66
	Turbulent	
	$0.035.(N_{Re})^{0.75}(N_{Pr})^{0.33}$	

The properties of the specific gas constant (R_{spec}), inverse heat capacity ($F_{u2T}(T)$) correlation, thermal conduction $F_k(T)$ correlation and viscosity $F_\mu(T)$ correlation are taken from the gas the node inherits from its parent.

2.2.1.3 Solid

Mass (m) – The total amount of mass in the node, the mass is constant and initial determined as $m = V\rho$, whereas density is extracted from the material of its parent.

Heat capacity (C_T) is taken from the material the node inherits from its parent.

2.2.1.4 Environment

Static convection coefficient (h) – Corresponds to the ambient atmospheric conditions, a stagnant environment would be associated with a low convection coefficient. A well-ventilated space or windy space may correspond to a higher value.

The environment node represents the atmospheric surrounding of the engine, it serves as a source of gas, a place of exhaust and a constant temperature source. It contains all the properties of a gas node, but never change from initial calculation. Additionally, the properties of mass (m) and volume (V) are equal to infinity for calculation purposes.

2.2.2 Faces

A face is a physical interface between nodes. A face can take many forms, whether gas-gas, gas-solid or solid-solid or any nodes with the environment. In general, a face contains an area and transmit energy between nodes based on transport, conduction and convection. Faces can have evolving properties or vanish when their two interacting nodes are no longer overlapping during periods of the cycle. There are 4 variants of faces as outlined in the following subsections

2.2.2.1 Gas-Solid

Surface area (A) – The wetted area of the solid node concerning the gas node:

- Normal to the radial direction: $A = 2r_{fc}\pi(y_{max} - y_{min})$
- Normal to the axial direction: $A = \pi(r_{max}^2 - r_{min}^2)$

Resistance (R) – Calculated from the surface to the center of the solid node:

- Conduction in the radial direction:

$$R = \frac{r_{fc}\ln(r_{ratio})}{A.k} \tag{21}$$

where: r_{int} = radius of the nodal interface.

r_{ratio} = The minimum of $\frac{r_{fc}}{r_i}$ and $\frac{r_i}{r_{fc}}$ (see Note)

Note: $r_i = \sqrt{r_{min}.r_{max}}$ as the position in the element where the conduction coefficient towards the inside is equal to the conduction coefficient towards the outside. In cases where x_{min} is zero, $r_i = \frac{2}{3}x_o$ representing the average radius of the body.

- Conduction in the axial direction:

$$R_{fc\to i} = \frac{L_{fc\to i}}{A_{fc}.k_i} \tag{22}$$

where: $L_{fc\to i}$ = Distance from the interface to the center of the solid node in the direction parallel to the group axis.

2.2.2.2 Gas-Gas: & Gas-Environment

Area (A) – Calculated the same as with Gas-Solid faces

Friction distance (l_f) – Represents the length that the face calculates its friction over. A graphical representation is found in Figure 2.4.

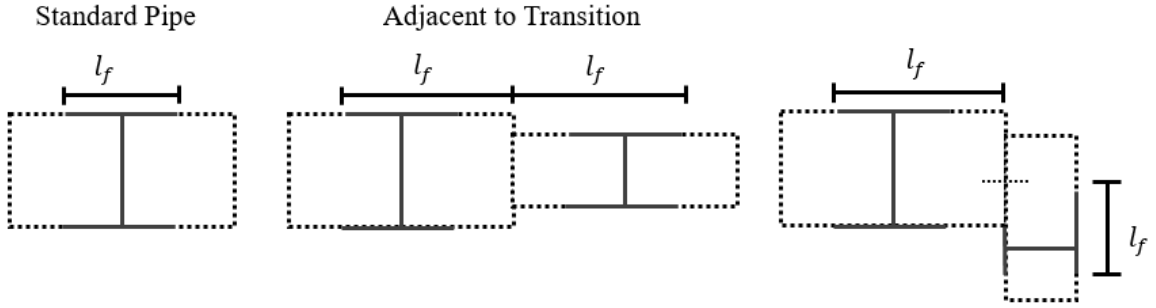


Figure 2.4: Geometrical cases and resulting friction length

In cases where the node leads into a transition where a minor loss coefficient is used, then this friction length extends to cover up until the transition. This only occurs in scenarios where the node does not branch, for example, where each node involved only has 2 gas faces.

Minor loss coefficient (K_{12}, K_{21}) – replaces the Darcy friction factor pressure loss, minor loss coefficients are calculated by first determining three areas: the initial area (A_1), the orifice area (A_2) and the final area (A_3). The minor loss coefficient is then calculated by the following equation.

$$K = \begin{cases} (1 - B^2)^2 & B > 0.76 \\ 0.42(1 - B^2) & otherwise \end{cases} \quad (23)$$

where: B = ratio of cross-sectional areas, equal to the smaller area divided by the larger area.

The vast quantity of potential permutations of this quantity as well as its evolution under laminar regimes are ignored under this implementation, this coverage is merely included as an estimate and is not the primary contributor to flow losses when compared to matrix passages found in Stirling engines.

Hydraulic diameter (d_h) – calculated the same as it is for gas nodes.

Conduction distance (l_c) – represents the length between neighbor node centers for thermal conduction, this is the average dimension of the interacting nodes normal to the orientation of the face.

Stability distance (l_s) – is the length used when solving for the local Courant number. This is the minimum dimension of the interacting nodes normal to the orientation of the face. In most situations it is equal to the minimum of the two aligned-node sizes. The Courant number is typically defined as:

$$N_{Co} = \frac{\delta . U}{l_s} \quad (24)$$

where: δ: The length of a time-step during iteration.

U: Gas velocity normal to the direction of l_s.

Reynolds Number (N_{Re})

The Reynold's number is calculated at the start of each cycle and as required after that for friction updates. The Reynold's number is defined here as:

$$N_{Re} = \frac{\rho . U . d_h}{\mu} \quad (25)$$

where: ρ: Density of fluid.

U: Velocity of fluid.

μ: Dynamic viscosity of fluid.

d_h: Hydraulic diameter of channel in direction of U.

Friction function ($\boldsymbol{F_{N_k}(N_{Re})}$)

Calculates the Darcy friction factor (N_f)

Radial Flow	Annular Flow	Cylindrical Flow
	Laminar	
$96/N_{Re}$	$96/N_{Re}$	$64/N_{Re}$
	Turbulent	
	$0.11\left(\frac{l_r}{d_h}+\frac{68}{N_{Re}}\right)^{0.25}$ [35]	

Mixing function ($\boldsymbol{F_{N_k}(N_{RE})}$)

Calculates the mixing enhancement factor (N_k), for all geometries.

Laminar: $N_k = 1$

Turbulent: $N_k = 0.022(N_{Re})^{0.75}.N_{Pr}$

Shear Factor ($\boldsymbol{C_{shear}}$) & Velocity Factor ($\boldsymbol{C_{velocity}}$)

Shear Factor is defined as the shearing rate of the gas node, in the axial direction, declared with units of m/radians. Often combined with velocity factor. Velocity Factor is defined as the relative motion of this gas face relative to the walls around it. Declared with units of m/radians.

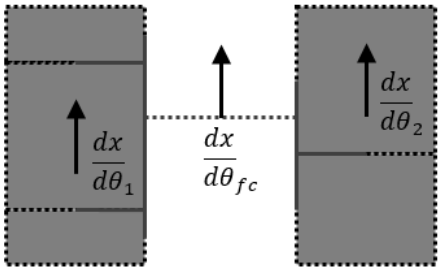


Figure 2.5: Shear and velocity factor input variables

$$F_S = \left|\frac{dx}{d\theta_1} - \frac{dx}{d\theta_2}\right| \tag{26}$$

$$F_V = \left(\frac{dx}{d\theta_{fc}} - \frac{1}{2}\left(\frac{dx}{d\theta_1} + \frac{dx}{d\theta_2}\right)\right) \tag{27}$$

2.2.2.3 Solid-Solid

Conductance (C) – Calculated from the center of one node to the other, these are the inverses of the resistances calculated under the gas-solid face (equations (21) and (22)), combined in series to allow for material discontinuities.

$$C = \left(\frac{1}{C_{i\to fc}} + \frac{1}{C_{fc\to j}}\right)^{-1} \tag{28}$$

2.2.2.4 Solid-Environment

Conductance (C) – Calculated from the center of the solid node to the environment using the constant convection coefficient combined in series based on the following formula.

$$C = \left(\frac{1}{C_{i\to fc}} + \frac{1}{h_j A_{fc}}\right)^{-1} \tag{29}$$

In practice the conductance of the engine with the environment will be a constant value, and therefore it possesses the same symbol as the conductance used for solid-solid interactions.

2.2.3 Node Contacts

A node contact is a temporary element that is used to define the contact of a node against the 1D surface of a connection. This allows all bodies to be discretized and these temporary data structures to be sent to the respective connection to be later combined into faces. For connections in the form of a cylindrical shell, a node contact represents a thin ring shape composed of a lower

and upper bound in the direction of the local axis normal. For other connections of the horizontal type, a node contact will be composed of an annular disk shape, with an inner and outer radius, lying on the connection plane and centered concerning the axis. These boundaries also move with the node, which facilitates the creation of faces with angularly dependent areas, existing only during the crossing point of two nodes. The interaction with bridges necessitates the inclusion of a local porosity, which represents how much of the total surface area is available, i.e. the hole drilled to access the top of the engine body for the power piston would reduce the surface area of the top plate.

2.2.4 Pressure Contacts

A pressure contact is a special surface used during simulation to connect a mechanism to surfaces on which pressure acts. Pressure contacts are exclusive to faces that are both moving and horizontally oriented. The properties of pressure contact include its area, direction and node index from which the pressure can be recovered from the output array. This pressure is converted into a force and sent to the mechanism during the mechanism loop.

2.2.5 Shear Contacts

Like a pressure contact, the shear contact approximates the proportion of shear drag from any gas channels parallel to the moving surface. The properties of a shear contact include the acting area, force direction and the face index from which shear is calculated. The force is calculated as one half of the pressure drop across the face, which is attributed to the shear drag against the wall.

2.3 Interactable Elements

Interactable objects encompass the group of objects that the user modifies, moves about, and interacts with. These objects can be thought of as a high-level perspective of the final numerical model, which is produced when the model file is discretized. These elements all work within the property inspection interface, can be created via the GUI, and contain the functionality to translate their settings into numerical elements containing their own complex functionality.

2.3.1 Groups

Groups are collections of bodies that all lie around a common axis of symmetry. Groups contain a set of physical properties, including orientation data for their axis and the bounding box that surrounds its contents. The group component also includes the functionality to form connections between the bodies it encapsulates and the environment. In brief, this function collects all the segments of all the connection at which a body intercepts, it then removes all the segments that are covered twice by any body (i.e. a body on either side). The remaining segments after this algorithm are either part of an illegal open space internal to the engine or are exposed to the surroundings. At the point of discretization this information is passed down to the respective connections a temporary construct known as a node contact featuring the gas node that represents the environment. After processing, this results in connections that facilitate energy and mass exchange with the environment when the model is simulated.

2.3.2 Bodies

Bodies represent a cylindrical or annulus shaped element that is aligned with a group axis. A body can be any material, solid or gaseous. Bodies contain references to 4 connections that serve to define its dimensions in the axial and radial directions. The primary function of a body is to be discretized into nodes and faces. Those nodes that lie on a boundary are passed as node contacts to connections. A body containing gas can also contain an internal structure represented by a Matrix component, which it provides its created nodes to be further modified. Bodies also contain functionality for validation, depending on the material. For example: solid bodies cannot change its dimensions but may translate. Meanwhile, a gaseous volume can both translate and stretch in their axial direction. Neither material allows for bodies to overlap or invert, which prevents the model from simulating an engine that couldn't exist or function.

Bodies can be discretized by two modes, which are shown in Figure 2.6, these modes can be optionally applied to one of or both axial and radial directions:

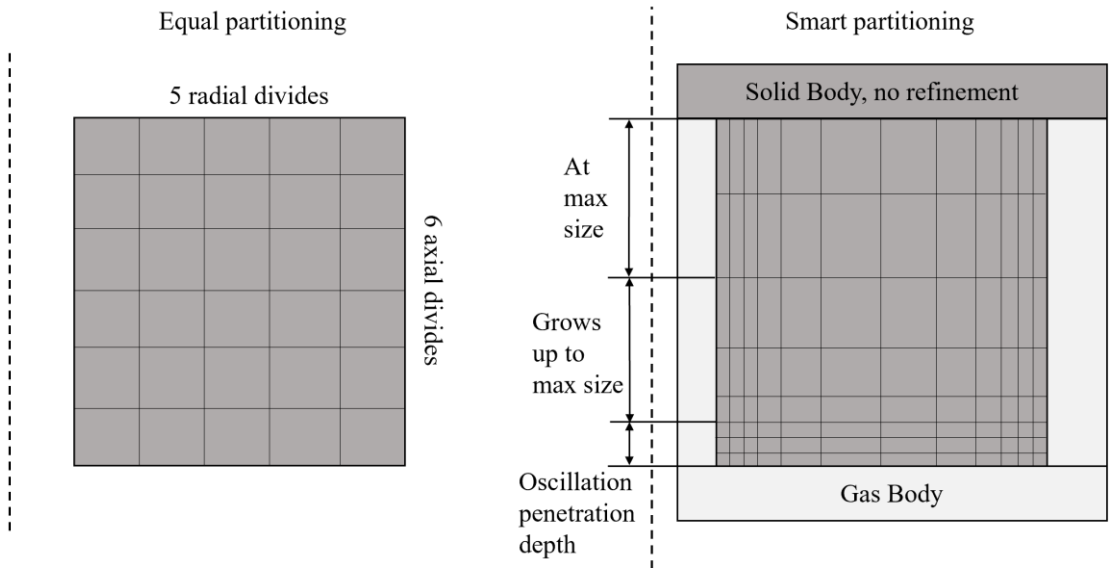


Figure 2.6: Discretization modes for body

Equal partitioning – The body is sliced into several equal layers in both the radial and axial directions.

Smart partitioning – In solid bodies this discretization is dependent on whether a side is in contact with a gas node or within a specific distance of a gas body. Only a small part of a side must be in contact with a gas node to activate this function. But at those edges a specified number of nodes will be placed within the oscillation penetration zone, a zone defined by the thermal diffusivity and expected frequency of the engine test (discussed in section 6.2.1). Beyond that zone the node size grows by a specified growth factor to a maximum node size. If neither side is in contact with a gas node the body is discretized coarsely with equal partitioning such that the node size is not greater than the maximum node size.

In Gas nodes this discretization works along the discretized direction and creates a series of thin entrance nodes over the first and last 15% of the total length. Beyond these regions the nodes grow using the prescribed growth factor. This style of discretization is inspired by the work of Anderson [48] who applied this technique to regenerator and heat exchanger elements. These elements are discussed in the next subsection as matrixes.

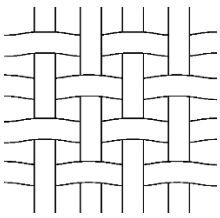
2.3.3 Matrixes

Matrixes are found nestled within gaseous bodies; these elements represent a variety of fine channeled geometries such as regenerators and heat exchangers. These elements are closely in contact with the gas network and each has a porosity and geometry that merits an override of the default defined hydraulic diameter (D_h), volume (V), area (A), Darcy friction factor (N_f) correlation, Nusselt number (N_{NU}) correlation, and Axial Mixing enhancement coefficient (N_k). When the matrix takes its parents nodes, it both modifies the provided nodes for the listed properties and adds solid sources, surface nodes and faces which model the solid components of the heat exchanger or regenerator as a nodal network. The following sub-sections discuss the different types and their different properties.

2.3.3.1 Regenerators

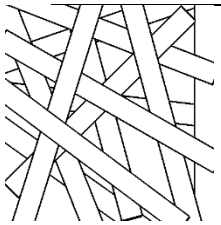
The types of common Stirling engine regenerator structures and their discretization are outlined here. For regenerators which are notably almost always laminar due to the domination of viscosity, only the laminar correlation is provided. Property correlations, which for regenerators are taken from Gedeon [35], are summarized in Appendix B of this thesis. The Darcy-Weisbach equation is used here instead of Darcy's law for flow through porose media both because it is used successfully in SAGE [35] and as a consequence of maintaining consistency with the rest of the model.

2.3.3.1.1. Woven Screen



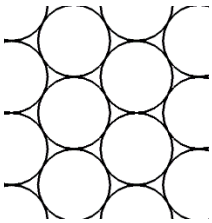
A woven screen regenerator is composed of a tight weave of filaments, often arranged in layers perpendicular to the flow direction to minimize parallel conduction losses. This is like the perforated screen type regenerator that is not implemented here. The woven screen has 2 inputs: porosity (β) and wire diameter (d_o).

2.3.3.1.2. Random Fiber



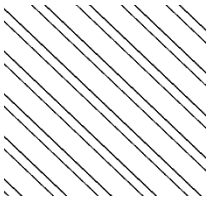
A random fiber regenerator is usually composed of felt or batting of randomly oriented fibers. The random fibre matrix has 2 inputs: porosity (β) and wire diameter (d_o).

2.3.3.1.3. Packed Sphere



A packed sphere regenerator is composed of many small packed spheres, sometimes sintered together. The packed sphere matrix has 2 inputs: porosity (β) and sphere diameter (d_o).

2.3.3.1.4. Stacked Foil

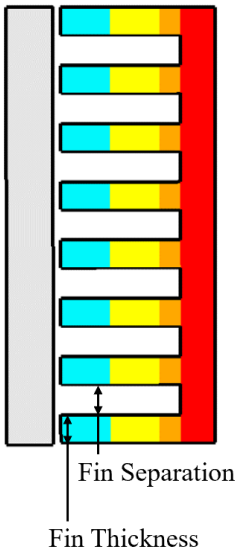


A stacked foil regenerator is composed of many thin parallel channels between thin foil elements. As this model is the most like an open channel, it provides a laminar and turbulent friction and Nusselt number definition. The stacked foil matrix has 3 inputs: the gap width (l_g), thickness (l_t) and surface roughness (l_r).

2.3.3.2 Heat Exchangers

Heat exchangers come in a wide array of different types; a selection of implemented types is described here. In each of the diagram's heat flow is identified by coloration with red at the heat source and blue as it gets farther from the heat source. Air either travels into the page through the open spaces or as indicated by arrows. All the correlations and property calculations for heat exchangers can be found in Appendix B.

2.3.3.2.1. Fin Enhanced Surfaces



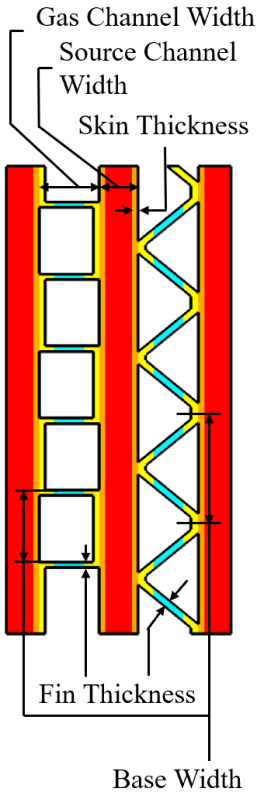
This type of heat exchanger is the case where one of the walls is the heat exchange surface, this surface is covered with long parallel fins that span across the gas space. This type of heat exchanger is common in a scenario where the engine body itself conducts heat to and from a source/sink of heat. Cases, where there are no fins and only a bare wall are handled natively by the conduction with the wall, without need for a matrix component.

Functionally, this matrix component allows the user to select a connection from which to grow the fins, the surface of this connection is

then integrated into the internal solid conduction network, which layers nodes normal to the selected connection.

Fin enhanced surface exchangers have 4 inputs and assumes rectangular fins: target connection, distance between fins (l_g), fin thickness (l_{th}) and surface roughness (l_r). Fin length is determined automatically by assuming that the fins go right up to, but don't touch the opposite side of the parent body.

2.3.3.2.2. Fin Connected Channels



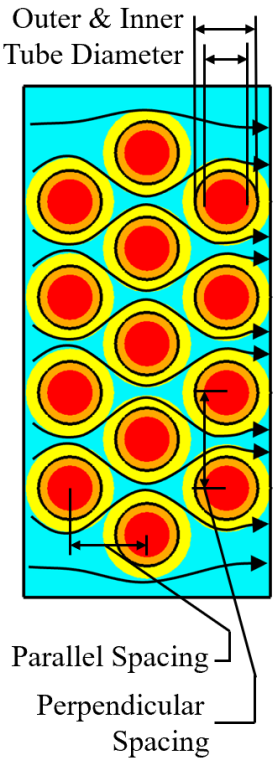
This type of heat exchanger encompasses the subclass of heat exchangers known as plate and frame heat exchangers. The main feature being that the cross-section is an alternating pattern of the two fluids, which persists through the depth.

The following two sub-types refers to the structure of the interstitial fins:

- Rectangular Gaps: The fins cross at 90° across the gas side forming many rectangular paths for the gas to flow through.
- Triangular Gaps: The fins zig-zag across the gas side forming many triangular paths for the gas to flow through.

This heat exchanger has several inputs including: fin type (rectangular / triangular), gas space between source channels ($l_{c,g}$), source channel width ($l_{c,w}$), skin thickness ($l_{c,wth}$), surface roughness (l_r), base width / fin separation ($l_{f,g}$) and fin thickness (l_{th}).

2.3.3.2.3. Fin Connected Tubes



This type of heat exchanger encompasses the subclass of heat exchangers known as compact heat exchangers or finned tube heat exchangers. The main feature of these heat exchangers is that one fluid (assumed to be the source/sink fluid) traverses through a series of tubes that are covered in surface enhancing fins or plates. The tubes are most often arranged perpendicular to the flow direction.

Fin Type

Continuous Plate: The fins of this subtype bridge across from tube to tube forming continuous plates. These are automatically produced when the user does not submit a fin length.

Individually Finned: The fins of this subtype are associated with just one tube.

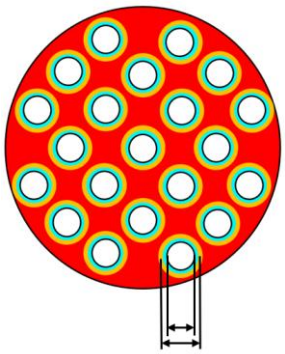
Tube Pattern

Staggered: Staggered tube means that each consecutive layer of tubes is offset relative to the previous one by exactly half the perpendicular tube spacing. This is seen in the figure to the left.

Aligned: Aligned tubes are aligned, such that each tube lies in the wake of the previous one. Aligned is generally not used unless a very low-pressure drop is the essential requirement [52]. Which is why it is not implemented here.

This type of heat exchanger accepts several inputs from the user including: spacing perpendicular to flow (l_{perp}), spacing parallel to flow (l_{para}), fin thickness (l_{th}), fin separation (l_g), tube outer diameter (d_o) and tube inner diameter (d_i). In which fin thickness and fin separation are identical to that identified for fin enhanced surfaces.

2.3.3.2.4. Tube Bank Internal



This type of heat exchanger is relatively common in high temperature engines, it involves the forcing of air through many parallel tubes each submersed in a thermally charged environment. The design attempts to minimize flow losses while providing maximum surface area and pressure containment ability.

This type of heat exchanger accepts 3 inputs: number of tubes (N), outer tube outer diameter (d_o) and tube inner diameter (d_i).

2.3.3.3 Discretization

2.3.3.3.1. Regenerators

Regenerators typically contain extremely fine geometry, a well-designed regenerator, one that behaves most like an ideal reversible device will maintain its temperature as close as possible with the gas's temperature. Thus, for a well-designed regenerator, the lumped mass assumption should be able to be applied with little error. As a result, a typical regenerator only requires a single layer of nodes. Discretization is straightforward then, simply construct a solid node for each gas node in the body and form a mixed face between the two elements. The properties relevant to discretization are as follows for each regenerator:

Table 2.1: Discretization specific properties for common regenerator types.

	Woven Screen & Random Fiber	Packed Sphere	Stacked Foil
Surface Area / Total Volume (A/V)	$4\frac{1-\beta}{d_o}$	$6\frac{1-\beta}{d_o}$	$\frac{2}{l_t + l_g}$
Resistance to average radius times Area $(R.A)$	$\frac{\ln\left(\frac{3}{2}\right) d_o}{2k}$	$\frac{d_o}{6k}$	$\frac{l_t}{4k}$

2.3.3.3.2. Heat Exchangers

Heat exchangers are different compared to regenerators, as their purpose is to transport heat from a physically separate space - the thermal reservoir - to the gas through their conducting surfaces. A well-designed heat exchanger should have as little as possible resistance as this ensures that the surfaces of the heat exchanger are as close as possible to the thermal source/sink, but often they include extended geometry which may help the heat transfer but not be exactly at the desired temperature. Therefore, heat exchangers are discretized along the path from the source to the gas. The discretization scheme for the implemented types of heat exchangers is depicted in Figure 2.7, through Figure 2.9 below.

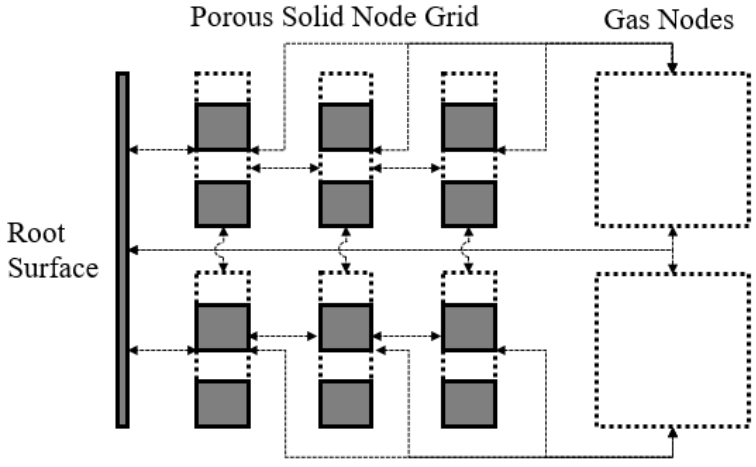


Figure 2.7: How elements are discretized in the fin enhanced surface type heat exchanger

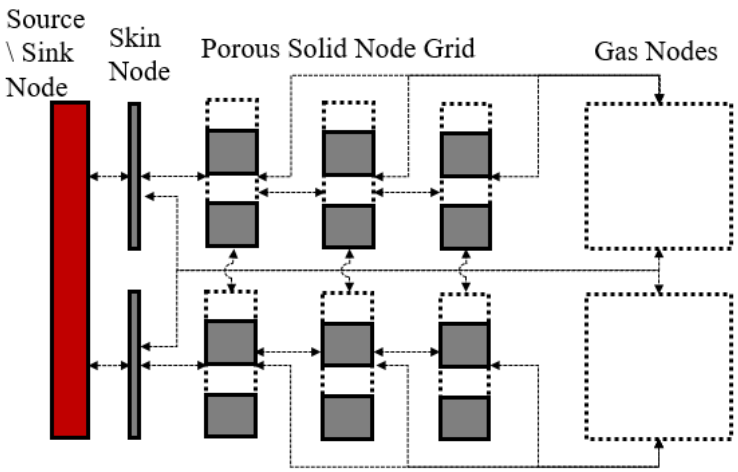


Figure 2.8: How elements are discretized in the fin connected channels and finned tube type heat exchanger

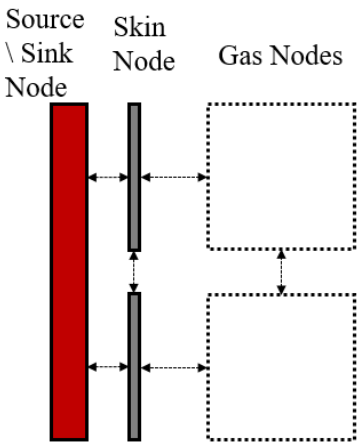


Figure 2.9: How elements are discretized in the tubes bank internal type heat exchanger

2.3.4 Connections

A connection represents a surface either as a cylindrical shell or as an axially normal plane. Connections have a position, an orientation and a reference to a frame. A connection can use the frame's motion profile to shift its position depending on the angular position, which can move the associated bodies. This only works when the connection is aligned as an axially normal plane.

To be discretized, connections find overlaps of node contacts, which over the course of discretization, have been received from the environment, bodies and bridges. In many cases the

properties of the faces that are generated from these overlaps will vary with respect to angular position, thus these properties are stored as arrays, one value for each angular increment.

2.3.5 Bridges

A bridge is a geometric construct that facilitates the interface between two bodies, which may or may not be part of the same group. These interfaces can occur between connections of perpendicular and aligned orientations. The referenced bodies then connect, in disregard for any existing external connections at that location.

There are four permutations of bridge definition. The first two are types which could have been constructed as a combined structure from the start but convenience or perhaps requirements by the program have made it more convenient to have separate. These versions are shown on Figure 2.10 below along with the third and fourth type. The third type of bridge is where the two selected connections are both horizontal, much like type 1, but their axis are misaligned such that the node interactions are only partial interactions. The fourth type is where there is a mix, where a horizontal connection contacts the side of a vertical connection.

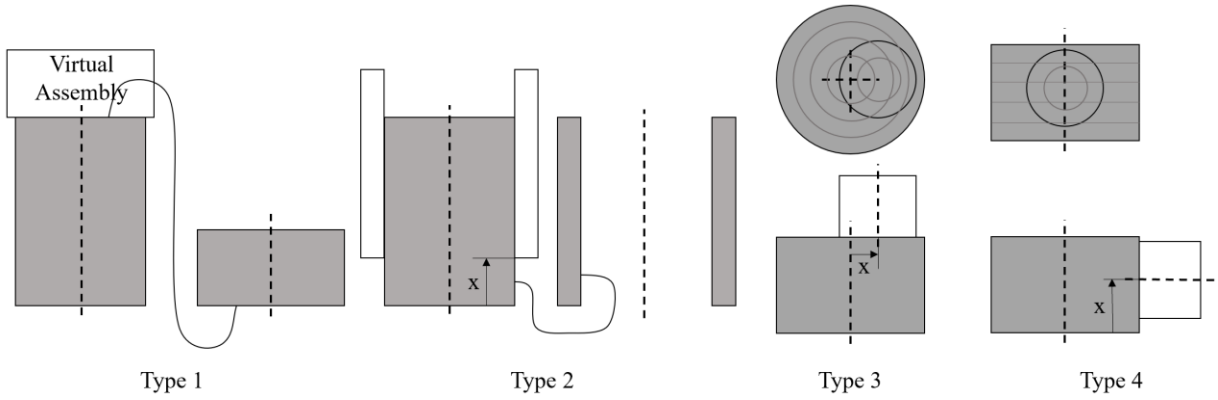


Figure 2.10: Permutations of the bridge component definition (1) two horizontal (disk) faces are stacked along a central axis (2) two vertical (annular shell) faces are aligned at some offset from the origin (3) two horizontal faces are stacked with axis offset by a specified amount (4) a horizontal face is perpendicularly mated up against a vertical face with the axis at a prescribed offset from the origin of the vertically aligned face.

Type 1 and 2 add their own node contacts to the register of the foundation connection, and trim node contacts on that register that both overlap the new contacts and are not from either body. Types 3 and 4, as their construction is much more involved, create a series of faces of size equal

to that which was produced by the overlap of 2 annular rings – in the case of type 3 – or an annular ring and rectangle – in the case of type 4. The software then modifies the existing node contacts by changing their porosity value, which will modify the area of faces created in subsequent operations within the connection. It is important to note that because the software assumes that the model is axially symmetric, any resulting faces are also axially symmetric, thus faces end up stretched around the entire body rather than towards one side of the body.

2.3.6 Leaks

A leak component is a special feature that connects two separate bodies as if connected by a small channel. When the leak is discretized, it forms a special face that stores the rate law parameters for use by the solver. The rate law employed by default here is of the general form, which has been applied as far back as 1881 [53].

$$\dot{V} = C.(P_1 - P_2)^{N1} \tag{30}$$

where: C: Leakage number

$N1$: Leakage exponent

2.3.7 Non-Connection

A non-connection was added so that the designer could create idealized representations. If two bodies were not supposed to interact via conduction, convection, or transport, then the non-connection can turn off these interactions by filtering the produced faces.

2.3.8 Custom Minor Losses

The custom minor loss feature was added to override the default defined minor loss coefficient created between any two bodies. This feature also allows the user to add facsimile of check valves by having a small loss in one direction, but a large loss in the other. Given the discussion defined in CHAPTER 3, this will only work as a check valve when the face is a part of a loop, due to the uniform pressure assumption, thus an alternative path must be provided, or the fluid will flow regardless.

2.3.9 Frames

A frame is a container for holding a position vector and mechanism reference. Connections that contain a frame reference and are subject to pressure or shear force produce a Pressure or Shear Contact object, which during simulation will pass these forces onto the mechanism itself.

2.3.10 Mechanism

Within the code, the mechanism is a container for a series of connected linear to rotational mechanism. These sub mechanisms all share a common angular motion state. The mechanism itself takes an accumulated driveshaft load as an input to its own internal friction, inertia, and load calculations to return an acceleration. Generally, the flywheel and power outputs are defined within this object. Currently the code does not support multiple mechanisms with multiple angular positions, which would be one way to simulate free-piston engines or engines that have a free-floating displacer piston.

The child linear to rotational mechanisms turn the rotation of the drive shaft into a translation, that can be applied to a boundary. During each calculation step, occurring once per angular increment, an average pressure force is calculated for all faces aligned normal to their motion. These pressure forces form a combined piston load for each installed linear to rotational mechanism – the forms of which can be found in the following sections. Each of these linear to rotational mechanisms is derived to solve its internal friction and inertia and provide to the driveshaft a pair of normal forces as well as a torque force.

Each mechanism contains stored coefficient vectors in the form of:

$$F = A(\theta)\alpha + B(\theta)\omega^2 + G(\theta) + E(\theta)F_p \quad \text{same as (8)}$$

where: $A(\theta)$: Coefficient on angular acceleration (α), represents the system inertia as a function of angular position (θ)

$B(\theta)$: Coefficient on angular velocity squared (ω^2), represents internal inertia as a function of angular position (θ)

$G(\theta)$: Gravitation force, as a function of angular position (θ)

$E(\theta)$: Coefficient on piston force (F_p), which represents how the piston force, when translated through the mechanism produces a load on the drive shaft.

In addition to the coefficients, all internal loads required to calculate the friction load (F_f) are also stored, which have their own equations of the same form. Friction is a relatively small component of internal forces, thus its effect on itself and normal forces is ignored and simply subtracted from the torque after its power consumption is calculated, via:

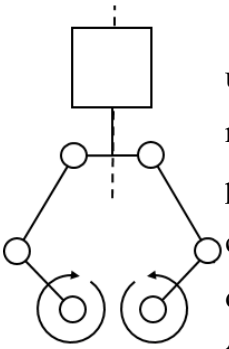
$$\dot{E}_{friction} = -\left|\omega T_{friction}\right| = -\left|v F_{friction}\right| \tag{31}$$

The following sub-sections are common mechanisms used by DTECL; additional mechanisms can be added to the code by following the template laid out by these. If a motion is desired, more than the mechanism behind it, then the custom profile mechanism attempts to predict some of the physics for such an unknown mechanism.

2.3.10.1 Slider-crank Mechanism

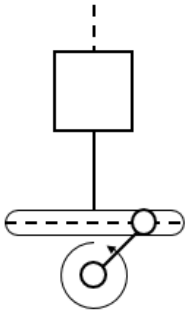
The slider-crank is by far the most recognizable linear to rotational mechanism. The slider-crank is used almost universally by internal combustion engines, this commonality leads it to be a convenient mechanism when designing Stirling engines. Constructed out of 3 components: the crank arm, the connecting rod, and the piston. There are three loss mechanisms associated with slider-cranks that are considered: friction between the crank and connecting rod, friction between the connecting rod and the piston and friction of the piston seal, all of which are subtracted from the final torque. The derivation of the parameters can be found in Appendix A.1.

2.3.10.2 Rhombic Drive



The rhombic drive is a very common mechanism in beta-type Stirling engines, utilized primarily for its compact design and reduced side loads. Also, the rhombic drive can be constructed such that it drives both the displacer and power piston on the same mechanism through the addition of a secondary set of connecting rods and a nested shaft. In its essence, a rhombic drive is simply a double slider-crank mechanism and thus its parameter derivation is built upon the solution of the slider-crank with some specific modification, this derivation can be found in Appendix A.2.

2.3.10.3 Scotch Yoke



The Scotch yoke mechanism is a relative of the slider-crank mechanism that, instead of a connecting arm, depends on a slot linkage to drive the piston forward. The Scotch yoke is often used because its side loads are more easily managed or relatively low due to the roller system. Another notable property of the scotch yoke is that it produces a truly sinusoidal motion profile. The derivation of the parameters can be found in Appendix A.3.

2.3.10.4 Ideal Sinusoidal Mechanism

The ideal sinusoidal motion model is intended for use at the early stage of engine development. The sinusoidal model is a frictionless scotch yoke and is only distinct as its definition interface is based solely on the properties of the sine wave itself without introducing linkage dimensions. The derivation of these parameters can be found in Appendix A.4.

2.3.10.5 Custom Motion Mechanism

The user can test different motion profiles for their effect on the thermodynamic cycle using a custom motion mechanism. This mechanism results in a model that approximates the inertia of the piston and driving mechanism through analysing the provided motion profile. The formulation is discussed in Appendix A.5.

2.4 Conclusion

Through the discussions presented in this chapter, it was established that the gas would be modelled as a one-dimensional pipe network of uniform pressure. All geometry would be considered axially symmetric, under the reasoning that well-designed Stirling engines are built in that fashion. Under that, the solid would be modelled as a two-dimensional network. The mechanism, due to low accelerations, would lag the gas network by short angular increments, in which the velocity was deterministic.

Those discussions lead to the establishing of a model definition composed of annular blocks of material, that connect to each other via mobile surfaces, grouped around a common axis. Bridges and a variety of surface modifiers were added to support specialized geometry. Fine structures are represented by network generating matrix components. These constructs decompose into a network of smaller allotments of material called nodes and the faces that link them together. The following chapter will discuss the mathematics required to solve this network.

CHAPTER 3. CORE MATHEMATICAL PROCESSES

The following sections outline most of the mathematics used to solve the model during a simulation. The mathematical complexities of specific components outlined in the subsections within CHAPTER 2. This chapter in combination with CHAPTER 5 brings it all together into a network solvable by a computer.

3.1 Terminology

The following terminology is defined here, other terms such as nodes, faces and the environment are defined in CHAPTER 2.

Region: A region is a set of gas nodes, which are always connected during the entire cycle through one path or another.

Loop: A loop occurs whenever there is more than one path between one part of a region to another part of a region. A loop that often occurs in gamma type engines is the path past the displacer and the path through the heat exchangers, which represent two different ways to get to form the compression to expansion space.

3.2 General Heat Transfer

3.2.1 Thermal Conduction Within Solids

The solid conduction model is based upon Fourier's Law, which calculate the thermal energy transfer rate ($\dot{E}_{cond}$).

$$\dot{E}_{cond} = k.A.\frac{dT}{dx} \tag{32}$$

where: k: Conduction coefficient of conducting material.

A: Cross-sectional area over which conduction occurs.

x: Position along the direction of heat flow.

This can be rearranged to suit the case of conduction between nodes.

$$\dot{E}_{cond,fc} = \frac{A_{fc}}{\frac{L_{i\to fc}}{k_i} + \frac{L_{fc\to j}}{k_j}}\left(T_i - T_j\right) \tag{33}$$

where: $A_{fc}, \dot{E}_{cond,fc}$: Cross-sectional area and thermal energy transfer rate of face, from node i to j.

$L_{i\to fc}, L_{fc\to j}$: Absolute distance, normal to the face, from the center of node i or j to the face's surface.

k_i, k_j, T_i, T_j: Conduction coefficients and temperatures associated with the nodes i or j.

In its final form, as seen in the model:

$$\dot{E}_{cond,fc} = C_{cond}.\left(T_i - T_j\right) \tag{34}$$

where: C_{cond}: Combined coefficient that converts a temperature difference into an energy flux.

Within the model faces can vary with angular position, thus this conductance property is condensed into a single interpolated property. For static faces only the result of the above coefficient is stored. This property is assumed to be constant concerning temperature.

3.2.2 Thermal Conduction Within Gases

Conduction between gas nodes is much like conduction between two solid nodes. Here only molecular conduction is solved. Radiation would also be solved here but is ignored in this model due to the low temperatures assumption. Thermal energy that is carried with mass flows is solved within the volumetric flow rate solving step, section 3.3.

$$\dot{E}_{cond} = k.A.\frac{\partial T}{\partial x} \tag{35}$$

This is arranged to suit the case of internodal conduction/convection. The factor N_k is a dimensionless conduction enhancement factor, which arises when turbulence or geometrical pathing enhances the streamwise mixing action.

$$\dot{E}_{cond,fc} = \frac{N_{k_{fc}}.k_{ij}.A_{fc}}{L_{i\to j}}\left(T_i - T_j\right) = C_{cond}.\left(T_i - T_j\right) \tag{36}$$

where: $N_{k_{fc}}$: Conduction enhancement factor.

k_{ij}: Thermal conduction coefficient measured at the face, equal to the average value of node i and j's conduction coefficient.

$L_{i\to j}$: Cumulative distance between the center of node i to the center of the face to the center of node j.

3.2.3 Thermal Conduction Between Solids and Gases

The conduction model between gases and solids is based upon the combination of conduction and convection; radiation is ignored.

$$\dot{E}_{cond} = \frac{A_{fc}}{\frac{L_{i\to fc}}{k_i} + \frac{1}{h_j}}\left(T_i - T_j\right) \tag{37}$$

where: Node i is the solid node and node j is the gas node.

h_j: Is the convection coefficient produced by gas node j's internal geometry and flow conductions.

This is arranged to suit the case of internodal conduction/convection.

Due to the existence of variable area contacts, resistance is stored as the product of thermal resistance and area. The following equation is modified to move area to the numerator, and use RA in the denominator. As resistance is equivalent to a constant over area, multiplying by area gives a constant. In this way, only area must be interpolated as resistance is proportional to the inverse of area.

$$\dot{E}_{cond,fc} = \frac{A_{fc}}{R_{i\to fc}.A_{fc} + \left(\frac{d_h}{N_{NU}.k}\right)_j}\left(T_i - T_j\right) \tag{38}$$

where: N_{NU}: The Nusselt number equal to $\frac{h.d_h}{k}$

d_h: Hydraulic diameter with respect to the flow in node j

In a special case of constant convection coefficient, the system can be simplified to that of the solid conduction. This is what is applied for connections to the environment.

3.2.4 Shearing Conduction Enhancement

In Stirling engines with a displacer piston, there is always a region of gas, called the annular gap, that undergoes shearing. The act of shearing will affect the effective axial conduction coefficient. This effect is approximated by assuming two things, which are also displayed graphically in Figure 3.1:

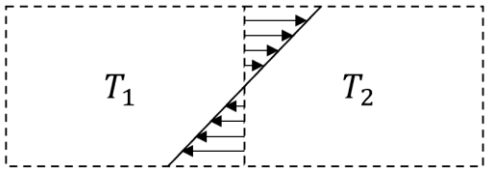


Figure 3.1: Illustration of shear driven mixing

1. Shearing conduction enhancement occurs independently of transport via bulk convection.
2. A gas node is a uniform temperature with a discontinuity at the face between.
3. The shear velocity profile is fully developed and linear.
4. After crossing the boundary, flows mix completely.

This equation introduces a non-dimensional number called the shear velocity factor, shear velocity is equal to the ratio of shear speed over rotational speed. The mass exchanged is equal to the following:

$$\dot{m}_{fc} = \underbrace{\left(\frac{A_{fc}}{2}\right)}_{\substack{Cross-section \\ over\ which\ it\ occurs}} \underbrace{\left(\frac{F_{shear}.\omega}{2}\right)}_{Average\ Velocity} \underbrace{\rho_{fc}}_{Density\ at\ Face} = \frac{1}{4}A_{fc}.F_{shear}.\omega.\rho_{fc} \tag{39}$$

where: F_{shear} = The face shearing rate expressed as velocity over angular speed.

ρ_{fc}: Density calculated at face. In the current implementation this value is taken from the node directly upstream from the face.

ω: Angular velocity of engine.

The rate of thermal energy conducted downstream by shear ($\dot{E}_{shear}$) is equal to the following:

$$\dot{E}_{shear} = c_v . \dot{m}_{fc} . \left(T_i - T_j\right) = \frac{1}{4} c_v . F_{shear} . \omega . \rho_{fc} . A_{fc} . \left(T_i - T_j\right) \quad (40)$$

where: c_v: Thermal heat capacity with respect to constant volume.

This converts into a conduction coefficient for shear (C_{shear}) which is added to the existing conduction coefficient:

$$C_{shear} = \frac{1}{4} c_v . F_{shear} . \omega . \rho_{fc} . A_{fc} \quad (41)$$

3.3 Determining Flow Rates

The following sections outline the determination, implicitly, of the flow rates between nodes of the engine. This is derived starting from the foundation of equal pressures.

3.3.1 Assumptions

The following assertions lead to inertia independent scheme for solving for the approximate internal thermodynamics of a Stirling Engine.

1. Pressure throughout connected regions is uniform in space but not time, in other words, pressure change due to temperature and volume changes is much greater than pressure changes from flow losses or acoustics.
2. The air within the engine behaves as an ideal gas, following the law: $P = \frac{m . R_{spec} . T}{V}$

3. The engine rotational velocity changes are negligible within small angular increments of the cycle. Within these increments velocity is assumed to be known, but velocity may still evolve in a rate that lags by an increment.
4. Boundary work on a single node within a region is distributed among nodes of the region as if all the nodes were grouped into one.
5. Potential energy and kinetic energy concerning the gas is ignored given the low densities of gas molecules and small vertical displacements.
6. Energy transport via radiation is ignored it is dependent on temperature to the fourth power which for low temperatures results in a much lower effect at low temperature compared to other thermal energy transport modes.

3.3.2 Deriving the Systems of Equations

The values of volume flow rate, internal energy, nodal mass and temperature of the engine are solved based on the equations derived in the following section.

In consideration of the inherent compressibility of the Stirling engine system and avoiding methods that encourage the emergence of undesirable acoustic effects, the following assumption was used as the basis on which to derive the set of equations. The engine was first divided into distinct regions, within which a uniform pressure would be enforced:

$$P_i = P_j \tag{42}$$

where: i, j: refer to two different nodes that fall within the same gas region, whereas a gas region is an area of the engine which is always fully connected throughout the cycle.

This equation states that the pressure of each node constituting a connected volume within the engine has equal pressure. Starting from here the following is true for all nodes within a region:

$$\left(\frac{m.R_{spec}.T}{V}\right)_{i,t} = \left(\frac{m.R_{spec}.T}{V}\right)_{j,t}$$

where: t: refers to the state at the current timestep.

Thus, after a time step, the same condition applies:

$$\left(\frac{m.R_{spec}.T}{V}\right)_{i,t+\delta} = \left(\frac{m.R_{spec}.T}{V}\right)_{j,t+\delta} \tag{43}$$

where: $t+\delta$: refers to the next state, after the timestep is traversed.

The specific gas constant: R_{spec} is assumed constant over a region, therefore it is removed in further calculations. The first quantity, the volume at the new time ($V_{i,t+\delta}$), is easily determined, as the volume at any angular position is predetermined by assumption 3:

$$V_{i,t+\delta} = f_{V_i}(\theta_{t+\delta}) \tag{44}$$

The second property, the mass of the gas node at the new time ($m_{i,t+\delta}$), is as follows:

$$m_{i,t+\delta} = m_{i,t} + \sum\left(\left(\dot{V}.y.\delta.\rho\right)_{fc}\right) \tag{45}$$

where: y: Sign of face with regards the sign convention of volume flow rate.
If i is listed second with regards to face fc then $y = 1$. Otherwise, $y = -1$.

The third property, nodal temperature at the new time ($T_{i,t+\delta}$), must be determined via an energy balance. The 1st law of thermodynamics is commonly represented as the following:

$$\Delta E_{tot} = \Delta Q_{tot} - \Delta W_{tot} \tag{46}$$

Whereas ΔU_{tot} is the change in the total internal energy of the control volume. ΔQ_{tot} is the transference of energy to the control volume through thermal energy. ΔW_{tot} is the transference of energy away from the control volume by a force acting over a distance? The internal energy can be expanded into kinetic, potential, and internal energy.

$$\Delta E_{tot} = \Delta E_{kin} + \Delta E_{pot} + \Delta U \tag{47}$$

The term ΔQ_{tot} can be expanded to include energy that is conducted to the control volume and energy that is transported to the control volume in the form of internal thermal energy.

$$\Delta Q_{tot} = \Delta t \sum \dot{V}.y.\rho.u + \Delta Q \tag{48}$$

The term ΔW_{tot} can be expanded to include the flow work, kinetic energy and potential energy of a flow as well as the boundary work.

$$\Delta W_{tot} = -\Delta t \sum \dot{V}.y.\rho\left(P.\hat{v} + \frac{U^2}{2} + g.z\right) + P\Delta V \tag{49}$$

Combining the expanded terms and converting into a derivative form the following equation is obtained:

$$\underbrace{\dot{E}_{kin}}_{\substack{Rate\ of\ change\\ of\ Kinetic\\ Energy}} + \underbrace{\dot{E}_{pot}}_{\substack{Rate\ of\ change\\ of\ Potential\\ Energy}} + \underbrace{\dot{U}}_{\substack{Rate\ of\ change\\ of\ Internal\\ Energy}}$$

$$= \sum \underbrace{\dot{V}.y.\rho}_{\substack{Mass\\ Transport\\ Rate\ Across\\ Boundary}} \left(\underbrace{u}_{\substack{Specific\\ Internal\\ Energy}} + \underbrace{P.\hat{v}}_{\substack{Specific\\ Pressure-\\ Volume\\ Energy}} + \underbrace{\frac{U^2}{2}}_{\substack{Specific\\ Kinetic\\ Energy}} + \underbrace{g.z}_{\substack{Specific\\ Gravitation\\ Potential\\ Energy}} \right)$$

$$+ \underbrace{\dot{Q}}_{\substack{Heat\\ Power\\ into\ the\\ System}} - \underbrace{\left(P\dot{V}\right)}_{\substack{Rate\ of\ Work\\ Applied\ on\\ the\ surroundings}} \tag{50}$$

Several simplifications are applied to this equation:

1. Gravitational potential energy is ignored due to the short vertical distances found in Stirling engines in combination with the low density of the working fluid.
2. $\dot{Q}$ and $\dot{W}_b$ are combined into a single term $\dot{E}_{ext}$ which encompasses the thermal energy conducted into the node and the boundary work or flow work acting externally on the region, based on assumption 4.

3. Kinetic energy between nodes is ignored due to the low speeds and low densities of the target engine environments.
4. Internal energy and flow work is combined into a single enthalpy term.

These simplifications result in:

$$\underbrace{\dot{E}_{kin}}_{3} + \underbrace{\dot{E}_{pot}}_{1} + \dot{U} = \sum \dot{V}.y.\rho.\left(u + \frac{P}{\rho} + \underbrace{\frac{U^2}{2}}_{3} + \underbrace{g.z}_{1}\right) + \dot{Q} - P.\dot{V}$$

Which results in the following:

$$\dot{E}_{int} = \sum \left(\dot{V}.y.\rho.\left(u + \frac{P}{\rho}\right)\right)_{fc} - P.\dot{V} + \dot{E}_{ext} \tag{51}$$

where: u_{fc}: Specific enthalpy, measured at the face, in the current implementation this value is calculated using the Van-Alibaba flux limiter [54] between a 1st order unwinding and 4th order polynomial to prevent numerical artifacts.

P_{fc}: Pressure as measured at the face, is the same as the pressure throughout the region.

ρ_{fc}: Density, measured at a face. Calculated using average of upstream and downstream values.

The composite term: $\left(\dot{V}.y.\rho\right)_{fc}$ is collapsed into $\dot{m}_{fc}$ in the next section for clarity.

For ideal gases it is commonly known that the change in temperature is dependent on the internal energy.

$$\frac{dT}{dt} = \frac{1}{c_v}\frac{du}{dt} \tag{52}$$

To calculate the next temperature:

$$T_{i,t+\delta} = T_{i,t} + \frac{1}{c_{v_{i,t}}}\left(\frac{m_{i,t}.u_{i,t} + \delta\sum \dot{m}_{fc,i,t}.\left(u_{fc} + \frac{P_{fc,t}}{\rho_{fc,t}}\right) - \delta.P_i.\dot{V}_i + \delta.\dot{E}_{ext_i}}{m_{i,t+\delta}} - u_{i,t}\right) \tag{53}$$

The equation for $T_{i,t+\delta}$ can be inserted into equation (43).

$$\left(T_{i,t} + \frac{1}{c_{v_{i,t}}}\left(\frac{m_{i,t}.u_{i,t} + \delta\sum \dot{m}_{fc,i,t}.\left(u_{fc} + \frac{P_{fc,t}}{\rho_{fc,t}}\right) - \delta.P_i.\dot{V}_i + \delta.\dot{E}_{ext_i}}{m_{i,t+\delta}} - u_{i,t}\right)\right)\frac{m_{i,t+\delta}}{V_{i,t+\delta}} = \frac{P_j}{R_{spec}} \tag{54}$$

Multiplying $m_{i,t+\delta}$ into the bracketed expression yields the following equation:

$$\left(T_{i,t}.m_{i,t+\delta} + \frac{1}{c_{v_{i,t}}}\left(m_{i,t}.u_{i,t} + \delta\sum \dot{m}_{fc,i,t}.\left(u_{fc} + \frac{P_{fc,t}}{\rho_{fc,t}}\right) - \delta.P_i.\dot{V}_i + \delta.\dot{E}_{ext_i} - u_{i,t}.m_{i,t+\delta}\right)\right)\frac{1}{V_{i,t+\delta}} = \frac{P_j}{R_{spec}} \tag{55}$$

Expanding the value of $m_{i,t+\delta}$ here:

$$\left(T_{i,t}.m_{i,t} + T_{i,t}.\delta\sum\left(\dot{m}_{fc}.u_{up}\right)_{i,t} + \frac{1}{c_{v_{i,t}}}\left(m_{i,t}.u_{i,t} + \delta\sum \dot{m}_{fc,i,t}.\left(u_{fc} + \frac{P_{fc,t}}{\rho_{fc,t}}\right) - \delta.P_i.\dot{V}_i + \delta.\dot{E}_{ext_i} - u_{i,t}.m_{i,t} - u_{i,t}.\delta\sum \dot{m}_{fc,i,t}\right)\right)\frac{1}{V_{i,t+\delta}} = \frac{P_j}{R_{spec}} \tag{56}$$

Collapsing the sums into a single sum, this is possible because they all reference the same series of faces that access the node i.

$$\frac{1}{V_{i,t+\delta}}\left(T_{i,t}.m_{i,t}+\delta\sum\left(\dot{m}_{fc,i,t}\left(T_{i,t}+\frac{1}{c_{v_{i,t}}}\left(u_{fc,t}-u_{i,t}+\frac{P_{fc,t}}{\rho_{fc,t}}\right)\right)\right)+\frac{m_{i,t}.u_{i,t}-\delta.P_i.\dot{V}_i+\delta.\dot{E}_{ext\,i}-u_{i,t}.m_{i,t}}{c_{v_{i,t}}}\right)=\frac{P_j}{R_{spec}} \tag{57}$$

Canceling out duplicate terms and reordering yields the following equation, which includes both $T_{i,t+\delta}$ and $m_{i,t+\delta}$. When a set over the entire region, implicitly solves for the value of $\dot{V}_{fc}$ when subjected to matrix inversion. Here, $\dot{m}$ is re-expanded to expose $\dot{V}$.

$$\frac{1}{V_{i,t+\delta}}\left(T_{i,t}.m_{i,t}+\frac{\delta.\left(\dot{E}_{ext\,i}-P_i.\dot{V}_i\right)}{c_{v_{i,t}}}\right)+\frac{1}{V_{i,t+\delta}}\sum\left(\dot{V}.y.\rho.\delta\right)_{fc,i,t}\left(T_{i,t}+\frac{1}{c_{v_{i,t}}}\left(u_{fc,t}-u_{i,t}+\frac{P_{fc,t}}{\rho_{fc,t}}\right)\right)=\frac{P_j}{R_{spec}} \tag{58}$$

The exact same procedure can be conducted on the right-hand side to produce the following equation.

$$\begin{aligned}\frac{1}{V_{i,t+\delta}}\left(T_{i,t}.m_{i,t}+\frac{\delta.\left(\dot{E}_{ext\,i}-P_i.\dot{V}_i\right)}{c_{v_{i,t}}}\right)&+\frac{1}{V_{i,t+\delta}}\sum\left(\dot{V}.y.\rho.\delta\right)_{fc,i,t}\left(T_{i,t}+\frac{1}{c_{v_{i,t}}}\left(u_{fc,t}-u_{i,t}+\frac{P_{fc}}{\rho_{fc}}\right)\right)\\&=\frac{1}{V_{j,t+\delta}}\left(T_{j,t}.m_{j,t}+\frac{\delta.\left(\dot{E}_{ext\,j}-P_j.\dot{V}_j\right)}{c_{v_{j,t}}}\right)\\&+\frac{1}{V_{j,t+\delta}}\sum\left(\dot{V}.y.\rho.\delta\right)_{fc,j,t}\left(T_{j,t}+\frac{1}{c_{v_{j,t}}}\left(u_{fc,t}-u_{j,t}+\frac{P_{fc}}{\rho_{fc}}\right)\right)\end{aligned} \tag{59}$$

The terms of the full equation in for form A$\dot{\boldsymbol{V}}=\boldsymbol{b}$ are as follows:

Values of each element of column vector $\boldsymbol{b}$. Here, each entry is for a face. Each face has two nodes a node which a positive flow exits and a node which a positive flow enters, these are presented as i_k and j_k respectively – where k is the face index.

$$b_k = F(i,j) = \frac{1}{\delta V_{i,t+\delta}}\left(T_{i,t}.m_{i,t} + \frac{\delta.\left(\dot{E}_{ext_i} - P_i.\dot{V}_i\right)}{c_{v_{i,t}}}\right) - \frac{1}{\delta V_{j,t+\delta}}\left(T_{j,t}.m_{j,t} + \frac{\delta.\left(\dot{E}_{ext_j} - P_j.\dot{V}_j\right)}{c_{v_{j,t}}}\right)$$

$$\boldsymbol{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{N_{fcs}} \end{bmatrix} = \begin{bmatrix} F(i_1,j_1) \\ F(i_2,j_2) \\ \vdots \\ F\left(i_{N_{fcs}}, j_{N_{fcs}}\right) \end{bmatrix} \tag{60}$$

where: N_{fcs}: The number of faces being solved.

Values for each row of matrix A, whereas the column is defined by the face associated with the value of $\dot{V}$. Each row contains all the inflows and outflows for a pair of nodes i and j.

$$g(i,fc) = \begin{cases} \dfrac{\delta}{V_{i,t+\delta}}(y.\rho)_{fc,i,t}\left(T_i + \dfrac{1}{c_{v_i}}\left(u_{fc} - u_i + \dfrac{P_{fc}}{\rho_{fc}}\right)\right)_t & \text{if node } i \text{ and face } fc \text{ touch} \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{A} = \begin{bmatrix} g(j_1,1) - g(i_1,1) & g(j_1,2) - g(i_1,2) & \cdots & g\left(j_1,N_{fcs}\right) - g(i_1,N_{fcs}) \\ g(j_2,1) - g(i_2,1) & g(j_2,2) - g(i_2,2) & \cdots & g\left(j_2,N_{fcs}\right) - g(i_2,N_{fcs}) \\ \vdots & \vdots & \ddots & \vdots \\ g\left(j_{N_{fcs}},1\right) - g(i_{N_{fcs}},1) & \cdots & \ldots & g\left(j_{N_{fcs}},N_{fcs}\right) - g(i_{N_{fcs}},N_{fcs}) \end{bmatrix} \tag{61}$$

There is a simplification to this when the region includes the environment, which is a node with constant pressure.

$$\left(T_{i,t}.m_{i,t} + \frac{\delta.\left(\dot{E}_{ext_i} - P_i.\dot{V}_i\right)}{c_{v_{i,t}}}\right) + \delta \sum_{faces\ in\ "i"} \dot{V}_{fc,t}\left(y_{fc,i}.\rho_{fc}\left(T_i + \frac{1}{c_{v_i}}\left(u_{fc} - u_i + \frac{P_{fc}}{\rho_{fc}}\right)\right)\right)_t = \frac{V_{i,t+\delta}.P_{env}}{R_{spec}} \tag{62}$$

$$b_k = F(i,j) = \frac{1}{\delta}\left(\frac{V_{i,t+\delta}.P_{env}}{R_{spec}} - T_{i,t}.m_{i,t} - \frac{\delta.\left(\dot{E}_{ext_i} - P_i.\dot{V}_i\right)}{c_{v_{i,t}}}\right) \tag{63}$$

$$g'(i,fc) = \begin{cases} \dot{V}_{fc,t}\left(y_{fc,i}.\rho_{fc}\left(T_i + \frac{1}{c_{v_i}}\left(u_{fc} - u_i\right)\right)\right)_t & \text{if node } i \text{ and face } fc \text{ touch} \\ 0 & \text{otherwise} \end{cases}$$

$$A = \begin{bmatrix} g'(i_1,1) & g'(i_1,2) & \cdots & g'(i_1,N_{fcs}) \\ g'(i_2,1) & g'(i_2,2) & \cdots & g'(i_2,N_{fcs}) \\ \vdots & \vdots & \ddots & \vdots \\ g'\left(i_{N_{fcs}},1\right) & g'\left(i_{N_{fcs}},2\right) & \cdots & g'\left(i_{N_{fcs}},N_{fcs}\right) \end{bmatrix} \tag{64}$$

The term $\dot{E}_{ext}$ represents the components of energy exchange to the node that can be approximated using a previous value of the Reynolds number as between iterations the flow rate changes are assumed to be small. This is defined:

$$\dot{E}_{ext_i} = \sum_{Gas-Solid} (y_i.C_{cond}.\Delta\mathrm{T})_{\mathrm{fc}} + \sum_{Gas-Gas} (y_i.C_{cond}.\Delta\mathrm{T})_{fc} \tag{65}$$

3.3.3 Verifying as a Polytropic Process

Stirling engines are a polytropic process, meaning that they exist anywhere along the spectrum of processes. The polytropic index is a representation of the type of process that is going on.

$$n = (1-\gamma)\frac{\delta q}{\delta w} + \gamma \tag{66}$$

where: $n = 0$: Isobaric Process $n = \gamma$: Isentropic Process

$n = 1$: Isochoric Process $n = \infty$: Isochoric Process

The work from a polytropic process is equal to the following:

$$w = \frac{R(T_2 - T_1)}{1-n} \tag{67}$$

$$w\left(1 - (1-\gamma)\frac{\delta q}{\delta w} - \gamma\right) = (1-\gamma)(w-q)$$

$$\frac{R}{1-\gamma}(T_2 - T_1) = \frac{c_p - c_v}{1 - \frac{c_p}{c_v}}(T_2 - T_1) = -c_v(T_2 - T_1)$$

$$q - w = c_v(T_2 - T_1)$$

This now aligns with the mathematics developed in the previous section; thus, the math should have no problem simulating the polytropic processes of a Stirling engine.

3.3.4 Considering Loops

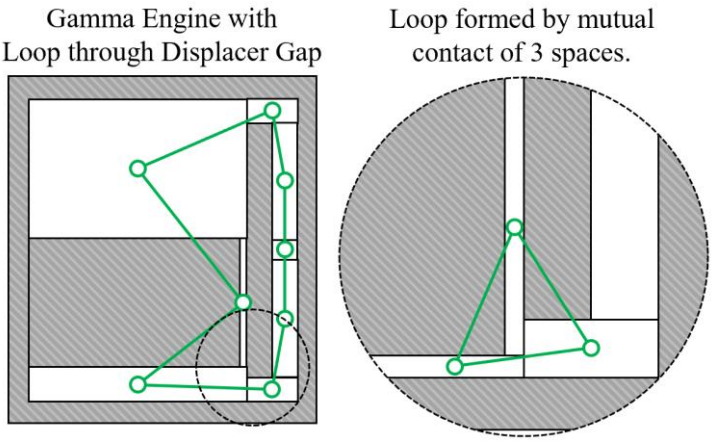


Figure 3.2: Examples of common loops found in Stirling engines.

In systems that contain loops, as illustrated in Figure 3.2, it is observed that for each independent loop added wherein the number of these loops is the same as in mesh analysis for solving circuits [55], a new equation is required. A loop exists anywhere a gas particle can take more than one path between any node an any other node. A common example, found in gamma type engines, is the thin boundary around the displacer, which allows some gas to not pass through the heat exchangers when traveling between compression and expansion spaces. This space is often minimized by close running seals such that it could be modelled by a narrow gas path or even a leakage component.

Each loop is represented by a characteristic volumetric flow rate, called a loop flow rate. There is one characteristic flow rate for each additional equation. The extra rows in the matrix will be used to assign a value to the loop flow rates, producing, out the infinite set of solutions from the indeterminant matrix, the solution that has those flow rates. This is done by having the row be all zeros except for a 1 in the corresponding face's column. The corresponding entry in $\boldsymbol{b}$ will be the

value of this loop flow rate. The following discussion will outline how these loop flow rates are determined.

Considering pressure to be akin to electric potential and a pressure drop to be akin to voltage in an analogous circuit then over the entire loop the pressure drop should be zero:

$$\oint \Delta P = 0 \tag{68}$$

Calculating pressure drop using the Darcy-Weisbach equation [31].

$$\Delta P_{fc} = \left(f(N_{Re}) \frac{L}{d_h} \frac{\rho . |U| . U}{2} \right)_{fc} \tag{69}$$

We can modify this term by considering the face's movement relative to the geometry around it. Hypothetically a translating face may have a gas flow rate that is zero across it but may still develop a pressure drop because it is moving relative to the walls. The faces velocity is precalculated in such a way that the product of the angle-dependent face velocity factor (F_V) and the instantaneous rotational speed equals the instantaneous face velocity.

$$\begin{gathered} U' = U + U_{fc} = U + F_V \omega \\ \Delta P_{fc} = \left(f(N_{Re}) \frac{L}{d_h} \frac{\rho . |U'| . U'}{2} \right)_{fc} \end{gathered} \tag{70}$$

This results in the following equation for each loop.

$$\sum \left(y \frac{f(N_{Re})}{2} \frac{L}{d_h} \rho . |U'| . U' \right)_{fc} = 0 \tag{71}$$

The equation introduces a non-linearity in the form of a squared velocity term as well as the friction factor's dependence on Reynold's number, which is also dependent on velocity. This equation is therefore solved by a root-finding scheme which sets the value of the set of characteristic loop velocities until pressure drop across all loops is equal to zero.

The derivative of this function concerning the change in the volume flow of a characteristic volumetric flow rate is equal to the following:

$$\sum_{\substack{For\ each\\ face\ in\\ loop}} \left(\frac{\partial \dot{V}_{fc}}{\partial \dot{V}_{loop}} \frac{\partial}{\partial \dot{V}_{fc}} \left(\frac{y.L.\rho}{2d_h.A^2} \right)_{fc} f(N_{Re,fc}).|\dot{V}_{fc}|.\dot{V}_{fc} \right) = \frac{\partial}{\partial \dot{V}_{loop}} \oint \Delta P \tag{72}$$

where: $\dot{V}_{loop}$: Characteristic flow rate for loop, selected to be independent of all other loops.

Manipulation of the expression gives:

$$\frac{1}{2} \sum_{\substack{For\ each\\ face\ k\ in\\ loop\ i}} \frac{\partial \dot{V}_k}{\partial \dot{V}_{loop}} \left(\frac{y.\rho.L.|U|}{d_h.A} \right)_k \left(\frac{U}{|U|} N_{Re} \frac{\partial f(N_{Re})}{\partial N_{Re}} + 2f(N_{Re}) \right)_k = \frac{\partial}{\partial \dot{V}_{loop}} \oint \Delta P \tag{73}$$

where: $\frac{\partial f(N_{Re})}{\partial N_{Re}}$: The change in the Darcy friction factor with respect to a change in Reynold's number.

The intent in finding the derivative of the loop pressure drop is to use it as part of the Newton-Raphson gradient descent algorithm. This algorithm makes incremental updates to a set of parameters – in this case a set of velocities called generally here as X – seeking the set of velocities at which the pressure crosses or equals zero. Each iteration step is as follows:

$$X_{n+1} = X_n - J_n^{-1}.F_n \tag{74}$$

where: X_n = The vector of independent variables at iteration n.

F_n = The vector of dependent variables at iteration n.

J_n = The Jacobian of F concerning inputs X at iteration n.

Here the independent variable is the loop volume flow rate, which is a single flow rate that lies in and only in the loop of interest, to minimize correlation during solving. The dependent variable is the loop pressure drop. The Jacobian is constructed from the derivatives of the loop pressure drop; the Jacobian formula is given below:

$$J = \begin{bmatrix} \frac{\partial F_1(X_n)}{\partial x_1} & \cdots & \frac{\partial F_1(X_n)}{\partial x_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_M(X_n)}{\partial x_1} & \cdots & \frac{\partial F_M(X_n)}{\partial x_N} \end{bmatrix} \tag{75}$$

where: $\frac{\partial F_i}{\partial x_j} = \frac{1}{2} \sum_{\substack{For\ each \\ face\ k\ in \\ loop\ i}} \frac{\partial \dot{V}_k}{\partial \dot{V}_{loop}} \left(\frac{y.\rho.L.|U|}{D_h.A} \right)_k \left(\frac{U}{|U|} N_{Re} \frac{\partial f(N_{Re})}{\partial N_{Re}} + 2f(N_{Re}) \right)_k$

While the selected velocities are defined by this algorithm, all other velocities are still dependent on the matrix defined in section 3.3.2. Additionally, the derivative with respect the loop flow rate for all other flow rates can be obtained through querying the corresponding column in the inverted matrix by (which is precalculated as only $\boldsymbol{b}$ is modified as part of the loop solving scheme).

3.3.5 Considering Flow Losses

Due to the uniform pressure assumption all nodes have the same pressure. In the real system, however, the flow loss would enact its effect by a rise or fall of the pressure acting on the piston faces. This must be considered to some degree as the work of some pistons, namely the displacer, is solely a function of this loss. This loss is solved by calculating the pressure in all nodes such that the total pressure is equal to the P_{region} defined in equation (77), and that the pressure drop between adjacent nodes matches equation (70). This results in a modified set of pressures that is an estimate of the pressure drop, this will be particularly effective when the difference in pressure is all that is required, such as the pressure difference across a displacer.

For each face, using the Darcy-Weisbach equation [31]:

$$P_1 - P_2 = \frac{1}{2}\left(K + \frac{N_f.L}{d_h}\right)\rho.\left|U_{fc}\right|.U_{fc} \tag{76}$$

For all nodes:

$$\sum P_{nd}.V_{nd} = P_{region}.V_{region} \tag{77}$$

The matrix in the style of Ax = b:

$$\begin{bmatrix} 0 & \cdots & \pm 1 & \cdots & \mp 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ V_1 & V_2 & \cdots & \cdots & \cdots & \cdots & V_N \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix} = \begin{bmatrix} \left(\frac{1}{2}\left(K + \frac{N_f.L}{d_h}\right)\rho.|U|.U\right)_1 \\ (\dots)_2 \\ \vdots \\ (\dots)_M \\ P_{region}.V_{region} \end{bmatrix} \tag{78}$$

3.3.6 Smooth Property Changes

For many properties in the model, their value changes relative to the crank angle. These properties called "x" may be linearly interpolated between crank angle or, for better results, they can be interpolated using a cubic spline. The cubic spline provides several benefits, it ensures changes, particularly in the derivative are smooth which improves the convergence of sensitive components such as the loop solving in section 3.3.3. The following discussion outlines the interpolation procedure, which considers the gradual change in speed of the engine between angular positions.

Taking the volume as an example, the instantaneous change in volume is interpolated via a cubic spline of the 4 points around the current simulation region. This cubic spline is derived such that the 2nd order central difference derivative at the start and endpoint of the section is the same, this avoids discontinuities in rate when transitioning between angular increments. The locations of the interpolation points are provided in Figure 3.3.

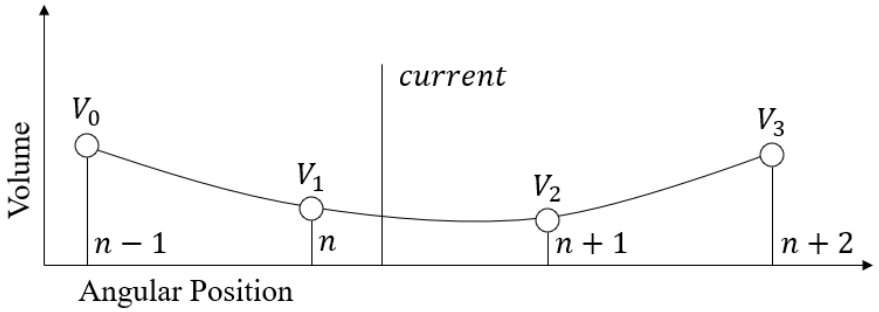


Figure 3.3: Angular locations of V_o through V_3

$$A.t'^3 + B.t'^2 + C.t' + D = V(t')$$

$$3A.t'^2 + 2B.t' + C = \frac{dV}{dt}(t')$$

where:

$$t' = \frac{t - t_n}{t_{n+1} - t_n} \qquad \Delta t = t_{n+1} - t_n$$

$$\left(\frac{dV}{dt}\right)_1 = \frac{(V_2 - V_0)}{2\frac{\theta_{inc}}{\omega_1}} \qquad \left(\frac{dV}{dt}\right)_2 = \frac{(V_3 - V_1)}{2\frac{\theta_{inc}}{\omega_2}} \tag{79}$$

$$A = \Delta t\left(\frac{dV}{dt}\right)_1 + \Delta t\left(\frac{dV}{dt}\right)_2 - 2(V_2 - V_1)$$

$$B = -2\Delta t\left(\frac{dV}{dt}\right)_1 - \Delta t\left(\frac{dV}{dt}\right)_2 + 3(V_2 - V_1)$$

$$C = \Delta t\left(\frac{dV}{dt}\right)_1$$

$$D = V_1$$

A similar procedure is applied for all dynamic properties. In addition to the cubic spline interpolation, each interpolated value is clamped to be above zero depending on the physical realism of a negative value occurring. Some properties, such as volume, which are featured on the

denominator of a calculation are clamped to be above some small tolerance value to avoid the small time-steps or errors that occur with smaller or zero values.

3.4 Turbulence

3.4.1 Open Channels Flows

Turbulence here is adapted from the implementation found in SAGE by Gedeon [35]. This implementation represents turbulence in open channel flows as a conserved property bounded between 0 and 1. Gedeon, through development of SAGE, observed that for oscillating flows while the flow was turbulent it exhibited properties like that of steady-state turbulent flows and while it was observed to behave in a laminar manner, its properties mimicked steady-state laminar flows. Thus, this factor, τ, attempts to predict the altered transitions between laminar and turbulent. In practice, this factor serves as a weight between the laminar and turbulent values of the Darcy friction factor (N_f) and the Nusselt Number (N_{Nu}). The associated conservation equation is as follows [35]:

$$\frac{\partial(\tau.\mathrm{A})}{\partial t}+\frac{\partial(\tau.U.A)}{\partial x}=\tau_{gen} \tag{80}$$

The weighting factor is carried with the flow and its generation follows a few rules.

Flows in the wake of large geometrical features such as those representing bends or area changes always receive a fully turbulent flow corresponding to a value of $\tau = 1$.

Generation of turbulence within nodes occurs exclusively when the flow condition is above Re_{crit} represented below [35]:

$$N_{Re_{crit}} = 200 \max\left(\frac{\sqrt{N_{Va}}}{0.075+0.112\omega.(t-t_0)}, 11.5\right) \tag{81}$$

The Valensi number (N_{Va}) represents the ratio of oscillatory fluid inertia to viscosity and is defined as:

$$N_{Va} = \frac{\rho . \omega . D_h^2}{\mu} \tag{82}$$

The value t_0 represents the time at which the flow was at a velocity of zero. The function in the denominator represents the growth of the momentum layer under sinusoidal oscillations, which is close enough for this model.

The generation or decay term for turbulence weighting factor is represented as [35]:

$$\frac{\partial \tau}{\partial t} = \frac{\omega \delta}{N_{Va}} \begin{cases} 0.008 N_{RE} . (1 - \tau) & N_{Re} > N_{Re_{crit}} \\ -0.25 N_{RE_{laminar}} . \tau^{3/2} & N_{Re} \leq N_{Re_{crit}} \end{cases} \tag{83}$$

Outflows and inflows induce changes in turbulence weighting equal to the following:

$$\frac{\partial \tau_i}{\partial t} = \frac{\dot{m}_{fc}}{m_i} \begin{cases} (\tau_{\mathrm{fc}} - \tau_{\mathrm{i}}) & \dot{V}_{fc} \text{ is entering node i through a pipe} \\ (-\tau_{\mathrm{fc}} + \tau_{\mathrm{i}}) & \dot{V}_{fc} \text{ is leaving node i} \\ (1 - \tau_{\mathrm{i}}) & \dot{V}_{fc} \text{ is entering node i through a minor loss} \end{cases} \tag{84}$$

3.4.2 Matrix Flows

Flow within the fine geometry of features such as regenerators or heat exchangers is considered a Matrix flow. Such flows develop rapidly and under oscillatory conditions are very close to steady-state due to the domination of the viscosity term. Therefore, the weighting factor between a turbulent and laminar value is as follows [35]:

$$F(N_{Re}^*) = \begin{cases} F_{lam} & N_{Re}^* \leq 0 \\ w . F_{lam} + (1 - w) . F_{turb} & 0 < N_{Re}^* < 1 \\ F_{turb} & 1 \leq N_{Re}^* \end{cases} \tag{85}$$

where: $N_{Re}^* = \dfrac{N_{Re} - 2{,}300}{4{,}000 - 2{,}300} = \dfrac{N_{Re} - 2{,}300}{1{,}700}$

and

$$w = {N_{Re}^*}^2 . (3 - 2N_{Re}^*)$$

The incorporation of the smooth step function is an improvement over the discontinuous curve applied in SAGE. This function applies to both the Darcy friction factor and the Nusselt number.

3.4.3 Variable Volume Spaces

Turbulence within variable volume spaces is generated by inflows and reduced by outflows and remaining turbulence is decayed as a function of time. An important distinction is that turbulence in variable volume spaces is not measured by the weighting factor т but is rather a specific turbulent kinetic energy κ.

The turbulence produced by an inflow is a function of the entrance velocity [35]:

$$\frac{\partial \kappa_i}{\partial t} = \frac{\dot{m}_{fc}}{m_i} \begin{cases} \left(\frac{1}{2}\left(\frac{\dot{V}_{fc}}{A_{fc}}\right)^2 - \kappa_i\right) & \dot{V}_{fc} \text{ is entering node "}i\text{"} \\ 0 & \dot{V}_{fc} \text{ is leaving node "}i\text{"} \end{cases} \tag{86}$$

where: κ_i: The specific turbulent kinetic energy for node i

Flows that leave a variable volume space do not change the specific turbulent kinetic energy. The entrance velocity turns its kinetic energy into the swirling motion observed in open chambers. This swirling energy is decayed according to the following rule, derived by Gedeon [35], [56] and presented by Cantelmi [57].

$$\left.\frac{\partial m\kappa}{\partial t}\right|_{decay} = -\frac{C_D}{0.021 D_h} m.\kappa^{\frac{3}{2}} \tag{87}$$

where: C_D: the turbulent energy dissipation constant for tube flow = 0.08

$0.021 D_h$: the spatial averaged length scale for tube flow and

κ: is the specific turbulent kinetic energy

Through manipulations:

$$\frac{\partial \kappa_i}{\partial t} = -\frac{5.8\kappa_i^{\frac{3}{2}}}{D_h} - \frac{\kappa_i}{m_i}\frac{\partial m_i}{\partial t} \tag{88}$$

Turbulence in variable volume spaces affects the values of the effective conduction and viscosity factors, also extracted from Gedeon [56]. These overwrite the default values of these properties and result in higher wall conduction and higher friction losses in variable volume spaces.

$$\begin{aligned} k_{eff} &= k + 0.021\rho.d_h.c_p.\sqrt{\kappa} \\ \mu_{eff} &= \mu + 0.021\rho.d_h.\sqrt{\kappa} \end{aligned} \tag{89}$$

3.5 Chapter Conclusions

Through this chapter the equations needed to solve for the energy exchange due to conduction was presented for all possible node combinations. Following this, the mathematics needed to solve for the volumetric flow rates of ideal gases with volume and energy changes was outlined. Then, the expansions applied when the network contains loops were discussed, allowing the code to solve arbitrary networks. The pressure correction due to flow friction was provided, allowing the uniform pressure assumption to still support the effect of flow losses across pistons. The cubic spline used for smooth property transitions and handling of angular accelerations was presented. The chapter concluded with the presentation of the turbulence handling mathematics derived from SAGE's [35] implementation. These theoretical formulations, lead into the next chapter where they are implemented into algorithms which decompose the interactable blocks into the network, and finally into a solution.

CHAPTER 4. SIMULATION

During the solving phase MSPM follows the flow structure in Figure 4.1 below, each of the actions are discussed in the following sections. All the project code can be found in Appendix G.

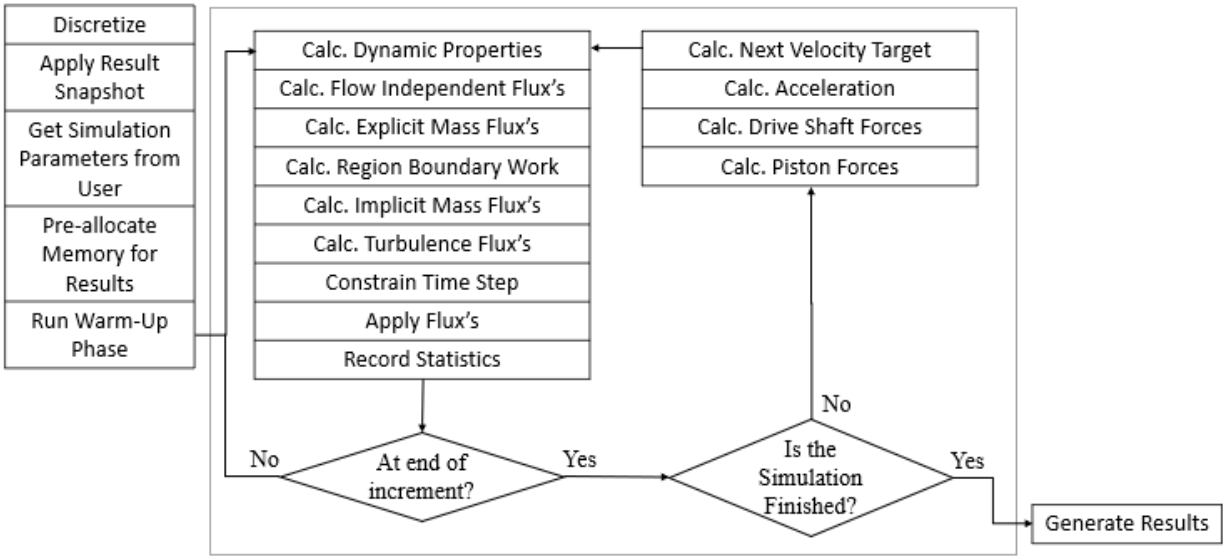


Figure 4.1: Process structure of the simulation loop, elements inside of the box are repeated until the simulation has timed out or converged.

4.1 Discretization and Conditioning

Many steps are involved in creating and conditioning the network for solving, these are outlined in the following sections.

4.1.1 Discretize all Components and Collect Discrete Elements

The model discretizes components in a particular order, which is shown in Figure 4.2. The discretization of each element is discussed in 0.

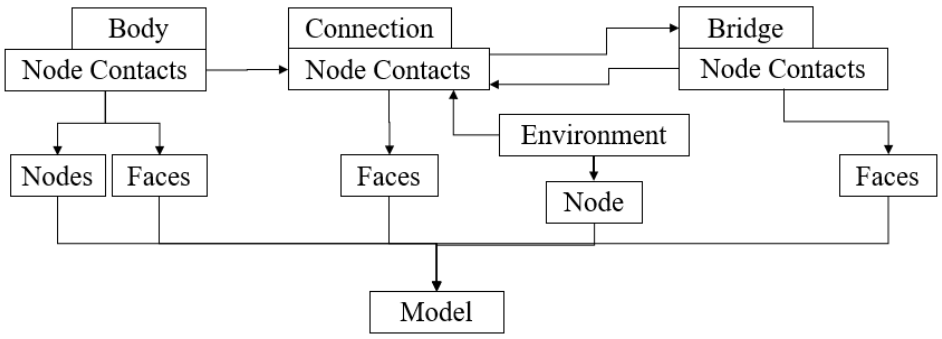


Figure 4.2: Flow of information during discretization

Bodies are discretized first, which generates the node contacts that are used by connections. Then the environment is discretized, and its singular node is distributed among the boundary connections. Following this, bridges are discretized as they will provide their own node contacts as well as modify the existing ones. Lastly the connections are discretized, which pair up the node contacts to form faces.

4.1.2 Decimate Nodes Based on Size

After the mesh is produced, a post processing step eliminates particularly thin nodes from the calculation. This step prevents the existence of nodes that would otherwise produce an unreasonably small timestep, dragging the entire simulation down for negligible gains in accuracy. Small nodes are merged into larger nodes if the timestep, as defined by the Fourier number, falls below a certain threshold. This timestep is constructed as follows:

$$\delta = N_{Fo} \frac{\left(\frac{dU}{dT}\right)_{nd}}{\left(\frac{d\dot{Q}}{d(\Delta T)}\right)_{fc}} = N_{Fo} \frac{Heat\ Capacity}{Conductance} \tag{90}$$

where: F_{Fo}: The maximum allowable Fourier number.

$\left(\frac{dU}{dT}\right)_{nd}$: The derivative of total internal energy vs temperature of the node. Equivalent to the heat capacity of the material found in the node.

$\left(\frac{d\dot{Q}}{d(\Delta T)}\right)_{fc}$: The derivative of heat flow rate across a face of the node verses the temperature difference across it. Equivalent to the conductance of the face.

The larger node then takes on the unmodified faces and appends the properties of the smaller node. This has a significant impact on the performance of the model at the loss of some small elements.

4.1.3 Assign Minor Loss Coefficients

A minor flow loss coefficient (K) applies to a face when the flow area changes between the first and second nodes. Faces in which this applies have two such coefficients a forward (K_{12}) and a backward (K_{21}) minor loss coefficient, corresponding to the two possible flow directions. These can be applied using the default equation presented in section 2.2.2 or can be overridden by the custom minor loss coefficient component.

4.1.4 Decimate Triads

The number of loops is a major factor in the run speed of the simulation. Oftentimes junctions occur between 3 nodes, which form micro-loops, increasing the load on the solver. The decimate triad's function finds such triads of nodes and assesses them, looking at the relative size of the faces. The node with the largest contact to the other two nodes becomes the base node and replaces the connection that lies between the two other nodes. Figure 4.3 below illustrates this process. The final area and loss coefficients of the non-eliminated faces are equal to the area weighted average of the values.

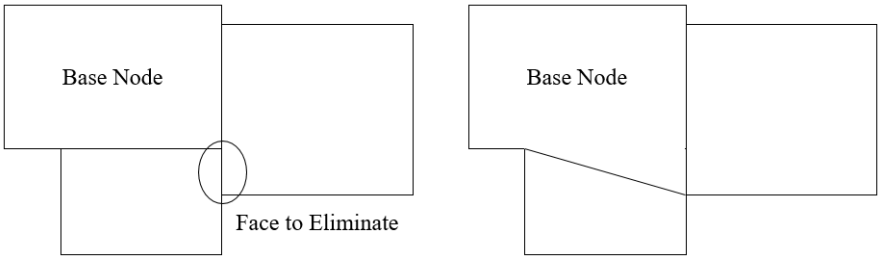


Figure 4.3: Example of a triad elimination action: faces are selected based on their relative size, the remaining 2 faces are then modified to compensate.

4.1.5 Assign Indexes to all Elements

Though it is convenient to work with discrete elements as objects (as in object-oriented programming), it is much faster to access vectorized elements in MATLAB. Therefore, a unique index is assigned to each node and face in preparation for vectorization. The indexes are assigned such that when sorted in ascending order the gas nodes appear before the environment nodes, which are followed by solid nodes. Similarly, gas faces lead mixed faces, which lead solid faces.

4.1.6 Vectorize Node and Face Properties

Using the previously defined index, nodes and faces insert their physical properties – which are defined in 0 – into arrays that are more computationally efficient to access than their current object-oriented format. Here also the dynamic properties are referenced and stored in a master array. Due to previous sorting the resulting property arrays are as small as possible as the most memory demanding elements are listed first.

Specialized elements such as leaks, shear and pressure contacts remain in their object-oriented format as they are typically few in number.

4.1.7 Determine Maximum Solid-Conduction Timestep

A loop through all the Solid Nodes calculates the absolute minimum allowable time step per angular increment based on the maximum Fourier number (N_{Fo}) defined in equation (90). If the conductance changes due to a sliding boundary the most conservative value (smallest timestep) is retained, this is derived from the definition of the Fourier number.

4.1.8 Determine the Conduction and Transportation Vectors

With irregular grids, one of the challenges is efficiently calculating the change in the nodal properties. This is a challenge because a node can have many faces and finding them for each node is a tedious task. even if a list of face indexes were obtained this would constitute many short and therefore inefficient vector operations. As MATLAB is very fast at large vector calculations, the goal is to define as many large vector calculations as possible, because the conduction values can change every frame it would be a challenging pursuit to do this efficiently by constructing a matrix.

The prework pseudo-code below produces sets of faces that can be added to the nodal values without overlapping each other. The result of this operation is a vector of vectors which contains parallel sets of 3 vectors, the first contains the sign of the operation, the second contains the vector of nodes on which the operation is performed and the third indicates the face. In the case of a grid mesh, this would produce at most 8 sets, no matter how large the grid was. (one for each face of a node, one for each sign).

```
Inputs: List of all Nodes and Faces
  Step 1: Initialize Vectors
  CondNds = vector containing the indexes of all Nodes
  CondFcs = vector containing the indexes of all Faces
  Nds1 = vector containing only the first node listed by each Face
  Nds2 = vector containing only the second node listed by each Face

  Step 2: Make backups of Nds1 and Nds2
  CondNds1 = Nds1 --- Duplicate of Nds1
  CondNds2 = Nds2 --- Duplicate of Nds2

  Step 3: Exclude nodes that are constant values (surrounding, source, etc.)
  Nds1(indexes where the Node has static properties) = 0
  Nds2(indexes where the Node has static properties) = 0

  Step 4: Calculate how many sets of vector to produce, based on the maximum
  number of times any one node is referenced.
  if any(Nds1 are not equal to 0)
      x = mode of Nds1 excluding 0's
      N1 = number of times x occurs in Nds1
  else N1 = 0
  if any(Nds2 are not equal to 0)
      x = mode of Nds2 excluding 0's
      N2 = number of times x occurs in Nds2
  else N2 = 0

  Step 5: Create vectorized references
  i = 1
  CondVectors = vector of vectors of length = 3*(N1 + N2)
  if N1 is not 0
      for k = 1 to N1 by stepping 1
          N = count of unique values in Nds1 excluding 0's
          CondVectors[i] = -1
          CondVectors[i+1] = vector of 0's of length = N
          CondVectors[i+2] = vector of 0's of length = N
          Counter = 1
          for x = 1 to length(Nds1) by stepping 1
              if Nds1[x] > 0
                  if (Nds1[x] is not already in CondVectors[i+1])
                      CondVectors[i+1][Counter] = Nds1[x]
                      CondVectors[i+2][Counter] = x
                      Nds1[x] = 0
                      Counter = Counter + 1
          i = i + 3
```

```
  Step 6: Repeat Step 5 for N2 and Nds2

  return CondVectors, CondNds1, CondNds2, CondFcs, CondNds

-- Usage (as found in simulation.m)
Using CondFcs, update all conductances and calculate energy flows using
CondNds1 and CondNds2
for i = 1 to length(CondVectors) - 2 by stepping 3
    Qnode[CondVectors[i+1]] = Qnode[CondVectors[i+1]] +
        CondVectors[i]*Qface[CondVectors[i+2]]
```

The equivalent data structure for transportation is obtained by the same method above but for solely the gas-gas faces and nodes. This is used to determine the nodal Reynold's number, which is simply the area weighted average of the Reynold's number of its participating faces.

4.1.9 Establish Gas Regions

Given that the model can be defined arbitrarily, the interconnected gas spaces within the engine, henceforth called regions, must be determined automatically. A region is distinct from another gas space if at any point in the cycle it is completely cut off from that other space; thus, allowing a build up in pressure. Such spaces are found via a recursive space filling algorithm starting at a root node. The output is a vector with region indexes for each gas node including the environment node. The pseudo-code below outlines the algorithm:

```
Inputs: List of all Nodes
  Outer Loop: Loop through all the nodes to find ones that are not grabbed
by the recursive function. Any new ones indicate an unreached region.
  n = 0
  region = vector of 0's of length = number of Gas & Environment Nodes
  for each Nd in Nodes
      if the Nd is a Gas Node and it does not have an assigned region
          n = n + 1
          region = PropegateRegion(Nd, region, n)
          if all nodes have a region then exit for each Nd loop
  return region

  Inner Loop: Add the current node as a region member, look for unreached
neighbors, call the function using them as a starting point
Sub Function PropegateRegion(Nd, region, n)
  if region[Nd.index] is 0 ... Nd does not have a region
      region[Nd.index] = n
      for each face associated with Nd
          if the face is a gas face and never completely closes
              node = other node of face relative to Nd
              region = PropegateRegion(node, region, n)
  return region
```

Post-processing of the output vector provides a list of nodes for each region. Faces are assigned to a region if both member nodes are within the same region. Also, the region that contains the environment node is treated differently during simulation, so it is indicated with a Boolean value if the current region is an environment region. It is treated differently because its pressure does not change, resulting in a simplified solution.

4.1.10 Find Loops within each Region

Loop finding is another area where a specialized algorithm is required that is composed of several steps. The first step eliminates dead-ends. Then faces that are within the region but are closed for parts of the cycle are found. Followed by the actual loop finding algorithm. The final output of this series of algorithms is two data structures. The first, **RegionLoops**, is a vector of arrays with an array for each region that has 3 rows, the first for a node index, the second for a face index and the third for a sign. The second, **RegionLoopsInd**, is a vector (corresponding to each region) of arrays that contains pairs of numbers, in columns, indicating the start and end column in **RegionLoops** for each distinct loop in the region. This data structure is shown in Figure 4.5. This algorithm is described in Figure 4.4 and also by the following code.

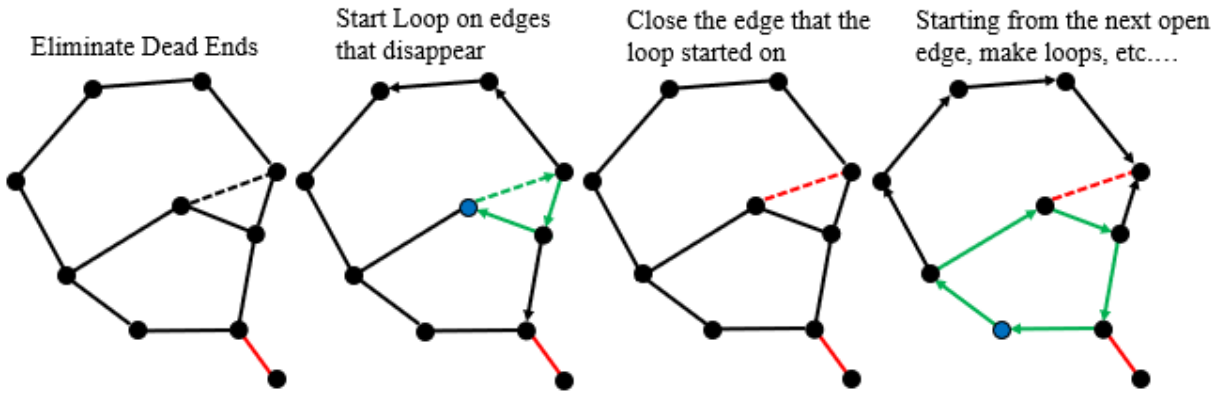


Figure 4.4: Loop finding algorithm illustration. (dashed) face that has an area of zero at any point of the cycle. (red) eliminated face. (blue node) starting point for algorithm. (green) discovered loop.

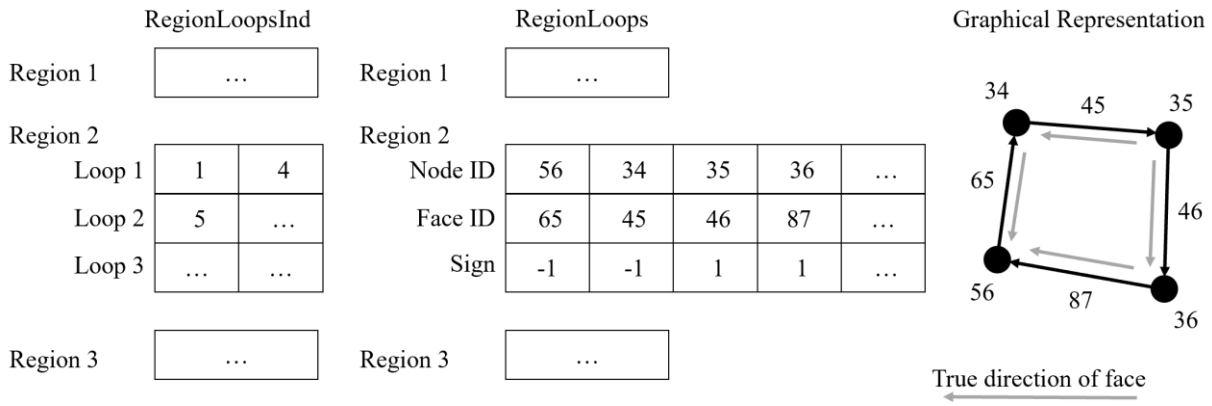


Figure 4.5: Loop data structure and graphical representation

```
-- Elimination of dead-ends
A node is a dead end if they have only one gas face, or they have two gas
face but one or both leads to a dead-end node. Mark these and all their
faces as closed in the closed_edge array.


open = empty
for i is 1 to the number of regions
    -- Region Enclosed Closing Edge Discovery
    Collect faces whose area goes to zero at some point but both nodes lie
    within the same region. Add these to the "holes" array and mark them
    closed.

    -- Loop Finding
    visited_edge = closed_edge
    lequ = 1
    lcount = 0
    N = number of faces in region i - number of nodes in region i + 1
    for k = 1 to N by stepping 1
        if k is less than or equal to the number of holes
            -- Find a loop that covers this hole, one must exist
            Start_Face = holes[k]
        else
            -- Find open edges and find a loop that covers it
            closed = []
            for each face in Faces
                if face is a gas face, close_edge[face.index] is false
                    ... and it is with region i
                    Start_Face = face
                    exit for each face loop
            Closed_Edge[face.index] = true
            Vis_Edge[face.index] = true

        closed = LoopNode([], Start_Face, first node of Start_Face)
        target = first node of Start_Face
        open = LoopNode(closed, Start_Face, second node of Start_Face)
        edge_closed = Start_Face
```

```
        -- Use open as a starting point to the path to "target"
        done = false
        while open is not empty and not_done
            len = length of open
            for x = len to 1 by stepping -1
                -- Expand open[x]
                LpNd = open[x]
                Add LpNd to closed
                For each face associated with LpNd.Nd
                    If the face is a gas face, is in region i
                        ...and Vis_edge[face.index]
                        visited_edge[face.index] = true
                        newNd = other node of face relative to LpNd.Nd
                        if newNd is the target
                            done = false
                            add LoopNode(LpNd,Fc,newNd) to closed
                        else
                            add LoopNode(LpNd,Fc,newNd) to open
            cut elements 1 to len from open

        if done
            -- Backtrace the loop
            current = last element of closed
            lcount = lcount + 1

            RegionLoopsInd[i][1,lcount] = lequ

            while not current is empty
                RegionLoops[i][1,lequ] = current.Nd.index
                RegionLoops[i][2,lequ] = current.parentFc.index
                if the first node of current.parentFc is current.Nd
                    RegionLoops[i][3,lequ] = 1
                else
                    RegionLoops[i][3,lequ] = -1
                lequ = lequ + 1
                current = current.parent

            RegionLoopsInd[i][2,lcount] = lequ - 1

            if the length of holes >= k
                RegionLoopsInd[i][3,lcount] = holes[k].index
            else
                RegionLoopsInd[i][3,lcount] = 0

            -- Close dead-ends from the nodes of edge_closed
            Not counting closed edges as faces, remove dead ends.

    LoopNode(parent, parentFc, node)
```

4.1.11 Define Pressure Loss Matrix

Given the assumption that pressure does not change throughout a region, it does not allow pressure drop to be naturally obtained by the solution. An approximation of the actual pressure is

obtained in solution by solving for the nodal pressure. Thus, there is a need to determine the faces that represent all the independent equations. The algorithm that does this is graphically represented in Figure 4.6 and in the following pseudo-code. During this phase a matrix was created which includes the sign of all the faces, the algorithm that creates this is not shown here. This algorithm is akin to finding the minimum spanning tree of the network with the modification of excluding the closing faces.

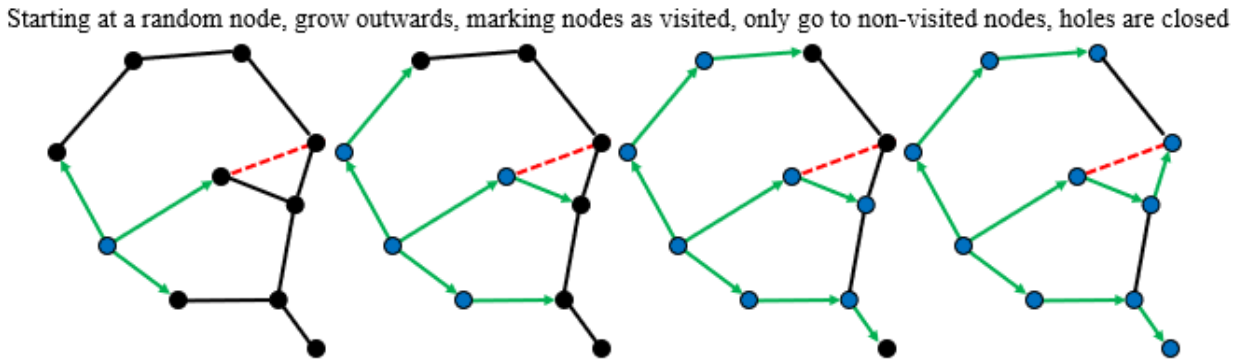


Figure 4.6: Determining the independent faces (dashed) face that has an area of zero at any point of the cycle. (red) eliminated face. (blue node) visited node. (green) set of independent equations obtained at iteration step

```
isvisited = vector of false of length = number of gas nodes
ActiveRegionFaces = vector, length = number of regions, of vectors
for i = 1 to number of regions by stepping 1
    k = 0
    ActiveRegionFaces[i]
    node = node in region i
    [ActiveRegionFaces[i], isvisited] =
        PropegateActiveFaces(node, isvisited, ActiveRegionFaces[i])

Function [fcs, visited_node] = PropegateActiveFaces(node, isvisited, fcs)
  isvisited [node.index] = true
  for each face associated with node
      if the face is a gas face in the region and whose area is always > 0
          if any of the nodes of this face are not visited
              add face to fcs
              [fcs, isvisited] = PropegateActiveFaces(
                  unvisited node of face, isvisited, fcs)
  return fcs, isvisited
```

4.1.12 Vectorize Node Faces

A different form than the transportation matrix, each node also requires, for the construction of the volumetric flow rates solving matrix, a list representing its faces. This takes the form of a vector of matrices. Each submatrix has 3 columns corresponding to the face index, the sign relative to the node and a 0 or 1 which indicates whether the face is implicit or explicit respectively.

Faces that do not fall within a single region are defined explicitly using the pressure difference across them. Explicit definition does bring instability but since it is between two regions, rather than 2 nodes, the effective node size is much larger. Explicit calculation of those faces is done because the two regions may be closed to each other during parts of the cycle. Over these parts they can generate very different pressures. Within Stirling engines however, this sort of phenomenon is relatively uncommon except for leaks and introduction of an explicit face will likely drastically slow down or destabilize the simulation.

4.2 Simulation Setup

4.2.1 Apply Snapshot

If the user wishes they may apply a snapshot of a previous test, snapshots are always taken at the same angular position (angular position of 0) which is the same angular position all simulations start on. All bodies, when created, are assigned an integer, which serves as a unique identifier. The same identifier is used to recast the data onto the body for the next simulation. A snapshot of nodal temperatures and pressures is saved for each body based on nodal positions relative to the bodily extremes (a value of 0 to 1). When recasting a snapshot, these non-dimensional positions are used in the 2D interpolation of nodal properties. Otherwise, if a body is new relative to the snapshot or has changed the phase of its material then the body maintains its default values. This flexible setup allows a much greater useful lifetime for results, as a modified engine would have similar property distributions to its original form.

4.2.2 Get Simulation Parameters from the User

The user is provided with a series of options that control the type of simulation that they are running. The controls and their summary are outlined in the following table:

Table 4.1: Simulation Parameters and Description

Maximum Simulation Time	Determines the absolute maximum amount of time the simulation will run. The actual simulation time will depend on other properties such as steady-state convergence or stalling.
End Condition	The user can type "SS" for a steady-state simulation termination condition or nothing to allow the simulation to run till time-out. The SS condition looks for convergence in the cycle power output to be under some tolerance.
Motion Condition	The user can type "C" for constant velocity simulation or "V" for variable velocity simulation. For a constant velocity, the simulation will run on the initial velocity for all increments. For the variable velocity simulation, the mechanism will be used to calculate changes in velocity throughout the cycle.
Initial Velocity	This is the initial velocity that the engine will be running at the start of the simulation.
Maximum Time Step	Generally, this not recommended as time-step is already automatically constrained, but the user has the option to prescribe an absolute maximum timestep when desired.

4.2.3 Pre-allocate Memory for Results

For simulations that are run using the constant velocity assumption the total number of data points to record is known, therefore these output arrays can be allocated at the beginning. For

variable velocity simulations, the output arrays must periodically expand in chunks to allow for further records. While MATLAB will automatically expand arrays when the provided index is beyond the scope of the array, it is more efficient to expand the array in large chunks to minimize the number of times the array must be copied.

4.2.4 Run Warm-Up Phase

The warmup-phase is inspired by laboratory experiments where engines with substantial thermal inertia are warmed up for some time to allow them to start running, as a warmed engine will generally run fast before slowing down to steady-state. With this simulation the same scenario occurs, allowing the engine to approach steady-state from a faster speed (in a variable speed test). This also will speed up convergence as components such as the piston, regenerator and walls will already have a temperature gradient, which may take a great deal of time to develop.

The warm-up phase converts all nodes to solid, using the cycle average geometry and a Nusselt number of 1 corresponding to pure conduction, region pressures are calculated to conserve mass, but warm-up phase calculations do no simulate gas flow, a neglection that significantly speeds up the calculation. When using thermal convergence acceleration (section 5.1) this step is not required as the temperature profile can show up rapidly by using the quickly acclimated gas temperatures, but this feature is retained as it can mimic a experimental process.

4.3 Gas Solver Loop

This is the actual simulation; the following sub-sections occur for each timestep.

4.3.1 Calculate Dynamic Properties

Properties that change according to angular position such as the hydraulic diameter, volume, area, friction length, relative velocity factor or stability length (length that is used in Courant number calculations) are interpolated according to the cubic spline formula. Also, within this section, properties that rely on correlations are updated, these include conduction coefficient, heat capacity, dynamic viscosity, nodal Reynold's number and the Nusselt number are all recalculated. If a function call is involved, then elements that use the same function are grouped together and

all functions are created such that they can handle vector inputs; this improves computational speed significantly as function calls to dynamic or anonymous functions are remarkably slow.

4.3.2 Calculate Flow Independent Flux's

Calculate any conduction fluxes. Some of these may be dependent on the flow conditions such as the Reynold's number, or Nusselt number but these properties are assumed to be slowly evolving relative to the size of the timestep. This section utilizes the conduction network produced in section 4.1.8 to apply calculated flux to their respective nodes.

4.3.3 Calculate Explicit Mass Flux's

Explicit mass fluxes are determined via the pressure drop across a boundary. Generally, these passages are small, given that during some part of the cycle their area is zero. However, they cannot be part of a region because they represent a perfect seal during the closed-off period, allowing the two regions to exhibit different pressures. The internal energy and mass transport are automatically handled in the implicit mass flux stage. Open channels are iterated to converge on a volume flow rate appropriate for the change in pressure, leaks determine flow rate via the pressure difference. Explicit faces are excluded from the timestep calculation as they can introduce extremely high velocities, the timestep will still dramatically fall as the gas is distrusted through the network.

4.3.4 Constrain Time Step Pre-Mass Flux

At this point the time step is restricted based on the Courant number for velocity and the maximum Fourier number for mixed heat conduction. Solid conduction is already analyzed using the precalculated angular timestep limitation, serving as the initial maximum timestep size.

4.3.5 Calculate Implicit Mass Flux's

Produce matrix A and b such that the solution of $Ax = b$ will give uniform pressure over all region nodes. The first section of pseudo code occurs before the differentiation between regular and environment region. The region with loops section occurs conditionally after both of those.

```
faces = ActiveRegionFcs of region i
```

```
nodes = nodes of region i
F2C = array that takes a face index and returns a column index associated
... with A
-- Structure of data:
... 1 column for each face
... The first row = face index
... The second row = sign of face relative to the node
... The third row = 1 if the face is explicit, 0 otherwise
A = matrix of square size = count all of region i's faces
b = column vector of size matching matrix A
```

1. Environment Region

Since the pressure of the environment is static, each node of a region that contains the environment maintains this static pressure in a simplified set of equations which are outlined in CHAPTER 3. The implementation of pseudo-code is as follows:

```
for row = 1 to the length of faces
    nd = nodes[row]
    b[row] = Vnew[nd]*Penv - T[nd]*m[nd] - dT_du[nd]*h*Qnode[ni]
    data = faces associated with nd
    for p = 1 to count of rows in data
        fc = data[p,1]
        X = h*data[p,2]*Fcrho[fc]*(T[nd] + dT_du[nd]*(Fcu[fc] - u[nd]))
        if data[p,3] is 1
            b[row] = b[row] - Fc_V[fc]*X
        else
            A[row,F2C[fc]) = A[row,F2C[fc]] + X
newV = A \ b
Fc_V[faces] = newV[F2C[faces]]
Update Fc_U, Fc_RE, Friction Factors, etc.
```

2. Standard Region

Each node is compared with one of its neighbors through equations outlined in section CHAPTER 3. Through the restricting action of all the paired equations, all nodes advance to a future point having a uniform pressure. The implementation of pseudo-code is as follows:

```
for row = 1 to the length of faces
    nd1 = first node for face[row]
    nd2 = second node for face[row]
    b[row] = (T[nd1]*m[nd1] + dT_du[nd1]*h*Qnode[nd1])/Vnew[nd1] -
             (T[nd2]*m[nd2] + dT_du[nd2]*h*Qnode[nd2])/Vnew[nd2]
    data = faces associated with nd1
    for p = 1 to count of rows in data
        fc = data[p,1]
        X = h*data[p,2]*Fcrho[fc]*(
```

```
            ... T[nd1] + dT_du[nd1]*(Fcu[fc] - u[nd1]))/Vnew[nd1]
        if data[p,3] is greater than 0 // It is a explicit face
            b[row] = b[row] + Fc_V[fc]*X
        else
            A[row,F2C[fc]) = A[row,F2C[fc]] - X
    data = faces associated with nd2
    for p = 1 to count of rows in data
        fc = data[p,1]
        X = h*data[p,2]*Fcrho[fc]*(
            ... T[nd2] + dT_du[nd2]*(Fcu[fc] - u[nd2]))/Vnew[nd2]
        if data[p,3] is greater than 0 // It is a explicit face
            b[row] = b[row] - Fc_V[fc]*X
        else
            A[row,F2C[fc]) = A[row,F2C[fc]] + X
newV = A \ b
Fc_V[faces] = newV[F2C[faces]]
Update Fc_U, Fc_RE, Friction Factors, etc.
```

3. Region with Loops

In regions that have excess faces, additional independent equations are provided in the form of loops, which all such regions with excess faces are guaranteed to contain. The equations are outlined in section 3.3.3. The method begins by estimating the root using the previous 2 answers. A record of the solution values is kept so that values can be extrapolated through time to improve the initial guess.

```
Function Inputs(this,region,F2C,startrow,A,b,Fcrho,Fcmu,time)
-- this = the simulation object, contains all nodal and face properties
-- region = index of current region, used to get recorded points and loops
-- F2C = F2C[face index] returns the column index that face is mapped to
-- startrow = row number in A where loop entries start
-- A = matrix as constructed by volume low rate solver prior to this
-- b = array as ...
-- Fcrho = array of face densities
-- Fcmu = array of face viscosities
-- time = current time, for extrapolation

-- Loop Definitions
Loop = RegionLoops array for region i
Ind = RegionLoopInd array for region i
Nloops = number of loops in region

-- UnCollapsed References (some faces are removed from the calculation as they
... do not affect the loop pressure drop.
Rows = vector of numbers from startrow to startrow + Nloops by stepping 1

-- Extrapolate values at this time-step
if 3 points are recorded
    for each loop velocity
        0 indicates the "t-3" recorded point
```

```
        1 indicates the "t-2" recorded point
        2 indicates the "t-1" recorded point
        prediction = y0*(((time-t1)*(time-t2))/((t0-t1)*(t0-t2))) +
                     y1*(((time-t0)*(time-t2))/((t1-t0)*(t1-t2))) +
                     y2*(((time-t0)*(time-t1))/((t2-t0)*(t2-t1)))

-- Define SkipLoop as a boolean indicator of whether or not the loop is considered
during this solution phase.
SkipLoop = vector of false booleans of length = number of loops
For p = 1 to Nloops by stepping 1
    If the loop is closed off during this increment
        A(rows(p), F2C(Ind(3, p))) = 1
        SkipLoop(p) = true
    Else
        A(rows(p), F2C(loop(2, Ind(2,p)))) = 1
        If predition was made
            b(rows(p)) = prediction(p)
        Else
            b(rows(p)) = volume flow rate of face index= loop(2, Ind(2, p)))

-- Calculate Inverse of "A" Matrix
Ainv = inv(A) // By LU Decomposition

-- Eliminate the rows of the solution that are not important
Indl = vector containing increments from 1 to the number of loops stepping 1
Remove skipped entries from both rows and Indl

-- Initialize Solving Loop
Iteration = 1
Max_Iterations = 300
Fn = vector of ones equal of length equal to number of active loops
Tol = 1e-8

If any loops need to be solved

    -- Newton-Raphson Method
    J = square array of zeros of length = the number of active loops
    While Iteration < Max_Iterations
        -- Define Jacobian
        For i = 1 to the length of Indl
            Elements = Ind[1, Indl[i]] to Ind[2, Indl[i]] stepping 1
            S = Loop[3, elements]
            Fcs = Loop[2, elements]
            For j = 1 to length of Indl
                DeltaV = column "rows[j]" of Ainv
                If i == j
                    [dfi_dxj, fni] = getCost(this, x[F2C[Fcs]], S, Fcs, ...
                        Fcmu[Fcs], Fcrho[Fcs], DeltaV[F2C[Fcs]])
                    J[i,j] = dfi_dxj
                    Fn[i] = fni
                Else
                    [dfi_dxj] = getCost(this,x[F2C[Fcs]], S, Fcs, ...
                        Fcmu[Fcs], Fcrho[Fcs], DeltaV[F2C[Fcs]])
                    J[i,j] = dfi_dxj

        -- Test Convergence
```

```
        If the sum of Fn is less than Tol then exit While loop

        -- Calculate the shift in x
        dx = Ainv[:,rows]*(J\-Fn)
        x = x + dx

        Iteration = Iteration + 1

Record Calculated values and their associated timestamp

this.Fc_V[faces in region] = x[F2C[faces in region]]

-- getCost Function
Inputs(this, x, S, Fcs, Fcmu, Fcrho, DeltaV)
-- Calculates the loop pressure loss given loop volume flow rates "x", also
calculates the derivative of the loop pressure loss.
```

4.3.6 Constrain Time Step Post-Mass Flux

After flow velocities are initially calculated the maximum timestep is updated. If the maximum timestep is smaller than the timestep that was used, then the flow rate calculation is repeated until this condition is satisfied.

4.3.7 Update Properties

Using the flow rates, the nodal internal energy, mass, and temperature (derived from internal energy) are calculated, in preparation for the next iteration.

4.3.8 Calculate Turbulence Flux's

Turbulent fluxes are calculated according to each element type. Turbulence values are incremented at steps that are limited by a maximum change in turbulence weight. The turbulence loop is repeated until the timestep is completely traversed by the limited steps.

4.3.9 Record Statistics

Having stored the indexes and sign of all faces that conduct to a source, to a sink or the environment in a pre-processing step, the program adds the total of these over the increment to a collection variable, that can be accessed by outside processing.

4.4 Mechanical Solver Loop

4.4.1 Calculate Piston Forces

The first step to calculating piston forces is to calculate the pressure drop. This value is defined exclusively by the volumetric flow rate. The Reynolds number is calculated as:

$$N_{Re} = \left| \frac{\left(\frac{\dot{V}}{A} + F_V . \omega\right) \rho . d_h}{\mu} \right|_{fc} \tag{91}$$

The following matrix contains 1 row for each independent face's pressure drop and a single additional row which ensures that the partial pressures of each node add up to the pressure of the region, multiplied by its volume. This region pressure is the pressure established through the volume flux solving section. The first $n-1$ rows of this matrix are precalculated.

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_n \\ P_{region} . V_T \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 & \dots & 0 \\ 0 & 1 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 1 & -1 \\ V_1 & V_2 & V_3 & \cdots & V_n \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{n-1} \\ P_n \end{bmatrix} \tag{92}$$

The final pressures are then used in conjunction with the pressure and shear contacts to calculate forces which pass onto the linear to rotational conversion functions via the following equations:

$$F_P = \sum y . A . P \tag{93}$$

$$F_s = \sum \frac{y . A}{2} \left(P_i - P_j\right) \tag{94}$$

where: y: The sign of the face relative to the orientation of the mechanism.

4.4.2 Calculate Driveshaft Forces

Each mechanism contributes a processing function that takes an input (including position, angular velocity, angular acceleration, and index of sub mechanism) and outputs the driveshaft forces including the two normal forces and torque. These are simply added up, as driveshafts can

take a wide variety of forms and the total force including the weight of the flywheel is calculated is multiplied by the driveshaft friction coefficient.

4.4.3 Calculate Acceleration

Acceleration is determined by simply calculating the acceleration induced on the flywheel via the sum of driveshaft torques.

$$\alpha = \frac{T}{I} \tag{95}$$

where: T: The total torque generated by the mechanism acting on the flywheel. This is produced via the translation of piston forces through the linear-to-rotational mechanisms onto the drive shaft.

I: The moment of inertia of the flywheel.

α: The angular acceleration of the flywheel.

4.4.4 Calculate Next Velocity Target

The angular acceleration produced in the previous section is assumed to have happened over the angular increment immediately preceding this calculation. Therefore, the acceleration is multiplied by that timestep to produce the change in velocity. The boundary motions experienced by the gas, over the next angular increment, will ramp up to that next velocity.

In closing this step, the solver has two potential strategies. It can re-enter the gas loop to solve the next angular increment. Or it can exit having satisfied one of the following conditions: it has reached steady state, it has run out of time or it has detected that the engine has stalled. Steady-State is detected via the difference between the current and previously calculated power falling below a tolerance. An engine stall is detected via the calculation of a negative angular velocity.

4.5 Conclusion

This chapter outlined the entire simulation process. The process started with discretization, then filtered the nodes for unnecessary loops and poorly sized nodes. Then the nodes were converted

into arrays of properties, along side several other structures designed to facilitate the solving of the solid and gas networks. Then the user was queried for details on the setup, the conditions to start from and the conditions of termination.

The main solving loop was characterized by an initialization phase, where temperature or flow dependent properties were recalculated given new conditions. Then flow independents were calculated such as conduction and explicit faces. Then the gas network was solved, considering changes in volume and energy introduced to each node. Then flow rate dependent properties such as mass and energy were distributed. Following this turbulence was transported, generated, and decayed.

At the end of each increment the mechanism took the cumulative pressure on its pistons as an impulse. This impulse was transferred through the linear to rotational mechanism, onto the driveshaft until finally causing the flywheel to either accelerate or decelerate for the next angular increment. The cycle can continue like this for many steps. The next chapter presents a series of advanced methods available in MSPM to reduce the number of steps, the time required for each step or use MSPM to automatically improve the engine.

CHAPTER 5. ADVANCED FEATURES

The following sub-sections outlines some of the successful tools used to enhance the convergence of the algorithm when a steady state is desired.

5.1 Solid Temperature Distribution Acceleration

One of the primary restrictions to reaching steady state is the rate at which heat diffuses into the body of the engine. A technique used by some researchers in the massively parallel computational fluids areas [58] is to decouple the gas and solid networks and on occasion calculate the steady-state temperature regime of the solid component based upon the mean thermal fluxes from the gas component. Often this is validated by the concept that temperatures in the solid evolve on a much slower rate than the temperatures in the gas. The algorithm, in this case is as follows.

The algorithm builds off the following equation, which applies for every solid node for a given instant in time:

$$Q_{in,i}(t) = \left(\sum_{\substack{other\ solid \\ nodes\ (j)}} C_{ij}(T_j - T_i) + \sum_{\substack{adjacent \\ gas\ nodes\ (k)}} C_{ik}(T_k - T_i) \right)_t \tag{96}$$

The solution that this algorithm is seeking will solve for all T_i such that $Q_{in,i}$, the flux into each solid node, is zero when integrated over the entire cycle. Since the conductance between solid nodes is only dependent on angular position, and velocity change during the cycle is assumed to be negligible in a well, then the cycle averaged conductance between solid nodes $C_{ij,eff}$ is the following:

$$C_{ij,eff} = \begin{cases} C_{ij} & For\ static\ faces \\ \dfrac{1}{2\pi}\displaystyle\sum C_{ij}(\theta)\, d\theta & For\ dynamic\ faces \end{cases} \tag{97}$$

where: C_{ij} = Static value assigned to conductance between node i and j

$C_{ij}(\theta) =$ Angular dependent value of conductance between node i and j

$d\theta =$ Angular increment that separates unique values in the dynamic values lookup table.

The conductance between the gas and a solid node depends on velocities and temperatures, and therefore the effective conductance $C_{ik,eff}$ for these nodes is equal to the following:

$$C_{ik,eff} = \frac{1}{\sum \delta_t} \sum \left(\frac{\delta}{R_{ik} + \frac{1}{A_{ik} h_k}} \right)_t = \frac{1}{\sum \delta} \sum \delta C_{ik_t} \tag{98}$$

where: $\delta_t =$ Instantaneous timestep between which each conductance samples are gathered.

$C_{ik_t} =$ Instantaneous conductance between the gas node and solid node.

$A_{ik_t} =$ Instantaneous value of the surface area of the mixed face.

$R_{ik} =$ Thermal resistance of the solid component of conduction.

$h_k =$ Convection coefficient, as derived from the Nusselt number, associated with the gas node.

The effective value of $T_{ik,eff}$ with respect to the faces that it interacts with is dependent on the instantaneous value of conductance for each face. Thus:

$$T_{ik,eff} = \frac{\sum (\delta C_{ik} T_k)_t}{\sum (\delta C_{ik})_t} \tag{99}$$

The cycle averaged version of equation (96) is as follows:

$$\oint Q_{in,i} = \sum_{\substack{other\ solid \\ nodes}} C_{ij,eff}(T_j - T_i) + \sum_{\substack{adjacent \\ gas\ nodes}} C_{ik,eff}(T_{ik,eff} - T_i) \tag{100}$$

Since every solid flux should integrate to zero over the cycle, this forms a set of equations, which can be arranged in matrix form ($A\boldsymbol{T} = \boldsymbol{b}$):

$$\begin{bmatrix} \sum_j C_{1j,eff} + \sum_k C_{1k,eff} & -C_{12,eff} & \cdots & -C_{1n,eff} \\ -C_{21,eff} & \sum_j C_{2j,eff} + \sum_k C_{2k,eff} & \cdots & -C_{2n,eff} \\ \vdots & \vdots & \ddots & \vdots \\ -C_{n1,eff} & -C_{n2,eff} & \cdots & \sum_j C_{nj,eff} + \sum_k C_{nk,eff} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} \quad (101)$$

where:

$$b_i = \sum_k C_{ik,eff} T_{ik,eff} = \sum_k \sum_t (\delta C_{ik} T_k)_t$$

The resulting set of temperatures are adjusted to account for the current offset from the mean cycle temperature, this equation appears as:

$$T_{i,new} = A^{-1} b + T_{i,0} - \left(T_{i,avg} + \frac{1}{2} \left(T_{i,0} - T_{i,0\,prev} \right) \right) \quad (102)$$

where: $T_{i,0}$ = Temperature of node at the end of this cycle (last measured temperature)

$T_{i,0\,prev}$ = Temperature of node at the end of previous cycle

$T_{i,avg}$ = Average temperature of node as measured over the previous cycle.

The concluding formula attempts to recapture the oscillations that each node experiences over the cycle. As used in the solver, the engine is cycled until reaching convergence with this method. The last cycle is then conducted without this acceleration and with a tighter timestep. This final step ensures that the results are relatively free of numerical artifacts.

The performance of this algorithm was compared against natural convergence on the EP-1 test engine, an experimental engine compared against in CHAPTER 7, from a cold state. The log plot in Figure 5.1, below, illustrates the convergence behaviour. The initial sharp climb in both models is due to the rapid temperature changes of the gas volume experienced over the first few cycles. The remaining period involves the gas exchanging heat with the solid elements of the body until the amount of energy exchanged over the cycle is zero. The resulting algorithm converged to 2% of the final value in 9 cycles, equivalent to approximately 9 seconds in simulated time, the

unaccelerated model would converge to this level of tolerance after 2057 cycles, approximately 34 minutes of simulated time. The two simulations converged on the same value within 0.01% of each other. This indicates that acceleration did not significantly alter the result of the simulation, but rather improved the rate at which this result is obtained.

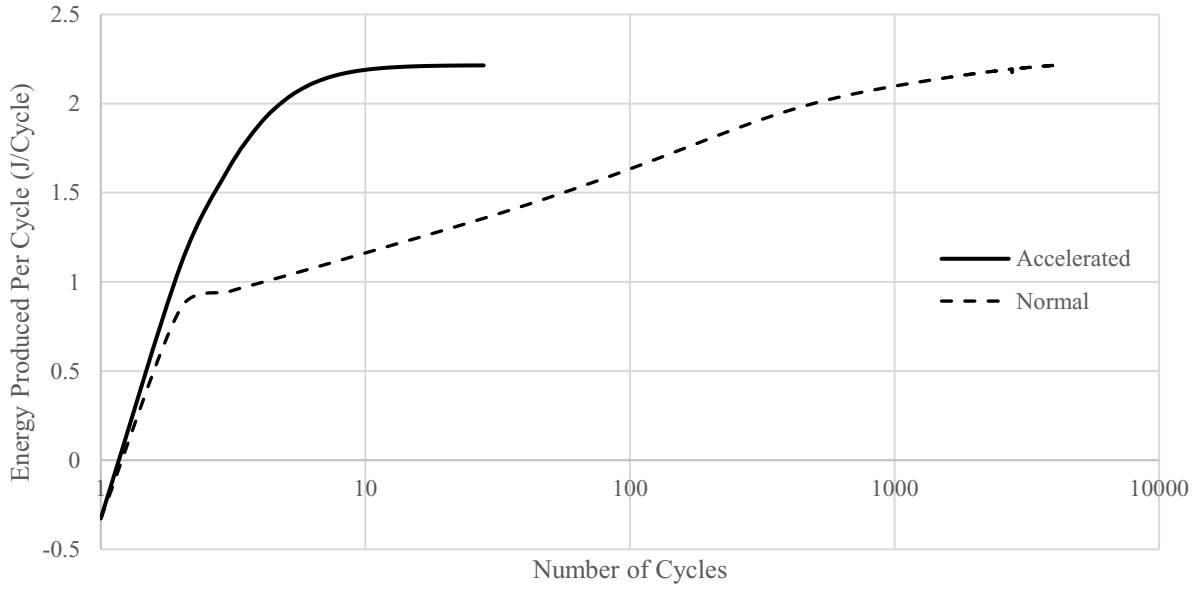


Figure 5.1: Comparison of accelerated vs natural convergence of Stirling engine performance of the EP-1 model (defined in Appendix C)

5.2 Progressive Refinement

Taking inspiration from multi-grid methods discussed in [59] which are effective convergence enhancement tools for CFD solvers, the following section outlines progressive refinement as a tool to accelerate an incremental simulation to a steady-state position. The strategy that would be undertook by this is to run the engine on a coarse model to establish a quick overall picture of the macroscopic behaviour of the engine. Then progressively run the engine on a series of finer grids, before ultimately establishing the final temperature distribution with the desired grid size. The Snapshot feature would assist with interpolating between different granularities.

The speed at which the gas system may run is theoretically proportional to the number of gas nodes divided by the size of each node. Ideally, due to the reduction of the number of nodes by the same amount, the simulation will run at speeds proportional to the inverse of the number of nodes

squared. In the EP-1 simulation model, which is a comparison with a real-world engine found in CHAPTER 7, the trend shown in Figure 5.2 is found.

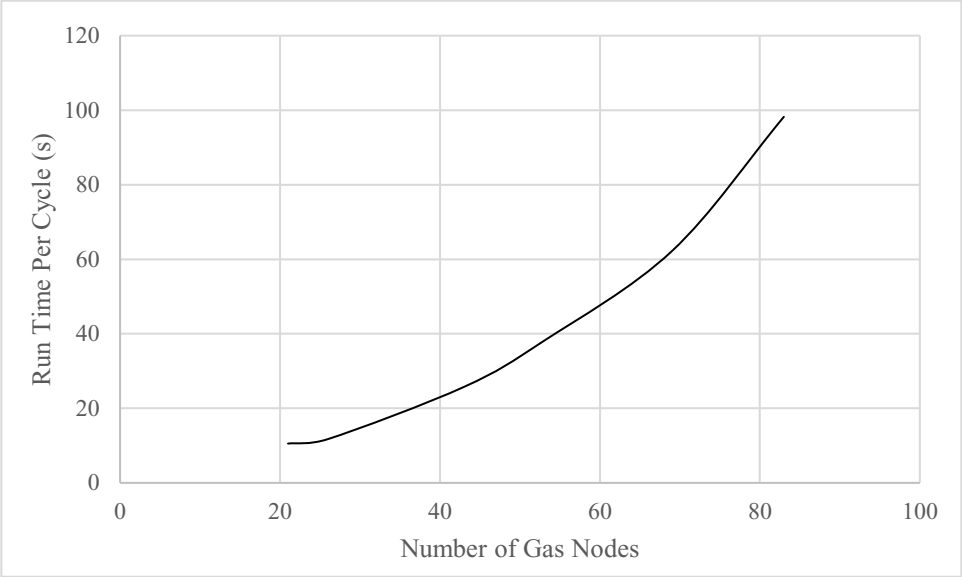


Figure 5.2: Computational Time vs Number of Gas Nodes,

The trend follows closely the power curve: $0.0011x^{2.5568} + 7.625$, it varies from the theoretical case of Cx^2 for the following reasons.

- Node densities are not high nor uniform enough such that node growth could be considered a uniform action.
- Loop calculation may be relatively independent of the number of nodes and have a significant impact on the run speed.
- Larger memory requirements can slow down operations through higher computational overhead, this is not included in the theoretical case.

During test sets this progressive refinement does not activate if following a similar experiment such as the snapshot from a previous experiment as this is typically close to the steady state for the following experiment. As a result, time investment into further development of this tool was not considered. It does however allow the user to quickly estimate the result from a more advanced model by reducing the number of nodes through modification of the de-refinement factor entry on the GUI, as discussed in CHAPTER 6.

5.3 Geometrical Optimization

Traditionally, engines have been designed by skilled experts, who start with defining the basic parameters of a design using low-order models and then through use of higher models, make small adjustments to improve the predicted performance of the engine. These adjustments can be made by computers as well, and learning algorithms have been incorporated into a variety of 3rd and 2nd order models in the past [35]–[37], [46]. The choice of learning algorithm depends on the runtime of each test, which for this model can take between 10 minutes for a detailed model to several seconds for a simple model. Other involved factors include the presence of local maximums, the existence of saddle points and the non-linearity of results. Thankfully, the power response of a Stirling engine given reasonable geometry will be continuous as discontinuities will only exist when two parts of the engines are separated into two regions for part of the cycle, likely a sub-optimal process. There is no guarantee of a single optimal geometry as Stirling engines can exhibit two possible optimal configurations, isothermal and adiabatic.

To conduct this optimization a combination of standard gradient descent with a line searching algorithm is applied. Wherein, after a step is made in the direction it is tested, if the step resulted in greater power then it is the new point, if the step did not then the step is backtracked. If the first step resulted in a reduction of power then the step length is backtracked then the step length is reduced by half trying again at the intermediate position, this is conducted until an increase is recorded, after which a new gradient is taken. If the first step was successful, then more steps are taken in that direction until a reduction in power occurs. The inclusion of this improves the rate of convergence of the optimization as a gradient calculation is very expensive.

The MSPM software can modify piston strokes, the position of surfaces (connections), the fill pressure and rotational speed to seek the optimal power. These are governed by the optimization scheme builder on the GUI.

5.4 Conclusions

This chapter contained a series of optional features which were designed to enhance the model. Temperature convergence acceleration resulted in 2 orders of magnitude improvement in convergence rate at a small computational cost while converging to the same state as natural

methods. The second section included a mesh refiner which allows the designer to choose between accuracy and computational speed. The third section outlined a geometrical optimizer which can be applied to optimize a given part of the engine, or the entire engine, allowing the designer to automate this part of the design process.

CHAPTER 6. MODEL USAGE

6.1 Constructing a Model

A model of a Stirling engine is initialized by opening the GUI interface. By default, a single group is created along with 2 orthogonal connections placed at the origin. From this point the user can construct their design.

Figure 6.1 shows the entirety of the main interface, from which all of the main functionalities can be accessed. In further sections each area of this GUI is broken down.

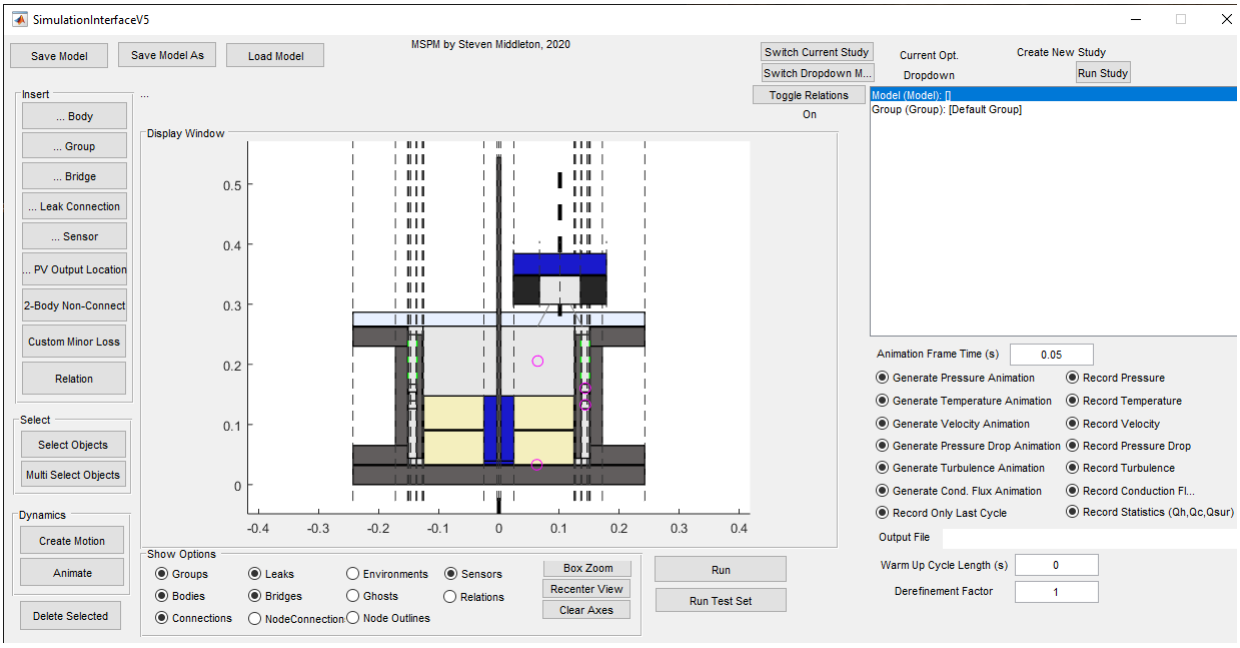


Figure 6.1: The main MSPM graphical user interface.

6.1.1 Display Window

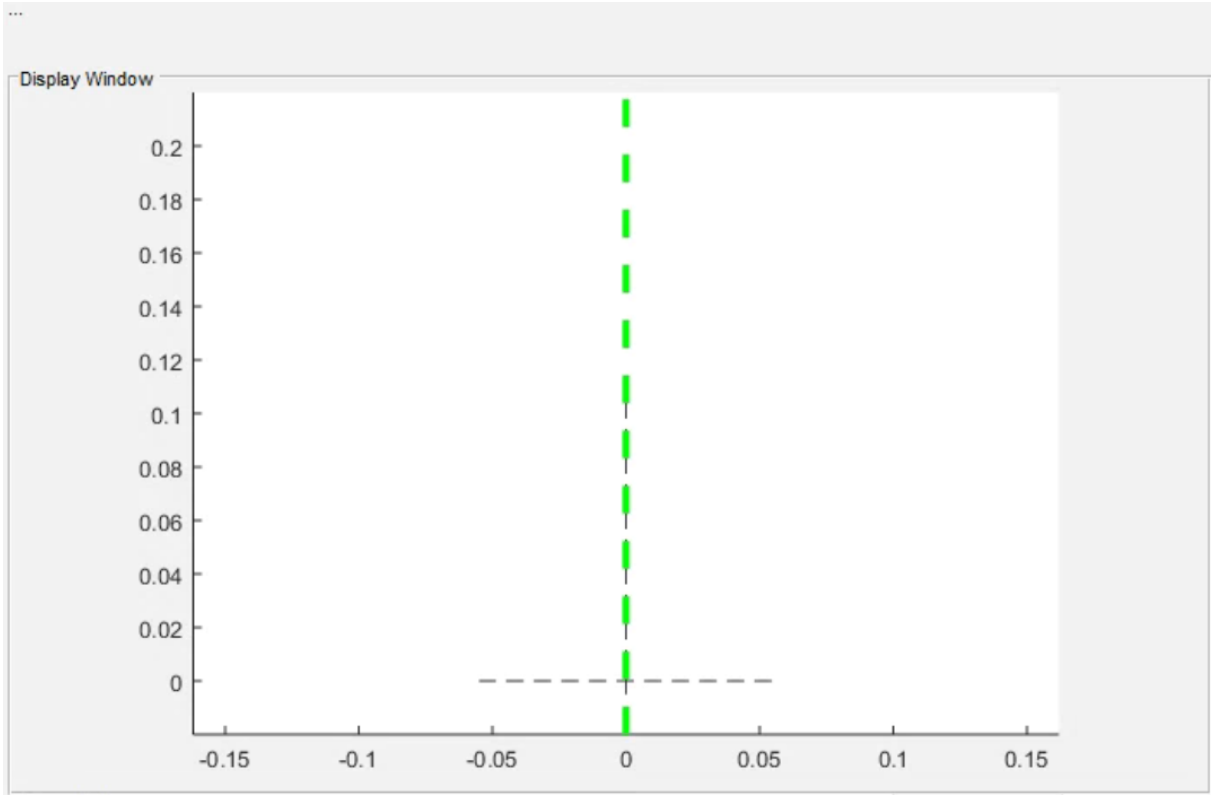


Figure 6.2: The main model display window

The display window displays the model view. The user can modify the view with the box zoom options. The default window contains all the geometry of the model, default views can be reset via the re-center view option. Mode specific instructions will appear above the display window, informing the user of the next step that they need to accomplish in the insertion of elements. When producing both live and output animations, the current display window acts as the animation scope. The model within this window is displayed in cross-section and each group is assumed to be azimuthally symmetrical.

6.1.2 Left Toolbar – Create, Destroy and Select

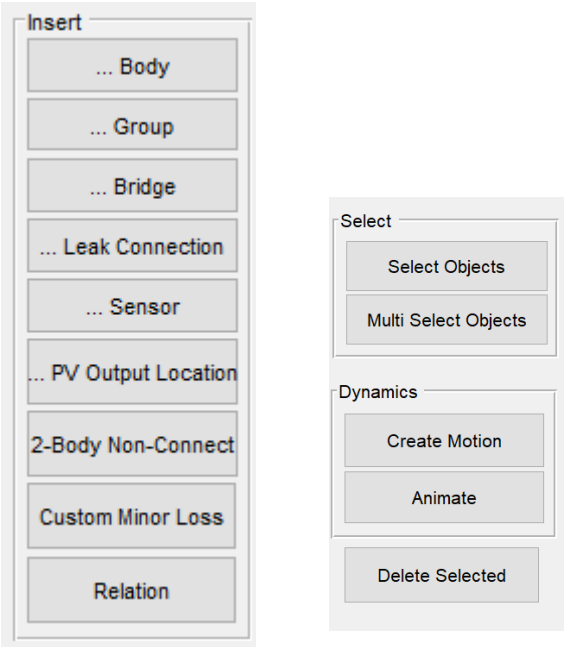


Figure 6.3: Create, Destroy and Select Toolbar

Here, using the group of controls seen in Figure 6.3, the user has the control to add to or delete elements from the virtual engine. The elements in order of appearance and their description is as follows:

6.1.2.1 Insert: Body

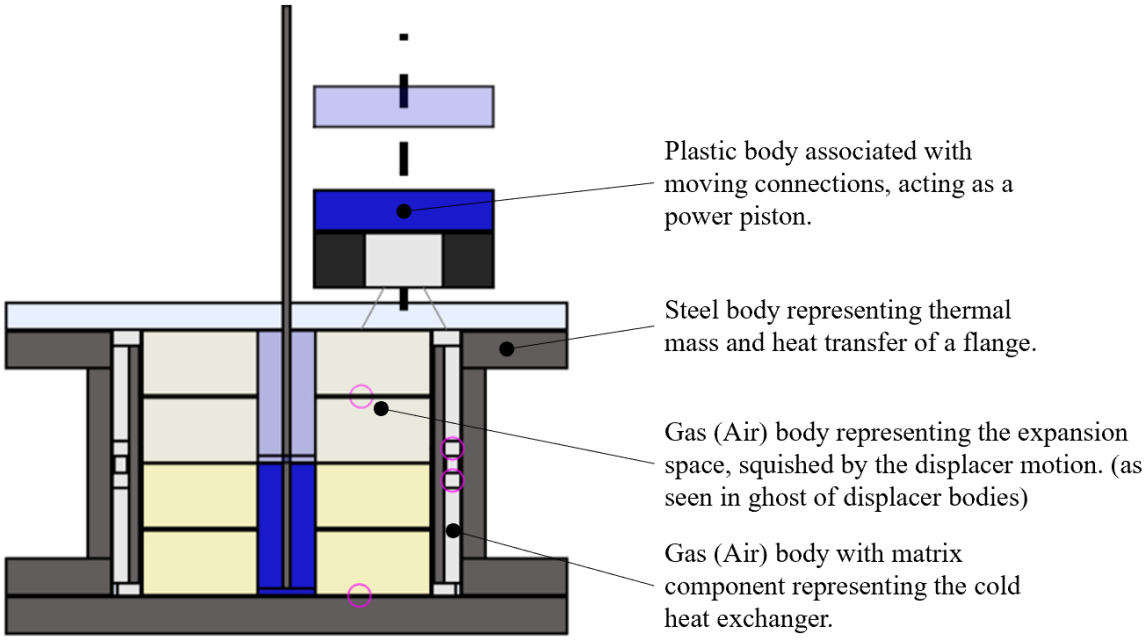


Figure 6.4: Examples of Bodies Being Used to Construct Geometry

Bodies as shown in Figure 6.4, are foundational elements of an engine model and the only means of representing a physical object. This is defined through the definition of 4 constraining surfaces, referred to as connections. There are multiple ways of creating these. A left mouse click will select the nearest properly oriented connection. On the 1st connection this can be any connection, horizontal or vertical. The even numbered connections will be oriented the same as their preceding connection with the 3rd connection being the opposite orientation as the first 2. On a right click, the model will ask for either an offset from the previous connection or, in the case of an odd numbered connection, an offset from the origin. If no connections have been created, then this first right creates a connection that is parallel to the axis (the radial direction). Care should be taken to always define mobile elements at their bottom position (bottom being the farthest in the negative direction). If a new group is required, then this can be added using the insert group functionality.

6.1.2.2 Insert: Group

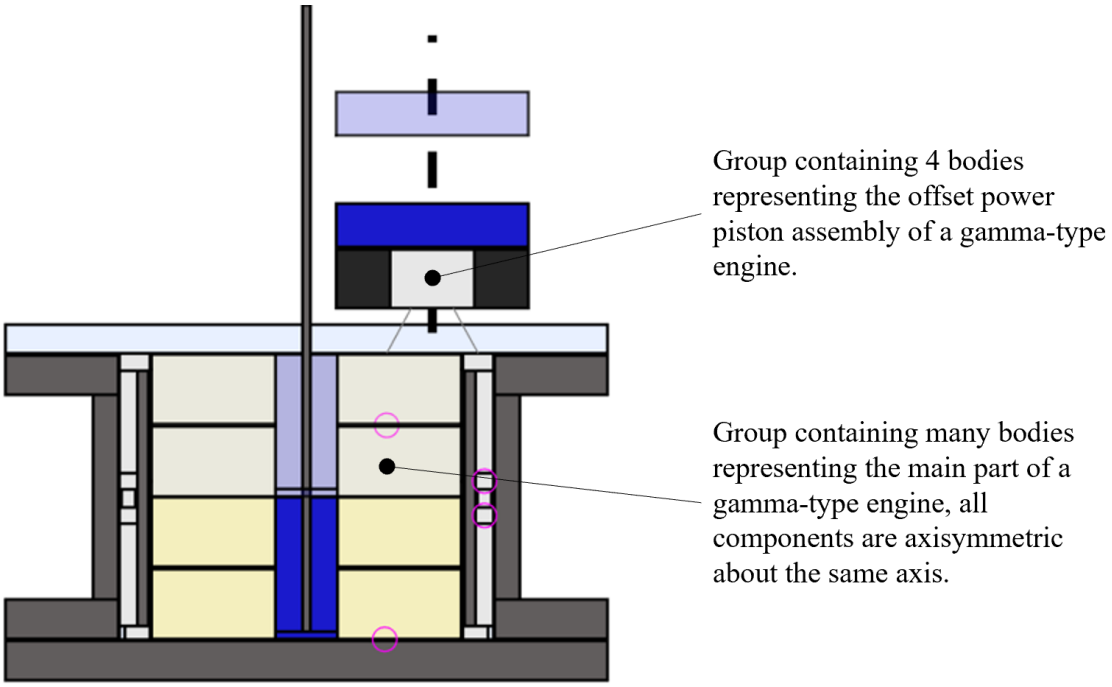


Figure 6.5: Example of an engine containing two groups, one for the main engine assembly and a second for a power piston offset from the main axis.

A group, as shown in Figure 6.5, is a container for a set of bodies which lie around a common axis of rotation. For a wholly axially symmetric engine, only one group would be required. A group can be inserted by using the left mouse button in the empty space of the display window. The software will insert a new group there. In post model assessment the created groups can be moved into a more compact or physically representative location by editing the position property of the group using the property inspector.

6.1.2.3 Insert: Bridge

If the engine design incorporates multiple groups, there may be a need to include a bridge into the design. Bridges connect one body to another via a connection interface. An example of the usage of a bridge in a practical engine is found on Figure 6.6.

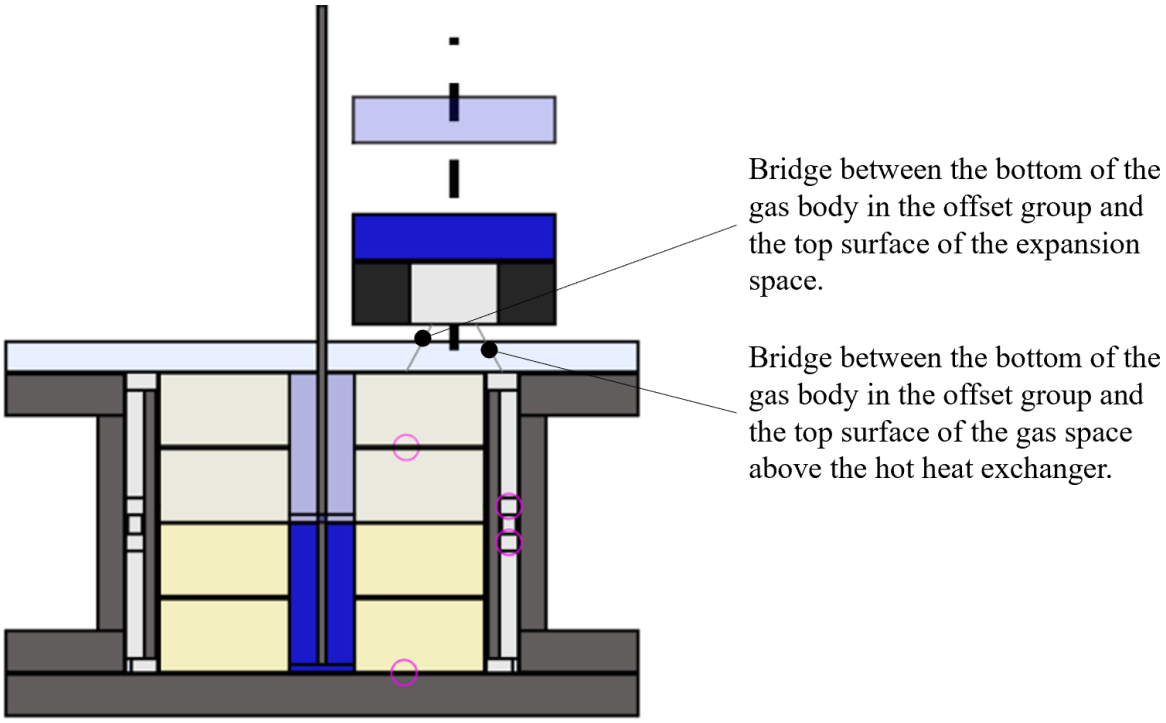


Figure 6.6: Example of a usage of the bridge component

Bridges can represent axially aligned connections, offset connections or even T-junction connections. It is important to note that the simulation does not support the non-symmetries that arise from any of the scenarios as there is no discretization in the direction of rotation. However, the software still utilizes the same area and hydraulic diameters of the connection. The available configurations to be used by a bridge are found on Figure 2.10.To produce a bridge the following steps must be followed:

Select the first connection: Select a connection which touches one of the bodies, in particular this body is called the foundation onto which the other body is added on. This connection may be in the horizontal or vertical orientation and represents the surface that the two bodies will meet against.

Select the first body: Select the body, that is touching the first connection. In the event of an offset, this body is considered static.

Select the second connection: This is the face of the second body that will interface with the first body. This may ask several times, as this connection may be in a different group than the first body-connection set.

Select the second body: Select the second body.

Input the offset from the origin: If the two connections are horizontally aligned, provide an offset from being coaxial. If one of the connections is vertically aligned, provide the offset of the center of the horizontally aligned participant from the origin of the vertically aligned participant. If both connections are vertical then the second body is offset from the first body (in addition to the local coordinates of the second body within its group) by the set amount.

6.1.2.4 Insert: Leak Connection

The leak connection connects two separate bodies with a leak function that provides a leak flow rate that is dependent on the pressure difference through the general formula:

$$\dot{V} = C.(P_1 - P_2)^{N1}$$

where: C: Leakage number

$N1$: Leakage exponent

The exponent and number depend on the properties of the leak. These can be obtained by observing the pressure drop of a physical engine of similar design or used as an aid in sensitivity studies. A leak is created by selecting two bodies to link together and then by providing the coefficients.

6.1.2.5 Insert: Sensor

Sensors are intended to be used to measure a specific property at a specific location and show the evolution of that property over the course of the experiment or over the course of a single cycle. This has two forms: a single point, which generates a line plot (the parameter vs time) and a line sensor, which generates a surface plot (the parameter at N points down the line vs time). The steps to create a sensor are as follows:

Selecting the target body: Select a body, from within which you will record the data.

Selecting an orientation: There are several options for this, you can select the center of the body, the center of the bottom, top, inside or outside face or an axial line through the middle either going in the *y*-direction (*y*-axis) along the group axis, or in the x-direction (x-axis) which is the radial direction.

Selecting the independent variable: The independent variable is the variable that changes in time but is only dependent on the motion of the engine. Currently, the two independent variables are time and angle. If angle is selected the variable will, in the end, have only recorded the last cycle (as it over-writes the same angular positions). If time is selected it will record each value uniquely with time until the simulation ends.

Selecting the dependent variable: Currently, this can be either temperature, pressure, or the turbulence weighting factor.

6.1.2.6 Insert: PV Output Location

PV Output locations are specialized sensors that are designed to output an indicator (pressure vs volume over a cycle) diagram. These features are created by **selecting a gas body**. Internally, the code will then scan the selected region (all gas bodies touching the selected body). Each variable volume space that it finds will be represented by an individual indicator diagram on the final plot. For example, the plot displayed in Figure 6.7 below is the indicator diagram produced by this sensor for a gamma type engine. A gamma engine has 3 variable volume spaces: the expansion space, the compression space, and the power piston space. The sensor also colors plots as blue if they produce positive power and red if they produce negative power and places a marker where the cycle start position was.

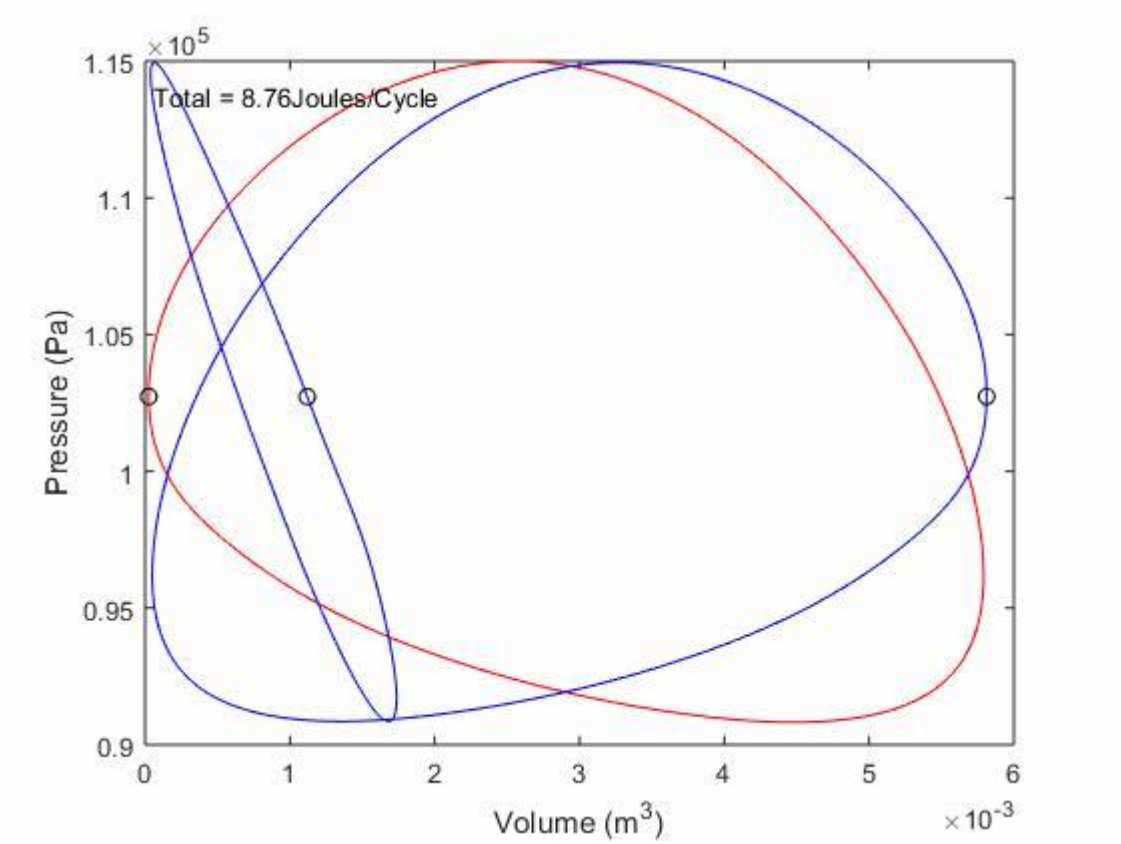


Figure 6.7: Example indicator diagram from PV Output sensor

6.1.2.7 Insert: Two Body Non-Connection

This feature was added to fit a specific problem, which is outlined here for clarity. The EP-1, the test engine that will be compared against, contains a flexible thin, rubber bellow. However, as solid bodies currently cannot stretch, and an immobile rubber sleeve would fail to model the thermal transport across the real system. Thus the Two-Body Non-Connection was added and prevented the gas body under the power piston from interfacing with the environment.

Thus, this feature involves two steps as follows:

Selecting a Body: This body will not connect to the second body by any means.

Selecting a Second Body: This second body will not connect to the first body through any means.

6.1.2.8 Insert: Custom Minor Loss Coefficient

This feature enables the user to create a custom minor loss at any boundary between bodies. The minor loss can be non-symmetric, which allows the user to, to a degree, simulate check valves in cases where a different flow direction is available. In cases where the check valves completely close off two gas spaces they will not work as only the loop solver uses flow losses to determine flow rates. In these cases, the user may have to create their own solution or create a piston that blocks the two spaces when desired.

Selecting a Body: Defines body 1.

Selecting a Second Body: Defines body 2.

Providing a name, K12 and K21: This user-form appears after the user creates the feature, the name is important for identification later, K12 is the minor loss for flow going from Body 1 to Body 2, while K21 is the flow going in the opposite direction.

These features can be deleted by finding them in the Model and following the instructions to delete the desired Custom Minor Losses.

6.1.2.9 Insert: Relation

This feature allows the selection of 2 connections to associate with each other. Doing so ensure that when one connection is moved that any connections or mechanism strokes that are associated with it will also move. A relation comes in several forms: (a) *constant distance*: when one connection moves the second moves the same amount, (b) *scaled*: when one connection moves the other moves an amount scaled by its distance from zero, (c) *scaled based on lowest value*: when one connections moves the other connection moves based on distance from the minimum extreme of this group of connections (or relative to the maximum if it is the minimum that moves), (d) *width*: when 4 or 6 connections are grouped together by having this relation type, any modifications are reflected. If the two extreme points move, the inner points shift by half that amount in the same direction. This is of particular use in cases where the heat exchangers sandwich the regenerator, lengthening one heat exchanger will length the other one and keep the regenerator centered between. (e) *Stroke*: selecting 2 connections and a mechanism will allow the difference between those connections to define the stroke. A unit change in that distance results in a unit change of

the stroke. (f) *Piston*: selecting 2 connections and mechanism will allow the difference between those connections to define the length of a piston. This relationship is only of physical suitability in the case of a displacer piston which moves within an encloser. A unit increase in the distance will result in a unit decrease in the mechanism stroke. Relationships can be toggled on and off via the Toggle relations button along the top of the GUI.

This feature was introduced to reduce the degrees of freedom used by the gradient descent algorithm.

6.1.2.10 Select: Select Objects

While this is activated, clicking on the graphical window will give you a list of elements that you may have wanted to select. Including, within a selection tolerance, a group, a connection and a body. Selecting an object with this mode will remove any currently selected objects from the list.

6.1.2.11 Select: Select Multiple Objects

Similar to select objects. However, this option appends the new object to the selected object list.

6.1.2.12 Dynamics: Create Motion

Using the create motion interface a frame can be connection. After creation, clicking on a body or a connection exposes the drop-down menu, where a reference frame can be added. The animate function can provide some feedback on the resulting motion. As a note, stretching solid bodies are not supported realistically in the model, so ensure that every element in compound shapes such as pistons are given the same movement.

Note that the motions that are define here can be found and edited through the property inspector window, as they can are stored under the default expandable object found there.

6.1.2.13 Dynamics: Animate

Pressing this button will begin a 30 second animation of the model's defined motion. Useful for understanding the phasing or interference caused by a prescribed motion.

6.1.2.14 Delete Selected

This function deletes (without undo) the selected element. This will also delete any element that relied on the deleted object.

6.1.3 Bottom Toolbar – View options

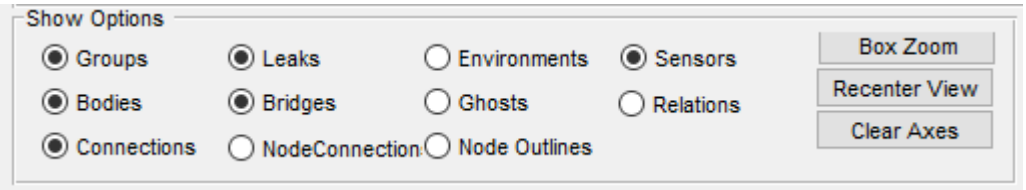


Figure 6.8: View options

The view options bar provides the user with the ability to modify what is shown in the display window. Several of these are self-explanatory: *Groups*, *Bodies* and *Connections* are common properties of any model. *Bridges* appear as lines that go from the center the side of one body, to the center of the side of another. Leaks is a placeholder for future development but will appear like bridges. *Node-Connections* connect the center of nodes together if those nodes share a connection via a face. *Node Outlines* simply places a marker at the center of all the nodes. *Environments* does not show the environment, but rather shows what the software has identified as the environment exposed surfaces. *Ghosts* show the maximum positions of any solid body that translates (as the minimum position is covered by the current placement). *Sensors* place a magenta marker or line segment along the area that will be measured by the sensor during simulations. Showing *Relations* update the colors on connections based on their existing geometrical relations with each other, those with multiple associates are colored in the default color, however.

The view option *Box Zoom* allows the user to zoom in on a box, the code maintains the aspect ratio, zooming in as much as it can. *Recentre View* resets the display window to its default all encompassing mode. *Clear Axis* is useful for removing graphics are plotting incorrectly or may represent deleted objects.

6.1.4 Top Toolbar – Save / Load options

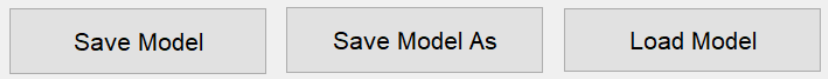


Figure 6.9: Save / Load options

The save options, allow a user to save a model, save the model as a specific name and load models. If there is an existing model that is called by the default name (which is the model's name), then the save model button asks for permission or a new name.

6.1.5 Top Toolbar – Geometrical Optimizer, Relation Toggle & Dropdown mode

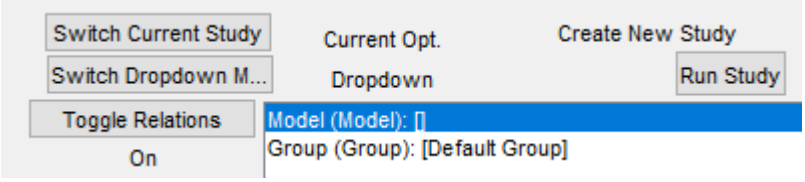


Figure 6.10: Geometrical Optimizer, Relation Toggle & Dropdown mode

6.1.5.1 Switch Current Study

The *Switch Current Study* button switches the optimization study that will run or be appended through interfacing with the dropdown, via the dropdown mode being in the "optimizer" setting. The text label to the right of it will cycle between the named studied or display "Create New Study", indicating that when this study is appended it will create a new optimization study. The study displayed here will be the one ran by selecting "Run Study".

6.1.5.2 Switch Dropdown Mode

This button toggles the text label to the right of it from blank to "optimizer", when the text label is blank the drop down will work normally. Otherwise, anything clicked on in the dropdown menu will be added as a degree of freedom to the optimization study indicated by the *Current Opt.* text label.

6.1.5.3 Run Study

This runs the indicated optimization study. It will also ask for a set of run conditions, which are in the same format as the test set structures. If the run condition structure contains a field called

"PressureBounds" it will assume that pressure is a degree of freedom. If the run condition structure includes "SpeedBounds" it will assume that speed is a degree of freedom.

6.1.5.4 Toggle Relations

Toggling this button from "On" to "Off" will make relations not work when a change is made, allowing you to change the position of connections or length of strokes in isolation. Turning it back to the "On" position will reactivate these relations.

6.1.6 Right Toolbar – Property dropdown and Simulation options

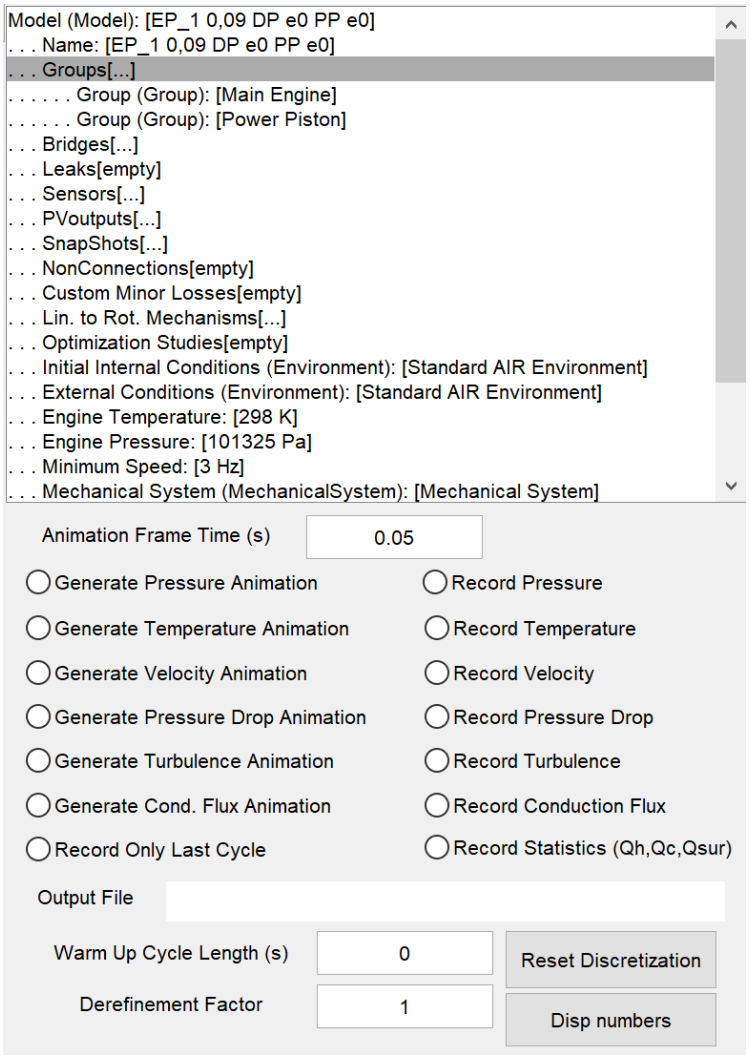


Figure 6.11: Property dropdown and Simulation options

The property drop-down shows by default the root object, represented by "Model (Model) [the name of this file]", which can be expanded to see a host of options or lists of other expandable

objects. Any selected objects will also appear at the bottom of this dropdown menu. Each object has multiple properties and child objects, that can either be edited, expanded or in some cases deleted from this menu. This is where motions are added to connections (or bodies), where discretization schemes are assigned and where matrixes are added to a body using the "Change Matrix" option as shown in Figure 6.12.

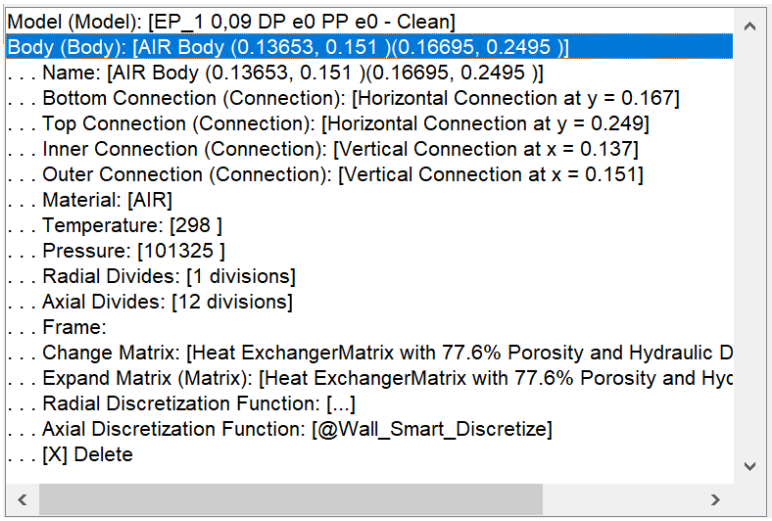


Figure 6.12: Properties of Bodies including location of Change Matrix where Matrix components are initialized

The options on the lower half of this side of the GUI refer to the simulation and simulation outputs. Checking these radio buttons will permit the software to record the referenced property and optionally generate an animation for quick review. The animation frame time refers to the amount of time that each frame of the animation covers. The output file is the path of a folder where you want the files to be saved. The warm-up cycle is a simulation option that is added for transient scenarios from start-up where the engine, is warming up for a period before turning over. The de-refinement factor is a global modifier that decimates the mesh by a set, approximately uniform, amount. A factor of greater than 1 will result in more nodes, while a factor of smaller than 1 result in less nodes.

6.1.7 Start the Simulation

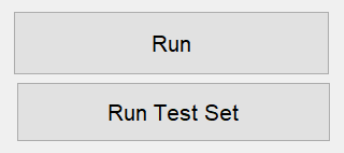


Figure 6.13: Run Interface

6.1.7.1 Run

Runs a single test, after querying the user for simulation parameters.

6.1.7.2 Run Test Set

Runs a single test by calling a test set function by name. Said function returns a structure that contains simulation parameters for several tests in series, these functions are stored as files in the Test_ Running folder. An exemplar test definition file is included below. This version is the default test definition for a gradient ascent and shows all the properties available. A test set function can output an array of structs to perform several tests in series.

```
function [RunConditions] = GA_Template()
    RunConditions = struct(...
      'Model','EP_1 0,09 DP e0 PP e0 - GA',...
      'title','',...
      'simTime',60,... [s]
      'SS',true,...
      'movement_option','C',...
      'rpm',60,... [rpm]
      'max_dt',0.1,... [s]
      'SourceTemp',90 + 273.15,... [K]
      'SinkTemp',5 + 273.15,... [K]
      'EnginePressure',101325,...
      'NodeFactor',1,...
      'Uniform_Scale',1,...
      'PressureBounds',[101325 3*101325],...
      'SpeedBounds',[60 1000] ,...
      'HX_Convection',1.0,...
      'Regen_Convection',1.0,...
      'Outside_Matrix_Convection',1.0,...
      'Friction',1.0,...
      'Solid_Conduction',1.0,...
      'Axial_Mixing_Coefficient',1.0,...
      'HX_C1',1.0,...
      'HX_C2',1.0,...
```

```
        'HX_C3',1.0,...
        'HX_C4',1.0,...
        'HX_SA_V',1.0,...
        'Regen_C1',1.0,...
        'Regen_C2',1.0,...
        'Regen_C3',1.0,...
        'Regen_C4',1.0,...
        'Regen_SA_V',1.0,...
        'Regen_Porosity',1.0);
end
```

Model refers to the file to load in, which is the same as the name property of the root object. *Title* will be the name that the results are saved under. *SimTime* is the amount of in simulation time allotted. *SS* is a flag indicated whether or not the simulation will stop at steady state. *Movement Option* can have defined either constant speed (C) or variable speed (V) indicating if the results should contain the velocity variations. ***R****pm* indicates the initial or target speed in revolutions per minute. ***Max dt*** indicates the maximum timestep to use, normally this only applies for exceedingly slow scenarios. ***SourceTemp***, ***SinkTemp*** indicates the temperature that will applied to constant temperature elements flagged as source or sink respectively, which are automatically identified by relative temperature. ***EnginePressure*** indicates the fill pressure of the engine, the internal volume of the engine is identified by the placement of a PVoutput sensor. ***NodeFactor*** is the mesh refinement factor applied to the test instance, which scales the number of nodes by this amount. ***Uniform_Scale*** scales the geometry by the specified amount in all directions. ***PressureBounds*** and ***SpeedBounds*** is used by gradient ascent to bound the search space for pressure and speed respectively. The next 6 fields allow the user to apply factors on each of the described properties, a factor of 1 uses the results of the default equations. The final set of equations modify custom type heat exchangers with correlations $N_{Nu} = C_1 N_{Re}^{C_2} N_{Pr}^{0.33}, N_f = C_3 N_{Re}^{C_4}$, surface area to gas volume ratios (SA_V) and porosity.

6.2 Discretization

In simulations there are two types of discretization, spatial and temporal. The following sections outline some recommendations and theory on discretization. These are controllable through interfacing with each body via the property drop-down menu, where the number of nodes in each direction can be controlled. Specialized functions that allow for better modelling of surface

gradients can be added by loading the wall smart discretize function as a discretization function. This function uses the global mesher properties. Those properties can be found under Model->Mesher. Other meshing functions can be added if required.

6.2.1 Spatial Discretization

The spatial discretization is how much space is broken up; it is simplest to assign this at the start of the simulation. If this is the case, certain assumptions have to be made by the designer to ration nodes to areas that truly need it. With spatial discretization of the solids the main concern is high gradients, as high gradients require greater node density to be properly modelled, particular at their edges. Three phenomena utilize these high gradients, which will be discussed in the next three paragraphs.

The first aspect is gas spring hysteresis which occurs between the gas and the very surface of the solids surrounding it. If this is the case then these surface nodes will experience strong gradients and curvature, which would vary depending on the expected frequency, and the thermal diffusion of the material. These oscillations are experienced throughout the material, but at a specific depth they become negligible. This depth, which is called the oscillation penetration depth was studied by Wang [60], who presented the following. The formula here is modified such that at this distance only 5% of the oscillation is present.

$$x_{0.05} = 3\sqrt{\frac{2\alpha_t}{\omega}} \tag{103}$$

where: $x_{0.05}$: Represents the distance at which the temperature fluctuations are at 5% of their original value.

ω: Angular velocity

α_t: Thermal diffusivity $\left(\alpha_t = \frac{k}{\rho c_T}\right)$

Beyond this point, temperatures experience a slowly evolving or static temperature profile, which is a phenomenon assumed by several Stirling engine modelers [35], [46]. The ratio of conduction, density and heat capacity is equal to the thermal diffusivity, a representation of the thermal inertia

of the material. The angular velocity (ω) is established at the beginning of the simulation as an estimate of the final angular velocity.

The second aspect is static conduction within the solids of the body. With first order discretization schemes the error associated with discretization increases proportional to the local element size, a length representing how far elements are from each other. This error also increases based on the distribution of values among the nodes, if a high gradient or curvature is to be represented then a fine grid is required. These areas namely exist in features that divide two areas of very different temperatures, or at interfaces of materials of very different thermal properties.

The third aspect is dynamic conduction. As Stirling engines contain moving components, there is an opportunity for momentarily high gradients to be generated when two components closely cross paths. This leads to gradients which exist both into the material depth as well as along the interface length.

For gases the same thing is true as for solid elements, however, the areas in which they occur are different. As the one-dimensional assumption prevents the modelling of the temperature gradients in large chambers, particularly off of walls, these areas are considered well mixed and don't require many nodes. To partially account for this and other factors gas nodes should include turbulence, a representation of how disturbed the flow is. Therefore, there may exist areas of high gradients in turbulence, such as areas directly following geometrical non-uniformities. These gradients persist for about one diameter from the entrance according to Gedeon [35]. Temperature gradients exist at the start and end of heat exchangers and regenerators, Anderson [48] studied this extensively, the exact breadth of the inlet gradient will depend on the effectiveness of the heat exchangers. In addition, Anderson identified that gradients can persist in the areas around heat exchangers, in particular after reversal events, highly diffusive schemes require many nodes to properly represent these moving gradients. Anderson utilized an advanced flux limiting scheme to preserve these gradients.

6.2.2 Temporal Discretization

Temporal discretization is how much time progresses after each flux calculation. For solids this is calculated based on the Fourier number, which sets a limit to the timestep based on the numerical volatility of a numerical element. This non-dimensional number is identified here:

$$N_{Fo} = \frac{\alpha_t . \Delta t}{\Delta x^2} = \frac{k}{\rho . c_T} \frac{1}{\Delta x^2} \Delta t = \underbrace{\left(\frac{k . A}{\Delta x}\right)}_{C_{fc}} \underbrace{\left(\frac{1}{\rho . c_T . \Delta x . A}\right)}_{1/C_T} \Delta t = \frac{C_{fc} . \Delta t}{C_T} \rightarrow \Delta t = N_{Fo} \frac{C_T}{C_{fc}} \quad \textbf{(104)}$$

where: N_{Fo}: Fourier number

α_t: Thermal Diffusivity

Δt: Timestep

C_{fc}: Thermal conductance of a face, used as $\Delta Q = \Delta t C_{fc}(T_2 - T_1)$, where T_2 and T_1 are temperatures of two nodes connected by a face.

C_T: Specific heat capacity of node, used as $\Delta Q = C_T(T_2 - T_1)$, where T_2 and T_1 are temperatures of the same node from different times.

Recommendations from Hensen and Nakhi [61] indicate that the iteration is stable – errors do not grow – for a Fourier numbers of 0.25 or less. Therefore, a Fourier number of 0.25 is selected as the maximum of any node. In determining the timestep, the entire pool of nodes is queried for the timestep limit.

For gases the maximum time step is established based on the Courant Friedrichs Lewy [62] condition:

$$N_C = \frac{U . \Delta t}{\Delta x} = \frac{\dot{V}}{A_{fc} . \Delta x} \Delta t \leq N_{C,max} \quad \textbf{(105)}$$

where: $N_C =$ Courant number, less than 1 for theoretical stability.

U = Speed at which information travels, the speed of the gas

Δx = Spatial difference between two measurement points. Between which the information is travelling.

This condition ensures that a property is not transported any farther than is calculatable by the underlying numerical system. The term Δt represents the time step, Δx represents the spatial distance between adjacent nodes and U represents the velocity.

Numerical algorithms that cover a longer distance, such as one that considers 2 neighbors on either side may be stable with a maximum courant number of 3 due to the added information. In practice however, these theoretical maximums are limited by lower node quality, the presence of destabilizing features and numerical errors, often by an order of magnitude.

6.3 Simulation Tools

6.3.1 Snapshot

A snapshot is an image of the engine at the 0^{th} angular position on the last cycle of the engine, this obtains a snapshot of all the bodies of the engine and records to the granularity of the body discretization. These are recorded in arrays of temperatures that are accompanied by *X* and *Y* values scaled to the body as if it were of unit dimensions, such that interpolating onto a modified body is a trivial manner. This option does not handle new bodies, instead leaving them with the default temperature values.

6.3.2 Test Set Running

A series of tests may be run using test definitions. These run in series, each test starting from the conclusion of the previous, the goal would be that an engine curve could be defined by setting the engine to run at a set of constant speeds in sequence. Each run can be told to look for a snapshot title which will by default be used as the starting point, otherwise it uses the last defined snapshot as a starting point. The use of snapshots allows this approach to construct an engine curve more quickly than starting from scratch each time.

6.3.3 Geometrical Optimization

The MSPM software includes a geometrical optimizer, which when given a series of parameters, will tune the geometry until the engine gives optimal power output. These parameters

include connection positions, mechanism strokes, charge pressure and engine speed. The optimizer makes use of gradient ascent to make small adjustments to the geometry in the direction of positive slope until it reaches either the maximum number of iterations or reaches a point at which the RMS of all gradients is below a set tolerance. Further details on this is found in 6.1.5 for interfacing with it and 5.3 for details into the algorithm.

6.4 Model Outputs

6.4.1 Engine Assessment

6.4.1.1 PV Diagram & Thermodynamic Work

Pressure-volume (PV) or indicator diagrams, produced by the PV output sensor, are an excellent descriptor of the engine's thermodynamic cycle. Several quantitative measures can be quickly extracted from the PV diagram. These are labeled on the sample indicator diagram below.

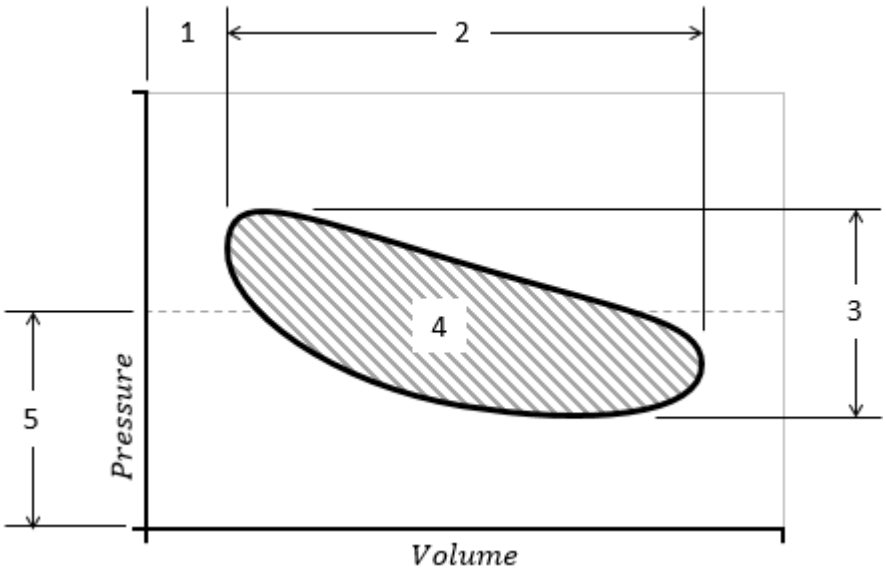


Figure 6.14: A plot and definition of the pressure-volume (PV) diagram

1. **Minimum Volume** – This quantity represents the minimal volume of the engine. This can be used for two imported parameters. The dead volume and the compression ratio.
    a. **Dead Volume** $V_{dead} = V_{min} - V_{DP,swept}$

This parameter represents the volume that does not change its temperature during the cycle, in practice these are all the spaces not swept by the pistons. This dead volume acts as a form of compliant boundary for the engine, which reduces the maximum pressure that the engine reaches. In general, this quantity should be minimized as much as possible.

b. **Compression Ratio** $r_c = V_{max}/V_{min}$

This non-dimensional parameter represents the proportion that the volume changes throughout the cycle. The optimum point of this value is a function of the temperature ratio but is influenced by a variety of factors including the mechanism design. Review and experimentation on low-temperature engines by Stumpf [12], indicates that an approximate value of this optimal point can be obtained as the value: $0.624(T_H/T_L) + 0.376$.

2. **Total Change in Volume** – This quantity represents the dV in the basic equation for pressure work $W = PdV$. However, increasing this quantity does not increase the amount of power produced linearly as various factors influence the power output of the engine.
3. **Engine Pressure Swing** – This dependent property of the cycle represents the P in the basic equation for pressure work $W = PdV$. This property is indicative of the magnitude of the temperature swing in combination with the volume change.
4. **Area Enclosed by the Curve** – This measure represents the amount of work, as defined by $W = PdV$ that the gas volume being observed sent to the mechanism. An engine that produces negative work would still maintain an area here, but the border would progress through time in the counter clockwise direction. A discrepancy between this value and the measured shaft power indicates the amount of energy lost to the mechanism.
5. **Average Pressure** – This quantity indicates the mean pressure that the engine operates at. This property is directly proportional to the amount of produced power, according to the West Number.

When used properly an indicator diagram captures most interactions between the gas and the mechanism. Proper use of an indicator diagram would capture all spaces that are being compressed or expanded. This is important as minute differences in pressure in these spaces can be

embodiments of flow friction effects. This results in an indicator diagram with multiple loops. The indicator diagram does capture shear from flows pushing past the piston.

6.4.1.2 Energy Transfer Statistics

The series of information defined here as Energy Transfer Statistics include values that go to and from major elements of the engine. These are defined in Figure 6.15 through the generic Heat Engine Diagram.

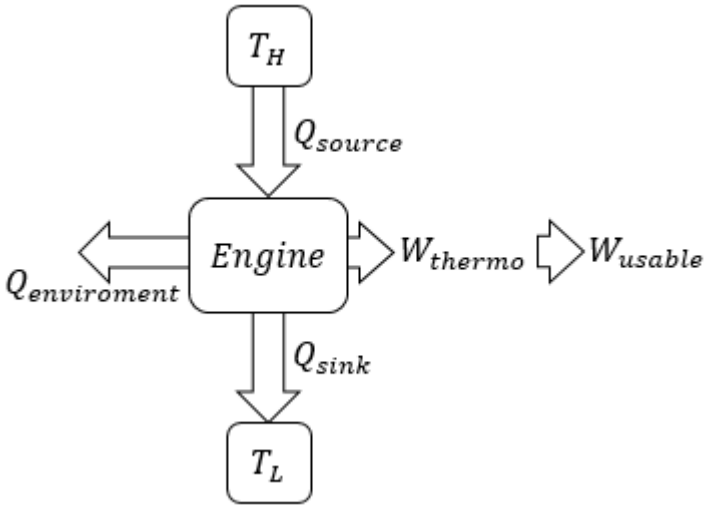


Figure 6.15: Generic Heat Engine Model

These terms are automatically generated by analyzing the given model for constant temperature elements and making note of all possible avenues of exit to such nodes, sources and sinks are differentiated by assigned temperature. The actual efficiency and Carnot adjusted efficiency of the engine are calculated as follows from these values.

$$\mu = \frac{W_s}{Q_{in}} \tag{106}$$

$$\mu' = \frac{\mu}{\left(1 - \frac{T_L}{T_H}\right)} \tag{107}$$

The actual efficiency is a measure of how well an engine converts one form of energy into another. However, all technologies that utilize heat to generate energy must be subjected to the limitation of Carnot which artificially undervalues machines that have a lower maximum

efficiency. Therefore, the second efficiency adjusts for this and is considered a better measure of the quality of an engine design, irrespective of the quality of its thermal sources.

6.4.1.3 Mechanical Work

Mechanical work is the integral of the equation $W = Td\theta$ over the tested time frame. The difference between the area of the sum of the PV diagrams and this measured quantity indicates the efficiency of the mechanical system at converting linear into rotational force. In dynamic and constant speed cases the instantaneous mechanical power is equal to the following.

$$Power = \underbrace{I.\omega.\alpha}_{\substack{Excess\ Power \\ given\ to\ Flywheel}} + \underbrace{T_{load}.\omega}_{\substack{Power\ Consumed \\ by\ Load}} \tag{108}$$

6.4.1.4 Sensors

Sensors define an explicit output from the model that will be automatically produced when the simulation completes. Single point sensors will produce data suitable for a line graph, line sensor output data that is suitable for a surface plot. The user can select from any of the properties in the model and compare them against either time or angular position. An example of the plots produces by this at the end of the simulation is found in Figure 6.17.

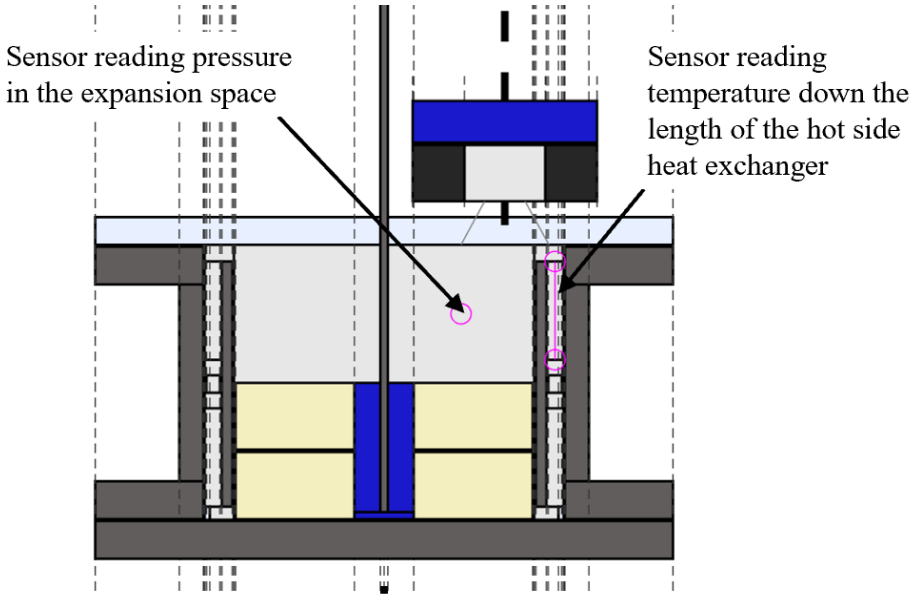
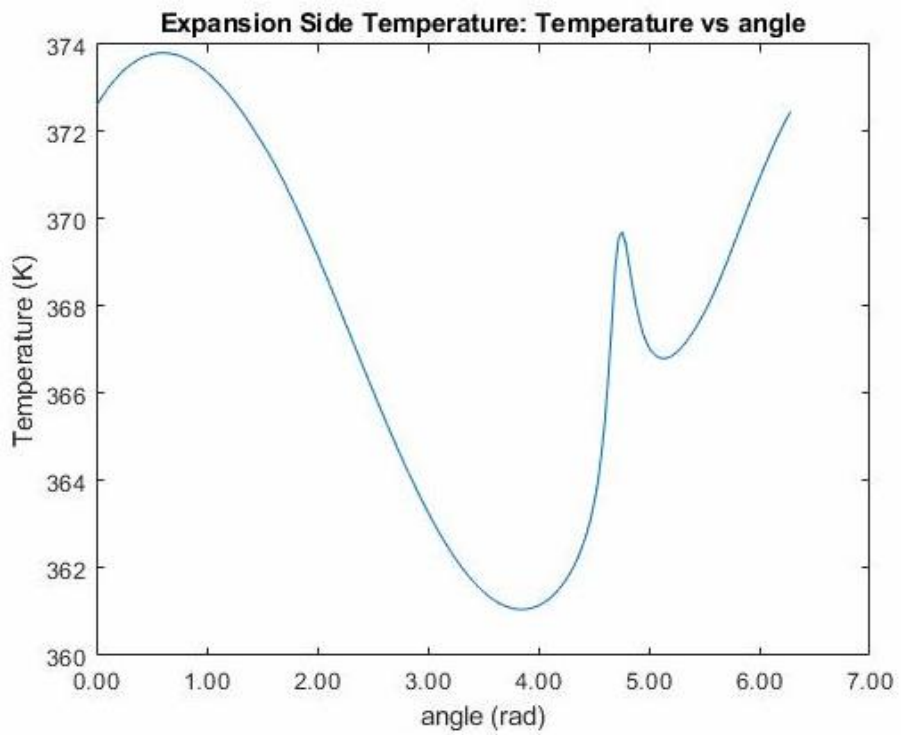
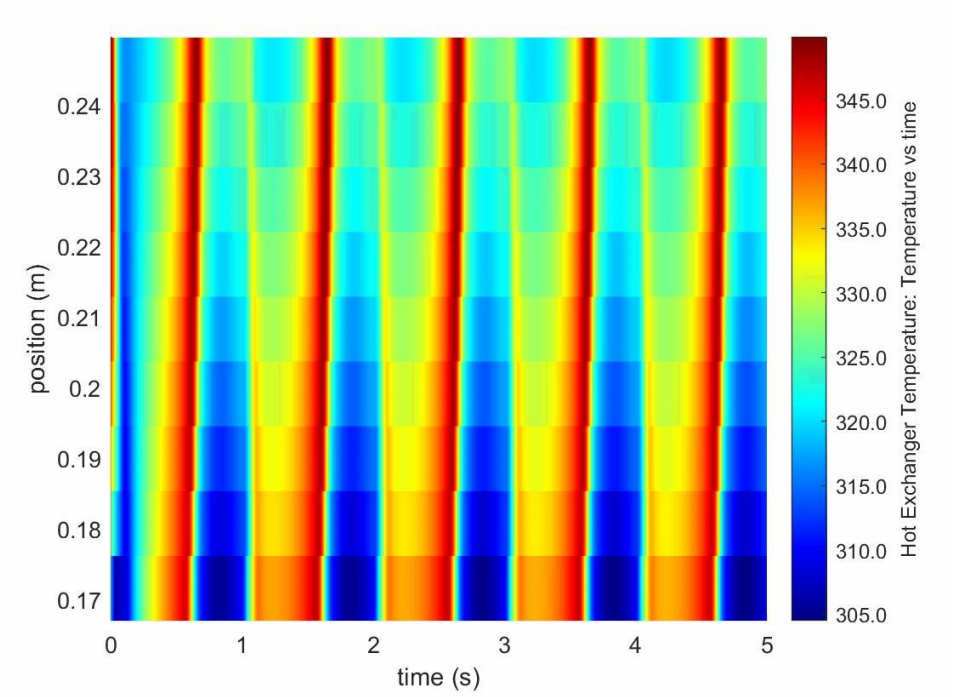


Figure 6.16: Sensor Usage Examples as shown in the GUI



(a) Temperature vs angle plot of expansion space of engine with a source temperature of 368 K, discontinuity between 4 and 5 matches up with when flow would reverse.



(b) Temperature vs time plot down length of a low effectiveness heat exchanger.

Figure 6.17: Output of sensor (a) point sensor (b) line sensor, locations shown on Figure 6.16

6.4.1.5 Heatmap Animations

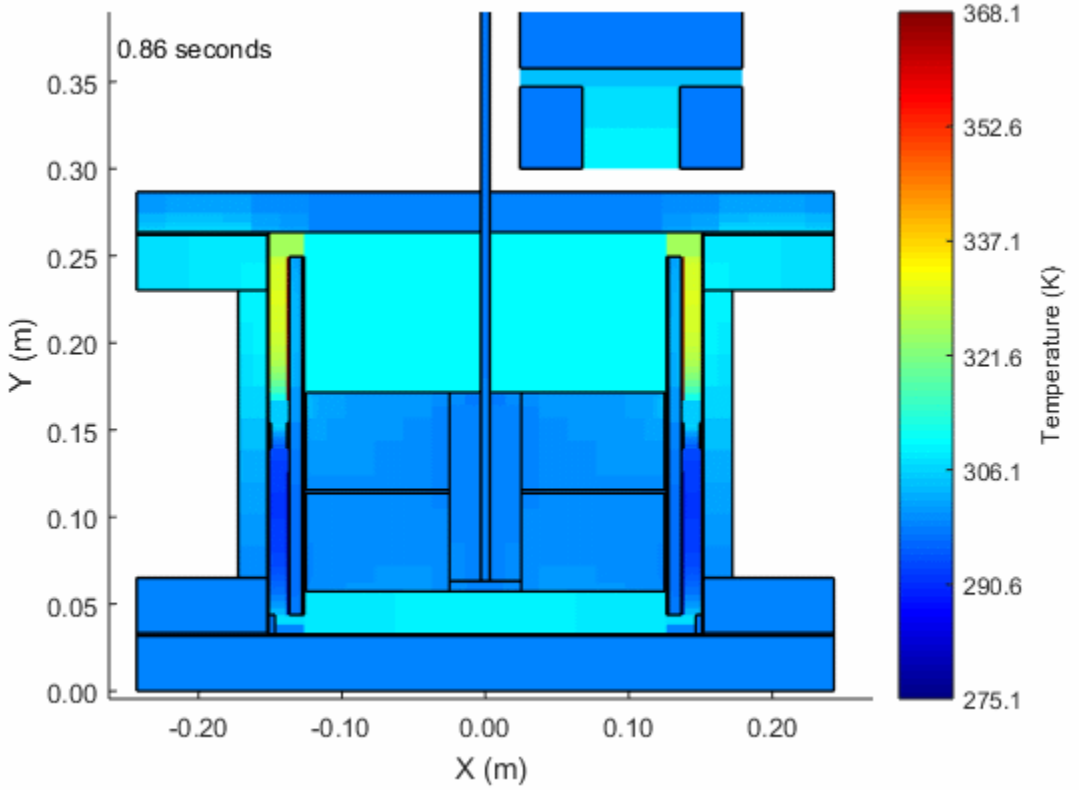


Figure 6.18: An example temperature heatmap snapped during an animation of the modelled Stirling engine

While not an integral part of the model, the software has the built-in capability to generate graphical outputs of properties. Figure 6.18 presents one of these outputs, which displays the temperature of different nodes through the engine. These types of animations may allow the designer to visualize the flow of matter, energy and motion of the engine allowing conclusions to be drawn more quickly. Pressure, turbulence, temperature, and conduction are plotted in this fashion. This is a function that is not normally found by default in Stirling engines codes, even commercial ones such as SAGE [35], but is relatively mainstream among generic CFD codes.

6.4.1.6 Conduction

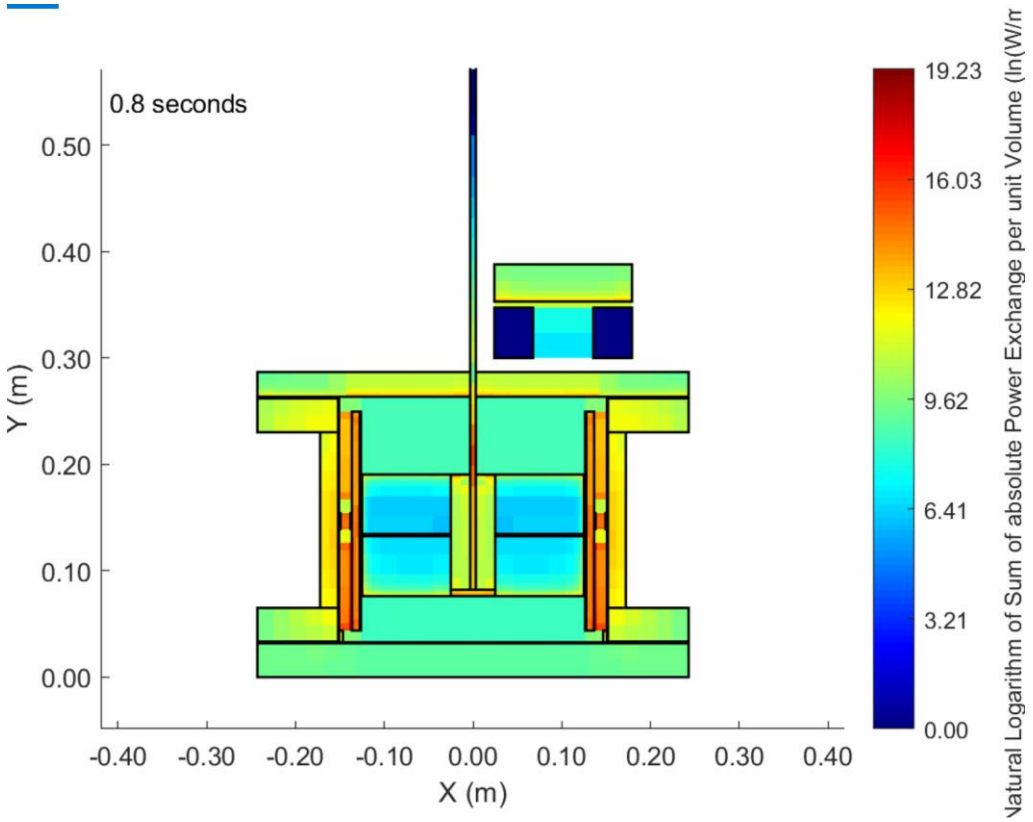


Figure 6.19: An example conduction heatmap snapped during an animation of the modelled Stirling engine

Volumetric conduction is a tool introduced in this thesis as a measure of the energy passing through an element as a function of its volume at any given time. This is calculated via the formula:

$$Cond = \ln\left(\frac{\sum_{all\ faces\ in\ nd}|e_{fc}|}{V_{nd}}\right) \tag{109}$$

The application of the natural logarithm is simply for enhancing the contrast when the value is plotted in the heatmap style. The purpose of this plot, though it lacks physical meaning, is to provide designers with the locations in which heat flows, which is generally undesired, outside of the heat exchangers. From the plot in Figure 6.19 it is observed that the central divider, that lies between where the displacer piston moves and the heat exchangers, exchanges quite a lot of heat, comparible to the heat exchangers themselves at that moment. The top and bottom caps of the engines on the other hand loose very little heat to the surroundings.

6.4.1.7 Face Based Animations

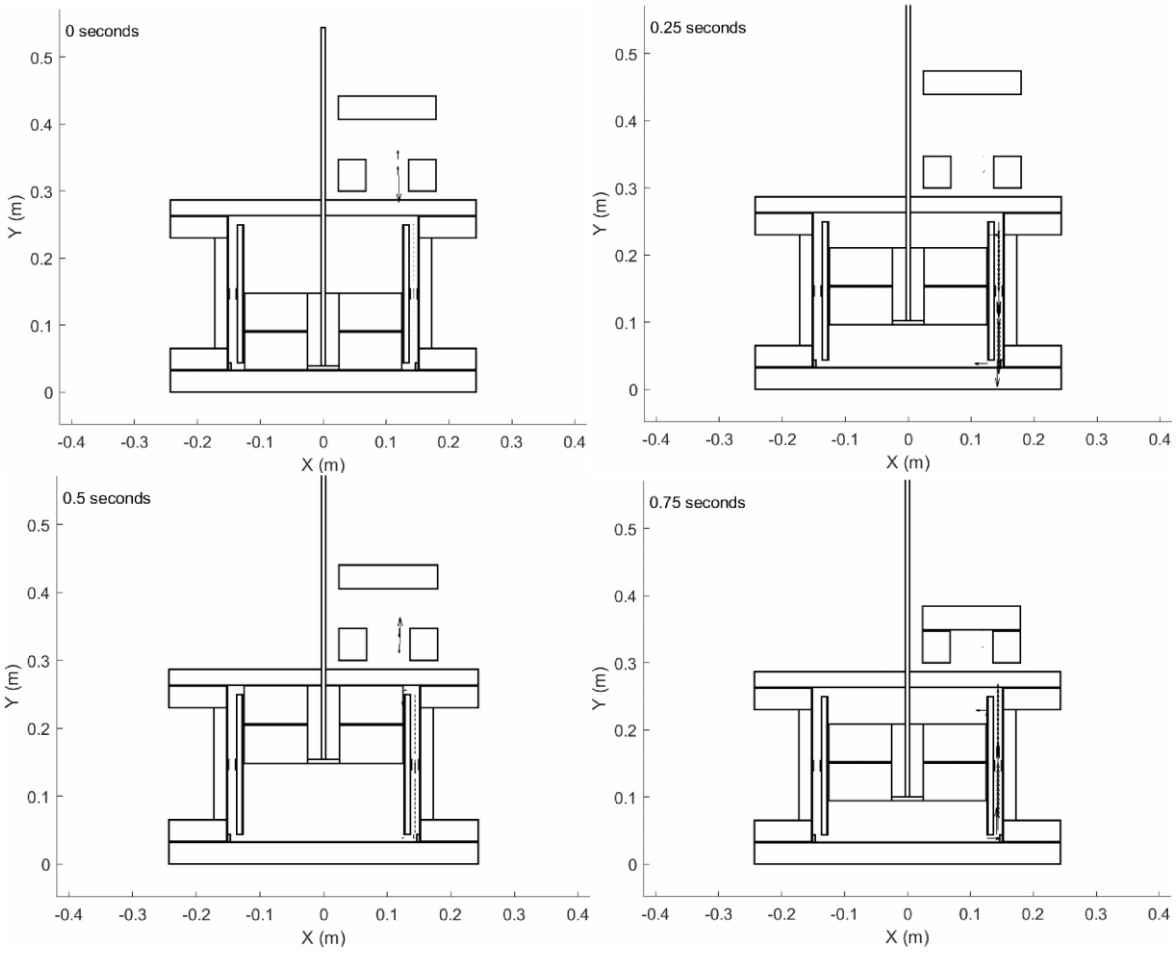


Figure 6.20: 4 frames of an instantaneous flow velocity plot snapped during an animation of the modelled Stirling engine (running at 1 Hz)

Velocity and pressure drop animations give insight into areas of the highest flow and pressure loss, it may serve as an indication to the designer of areas where the flow is bypassing or features that introduce most of the flow loss experienced by the system. An example of a face-based animation is in Figure 6.20. This animation depicts relative gas speeds in the engine.

6.5 Chapter Conclusions

This chapter outlined the basic usage of the GUI, an interface that allows the user to construct a complete model from blocks without any contact with the code. The software offers a variety of simulation tools which aid in the running of groups of experiments while the user is away and use

the results from previous experiments to kickstart the progress of the next. Outputs from the model use the GUI to generate indicator diagrams, acquire virtual sensor data and construct animations that provide a visual perspective to the acquired results. These visual features are unheard of among Stirling engine modelling programs beneath 4^{th} order simulations.

CHAPTER 7. VALIDATION

7.1 Theoretical Validations

Each of the following tests are conducted within the same environment and aims to show the flexibility of this software to provide results at varied levels of detail and geometry. These early tests allow for a certain level of confidence with regards to the performance of the model, before simulating full scale engines.

7.1.1 Steady-State Solid Heat Conduction

Steady-state solid heat conduction was validated using a composite annular ring, the inside was heated to an elevated temperature of 100 C and the outside was cooled to a temperature of 0 °C. The ring was composed of multiple materials, which exhibited different material properties. The equations used for the analytical model are as follows:

$$R_i = \frac{\ln\left(\frac{r_{max,i}}{r_{min,i}}\right)}{2\pi . k_i . L} \tag{110}$$

$$T_{start,i} = T_{end,i-1} = T_{start} + \frac{T_{end} - T_{start}}{\sum R_i} \sum_{i=1}^{i-1} R_i \tag{111}$$

$$T_i(r) = T_{start,i} - \left(T_{start,i} - T_{end,i}\right) \frac{\ln\left(\frac{r}{r_{min,i}}\right)}{\ln\left(\frac{r_{max,i}}{r_{min,i}}\right)} \tag{112}$$

where: R_i = The overall resistance of material layer i

$T_{start,i}$ = The temperature on the inside radius of material layer i

$T_{end,i}$ = The temperature on the outside radius of material layer i

The discretization and material composition are displayed in Table 7.1. The resulting temperature profile appears in Figure 7.1. The steady-state profile which emerges closely matches the analytically derived profile.

Table 7.1: Steady-state Heat Conduction Validation: Material Properties

Radius (m)	Material	Thermal Conductivity (W/mK)	Number of Nodes
0.1 – 0.15	Copper	401	10
0.15 – 0.1999	Carbon Steel	43	10
0.1999 – 0.2	ABS Plastic	0.25	5
0.2 – 0.25	6061 Aluminum	176.5	10

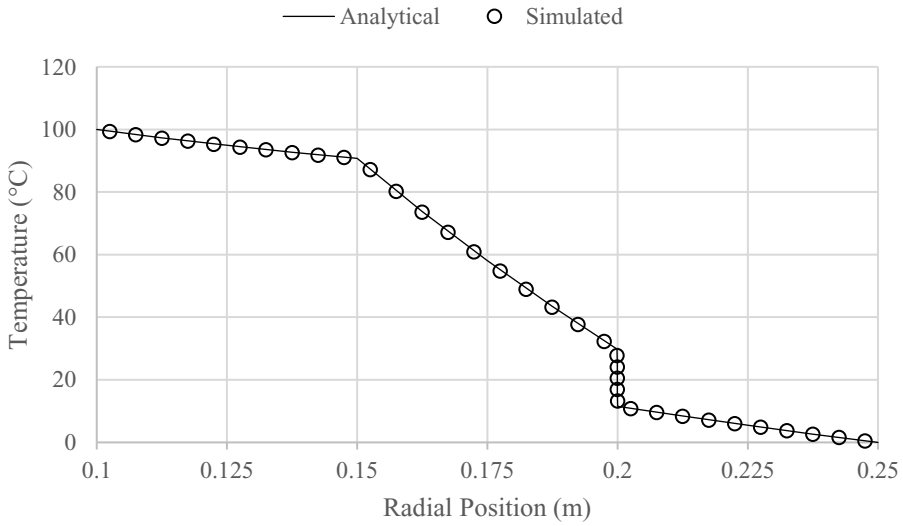


Figure 7.1: Steady-state temperature profile obtained via heat conduction through a layered annular conductor compared against analytical predictions

7.1.2 Transient Solid Heat Conduction

Transient solid heat conduction was validated through a comparison of the analytical solution of a cylinder heated by uniform convection. The discretization scheme and material composition are displayed in Figure 7.2 and Table 7.2 respectively. The cylinder of material is 15 cm in radius, 30 cm in length with a 3 cm thick outer layer of nodes of that are 1 cm square and an inner core of nodes of square dimensions of 2 cm square.

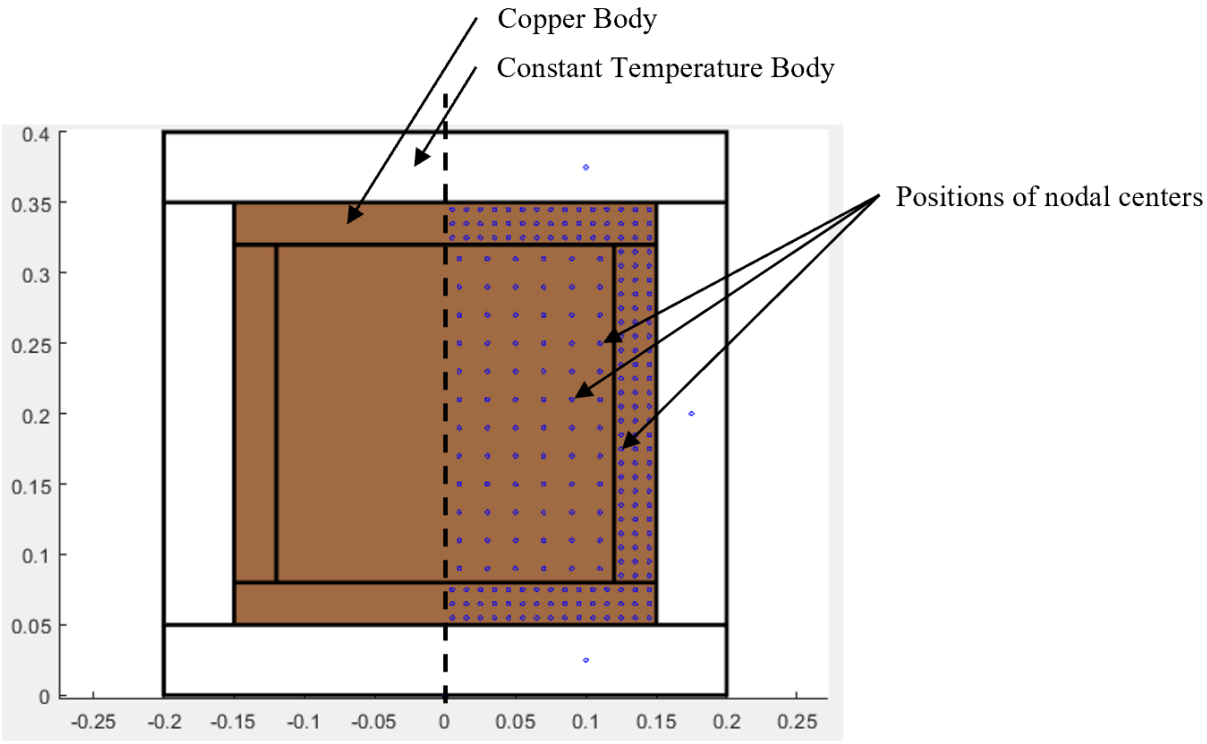


Figure 7.2: Discretization scheme for transient heat conduction test

Table 7.2: Experimental properties of Transient heat conduction test

Property	Value	Unit
Density	8960	kg/m^3
Thermal Conductivity	401	W/mK
Specific Heat Capacity	0.385	kJ/kg
Surface Temperature	100	°C
Initial Temperature	0	°C
Cylinder Length (L)	0.3	(m
Cylinder Radius (r_o)	0.15	(m)
Small Node Size	0.01	(m)
Large Node Size	0.02	(m)

The analytical profile is produced by the product solution between an infinite plate of thickness L and an infinitely long cylinder of radius r_o. For the plate's contribution the solution is derived from 200 terms of the Fourier series [63] using:

$$\theta^*_{x_{2L\ Plate}} = \sum_{1}^{\infty} \frac{4}{\pi} e^{-\left(\frac{n.\pi}{2L}\right)^2 \alpha t} \sin\left(\frac{n.\pi.x}{2L}\right) \tag{113}$$

where: $n = 1,3,5, \ldots$

The cylinder's contribution is derived from the numerically derived solution of the following equation, which is created from the heat equation in cylindrical coordinates. This is provided to MATLAB's ode45 solver in the subsequent set of equations.

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) \tag{114}$$

$$\frac{dT_1}{dt} = \alpha\frac{T_2 - 2T_1 + T_1}{dr^2} + 0$$

$$\frac{dT_i}{dt} = \alpha\left(\frac{T_{i+1} - 2T_i + T_{i-1}}{dr^2} + \frac{1}{r_i}\frac{T_{i+1} - T_{i-1}}{2dr}\right)$$

Boundary Conditions

$$T_N = 100 \tag{115}$$

Initial Conditions:

$$T_1, T_2, T_3, \ldots, T_{N-1} = 0$$

Thus, the center temperature of the short cylinder, Figure 7.2, is mathematically determined. A comparison between the analytical and simulated center temperature is shown in Figure 7.3. The simulated transient center temperature matches up closely with the analytically obtained solution.

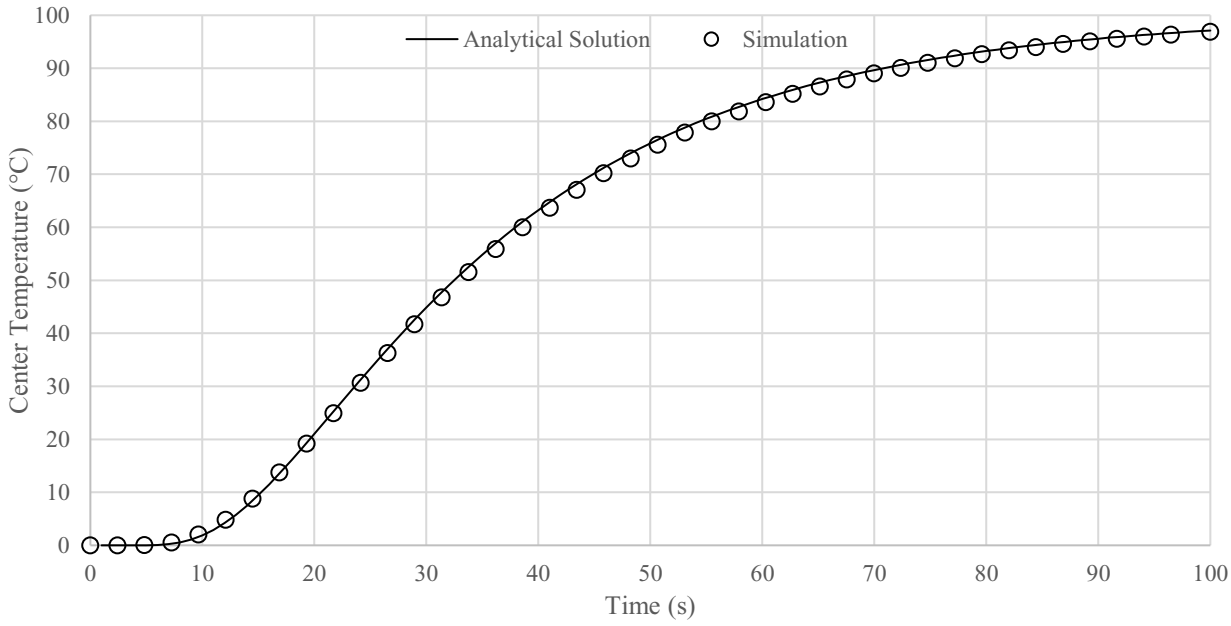


Figure 7.3: Analytically obtained results vs simulated temperature with time measured at the center of test block.

7.1.3 Adiabatic Compression/Expansion of Gas

The compression of a volume of ideal gas within a perfectly insulated chamber results in a curve in the Pressure vs. Volume space that follows the relationship defined by.

$$\frac{P.V}{T} = Constant \tag{116}$$

A perfectly insulated chamber was constructed within the program, a moving boundary applied a compression, expansion cycle to the gas. The pressure of the gas was measured and plotted after compressing from atmospheric conditions. The results are plotted in Figure 7.4, along with the simulated curve. The simulated compression-expansion cycle matched up well with the expected adiabatic trend.

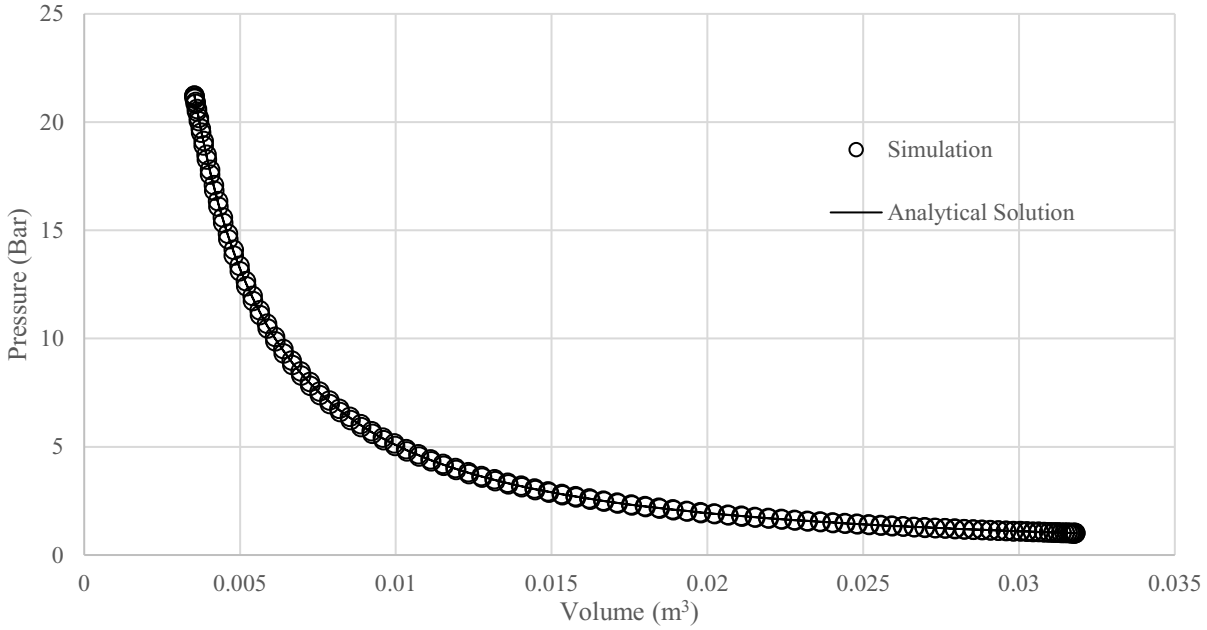


Figure 7.4: Analytically obtained results compared against simulation results in the case of adiabatic compression/expansion

7.1.4 Isothermal Compression/Expansion of Gas

The compression of a volume of ideal gas within a perfectly conductive chamber under compression over an infinitely long-time scale results in a curve in the Pressure vs. Volume space that follows the relationship:

$$P.V = Constant \tag{117}$$

A Chamber was constructed out of constant temperature material at a temperature of 298 K, the chamber was cycled at a frequency of 0.01 rpm to allow enough time for the gas to exchange energy with the wall. The initial conditions are used to generate the isothermal curve. The results are plotted in Figure 7.5, along with the simulated curve. The simulated compression-expansion cycle matched up well with the expected isothermal trend.

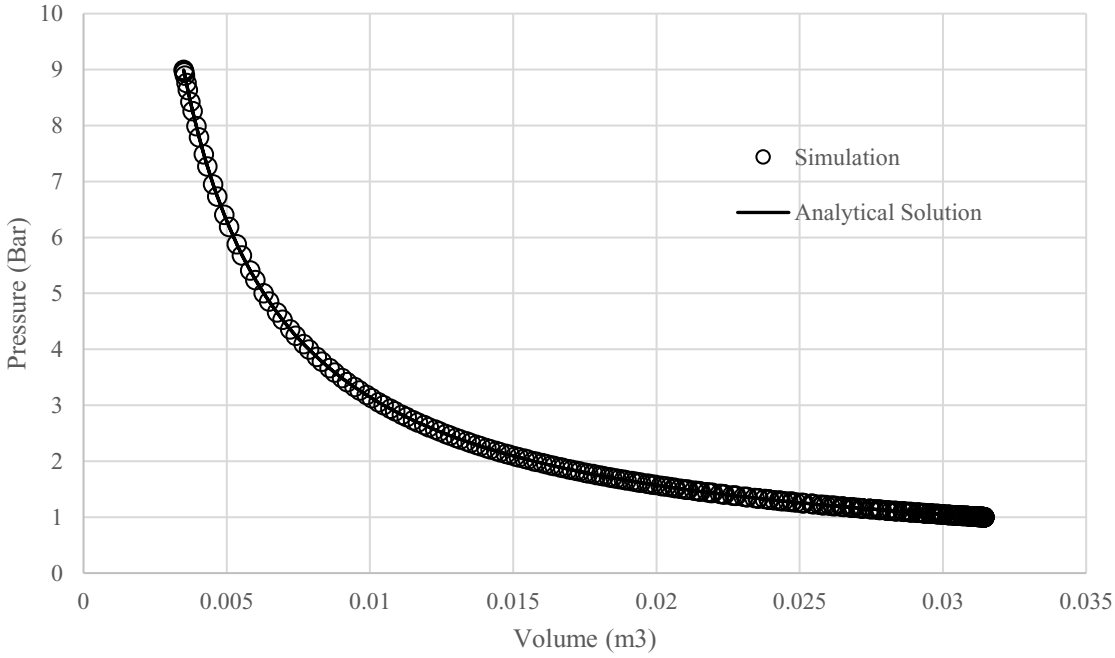


Figure 7.5: Analytically obtained results compared against simulation results in the case of isothermal compression/expansion

7.2 Comparison with Experiments

It was important to compare with experimental results within the low temperature regime in order to get a correct reflection of the accuracy of MSPM's predictions of the losses and effects which were important to a low temperature engine. Experimental results with suitable detail on the engine geometry could not be found in the literature, thankfully the works of DTECL had produced several low temperature engines with the EP-1 being the latest.

The following validations are a comparison of the model output with values obtained through physical experimentation on the EP-1 engine. These serve to assess the general performance of the model. Unless otherwise noted, error is calculated based on the percent difference in non-dimensional indicated power. This non-dimensional power is derived from non-dimensional pressure and volume, which are defined below:

$$P^* = \frac{P}{P_{avg}} \tag{118}$$

$$V^* = \frac{V - V_{min}}{V_{min} - V_{max}} \tag{119}$$

$$P' = \frac{P}{P_{avg}} \tag{120}$$

The EP-1 as discussed by Stumpf [12] was modified to host a drive train composing of circular or elliptical gears [64]. These studies were intended for the experimental analysis of the effect of non-sinusoidal piston motion on engine performance by Nicol-Seto [64]. Because this model can host mechanical components of arbitrary linear motions, this is an important comparison to see the accuracy of the model under those conditions as this phenomenon is one of the most difficult scenarios to model due being lesser studied oscillatory phenomena. The detailed geometry is found in Appendix C. Within the user interface the engine appears as a 2D cut-away view of the geometry, here the pistons are shown at their lowest point, the default position of the simulator.

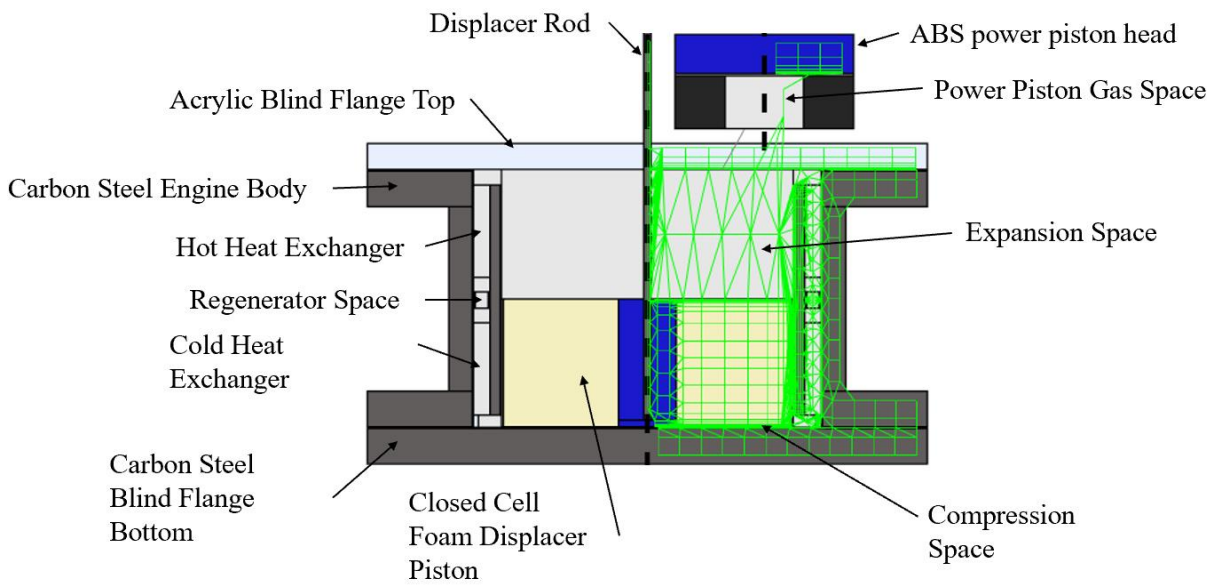


Figure 7.6: EPM engine body geometry as shown in graphical user interface of software

7.2.1 Constant Speed Steady-State Experiments

The engine's offset power piston is connected using a bridge component such that the geometry may be maintained as closely as possible. The model was run for several combinations of elliptical and circular gears, as outlined in the following table, the motion profiles for each of the following are calculated in Appendix D. All tests are conducted with a charge pressure equal to atmospheric (101,325 Pa) with a hot source temperature equal to 95°C and a cold sink temperature of 5ºC. All tests covered a range of speeds from 0.2 – 2.6 Hz. All mechanisms for displacer have a crank to connecting rod length ratio of 6, a value of 2 is applied for the power piston. All tests use a slider crank mechanism, but between the drive shaft either have a set of circular gears (standard) or a set of elliptical gears arranged in either a dwelling cycle (square wave), or to have a minimal velocity cycle (saw wave). Only tests 1-3 were conducted on a physical test engine, 4-6 are expansions upon the existing data set using untested but promising mechanisms. Test 1-3 were performed with the engine driving itself, loaded by a friction brake. The pressure was measured using a pressure diaphragm sensor. The volume of the experimental results is estimated with the bellow volume being calibrated via a shadowgraph technique [64]. Additional tests were also conducted on speeds from 0.2 Hz to 4.0 Hz, a scope beyond the 12 selected experimental tests.

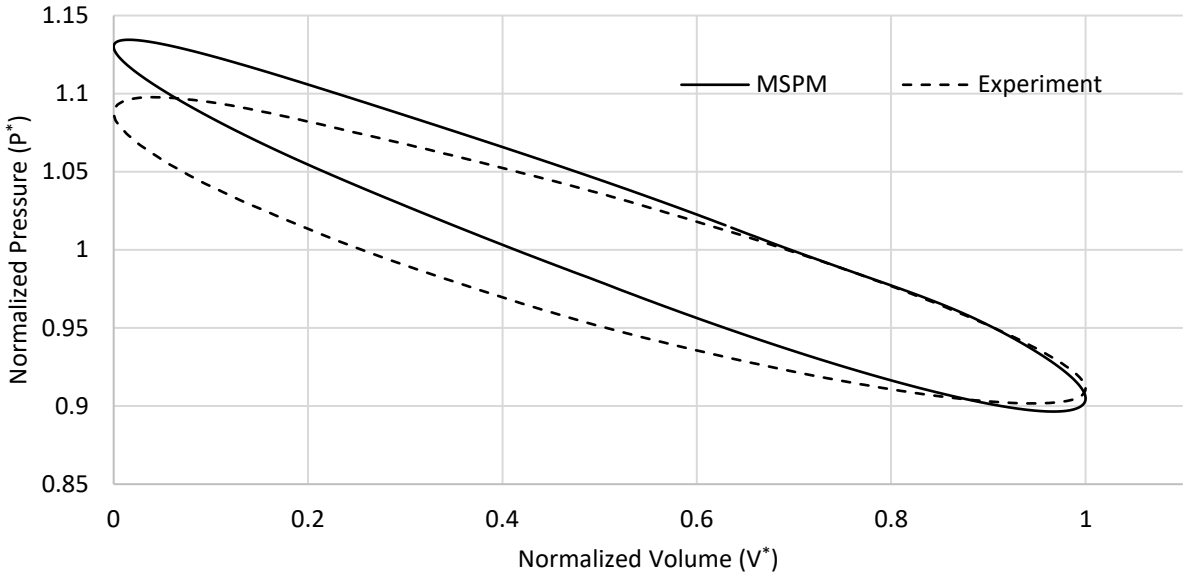
Table 7.3: EP-1 test sets

Test Set	Displacer Piston	Power Piston
1	Standard	Standard
2	1/5 Elliptical for square wave, dwelling cycle	Standard
3	1/5 Elliptical for square wave, dwelling cycle	1/5 Elliptical for square wave, dwelling cycle
4	1/5 Elliptical for saw wave, minimum velocity cycle	Standard
5	1/5 Elliptical for saw wave, minimum pressure loss cycle	1/5 Elliptical for square wave, dwelling cycle
6	1/5 Elliptical for saw wave, minimum pressure loss cycle	1/5 Elliptical for saw wave, minimum pressure loss cycle

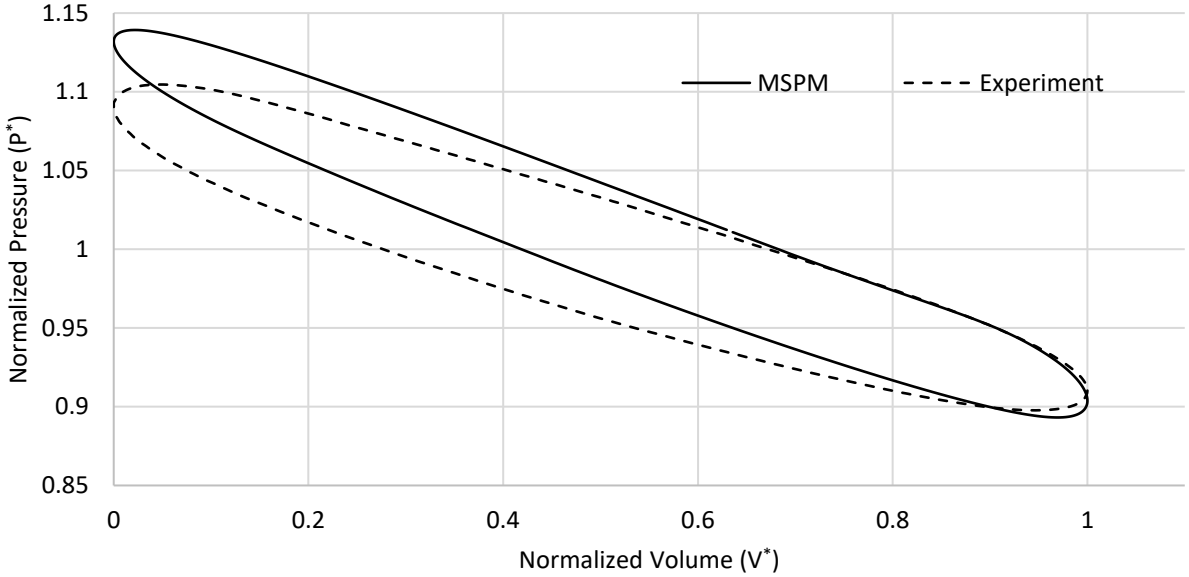
The mesh density settings applied to both the experimental and SAGE comparisons has an approximate mesh sensitivity related error of 0.8%, these results are shown in Appendix F and is assumed to be representative of all speeds and configurations.

The PV diagrams and thermodynamic powers are compared in terms of non-dimensional pressure and volume as the model was simulated at an average pressure of 101,325 Pascals, while the test engine tended to rest somewhere above or below that value.

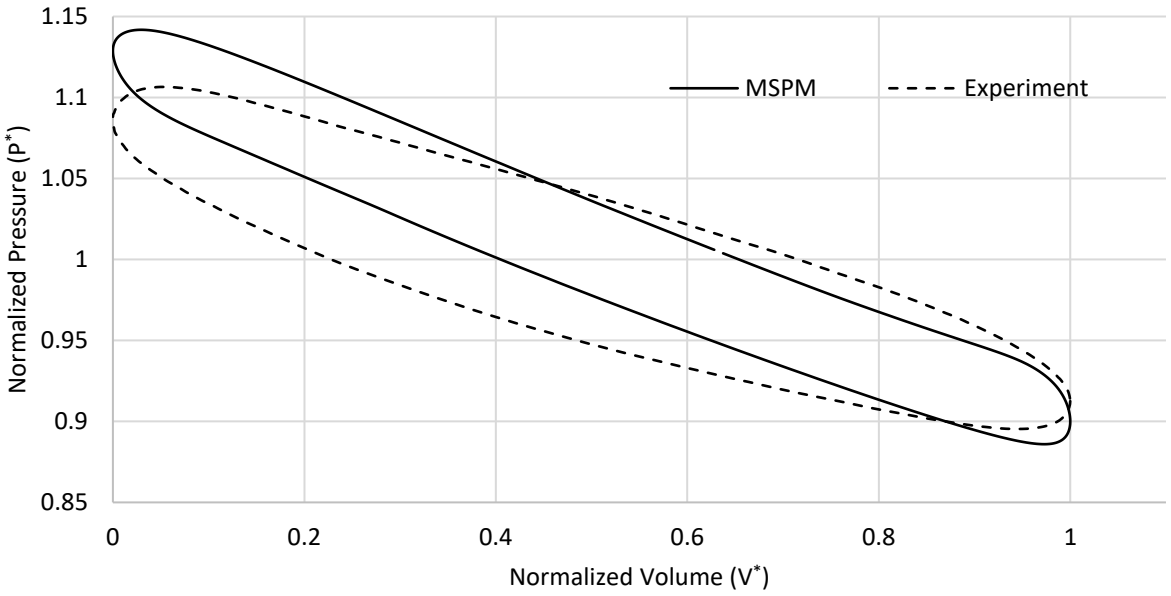
Figure 7.7 displays an indicator / pressure-volume diagram from both the experiment and simulation for the same conditions, given the default uncalibrated model output using properties taken from the solid model of the engine that was used for construction. Experimental results are attributed to Nicol-Seto [64].



(a) Both in standard arrangement – 1.1055 Hz



(b) Displacer piston with dwelling cycle, power piston with standard slider crank – 0.8818 Hz



(c) Both with dwelling cycle – 1.1992 Hz

Figure 7.7: Indicator diagram comparison between EPM-1 experiments and MSPM. (a) DP & PP: Standard at 1.1055 Hz (b) DP: Square Wave Elliptical, PP: Standard at 0.8818 Hz (c) DP & PP: Square Wave Elliptical at 1.1992 Hz

Over the 12 tests considered, MSPM had a maximum error of 43.1% and an average error of 30.6%. The shape of the indicator diagram is close, particularly at the ends where each of the configurations has a distinctive shape. The non-dimensional cycle energy extracted from the 12 matching experiments is displayed in Figure 7.8 below:

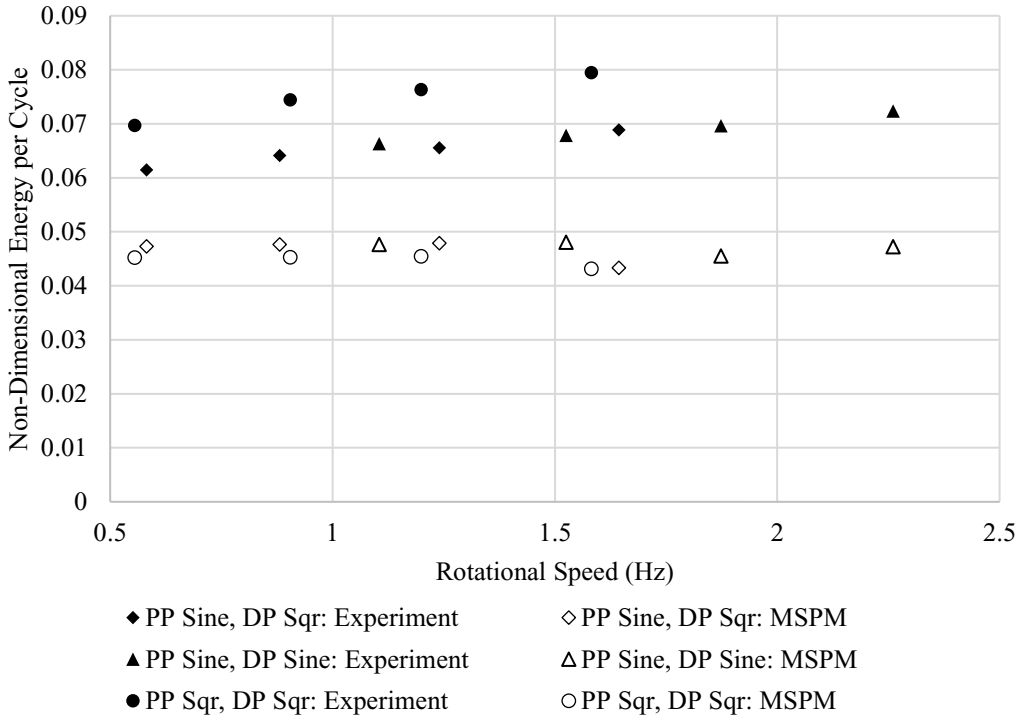


Figure 7.8: Non-dimensional power for each of the 12 matching experiments

The main sources of error are likely resulting from 2 areas. Firstly, the EPM-1 features a power piston which is facilitated by a rubber bellows. The bellows serves as a well sealed and low friction alternative to a piston-cylinder design. It is known [12], [14], however, to affect the pressure maximums by expanding and contracting in response to internal pressures. Secondly, the exact heat transfer and friction characteristics of the inline set of finned tubes with directing geometry is unknown. With the directing geometry, the exchangers resemble staggered tube banks, but with the directing geometry being non-conductive the model was compensated by multiplying the total surface area by half. It is likely that the friction characteristics are the most off as MSPM disproportionately disadvantaged motions that included rapid flushing through the heat exchangers with relation to the experiments. Determining the exact characteristics of these heat exchangers is out of the scope of this thesis. This second group of effects is strongly correlated to the broadness of the indicator diagram, which can be seen earlier in Figure 7.7. These combined errors are systematic, amendable by correction to the source temperatures, convection and friction correlations, though it is possible that they mask the errors produced via the modelling assumptions, further study with a more well understood experimental engine is necessary to assess the magnitude of those errors.

Along side the 12 matching tests, a total of 39 tests were conducted including the 3 mechanisms not tested experimentally (DP: Saw PP:Sqr, DP:Saw PP:Sine & DP:Saw PP:Saw) , these are shown following on Figure 7.9 and Figure 7.10.

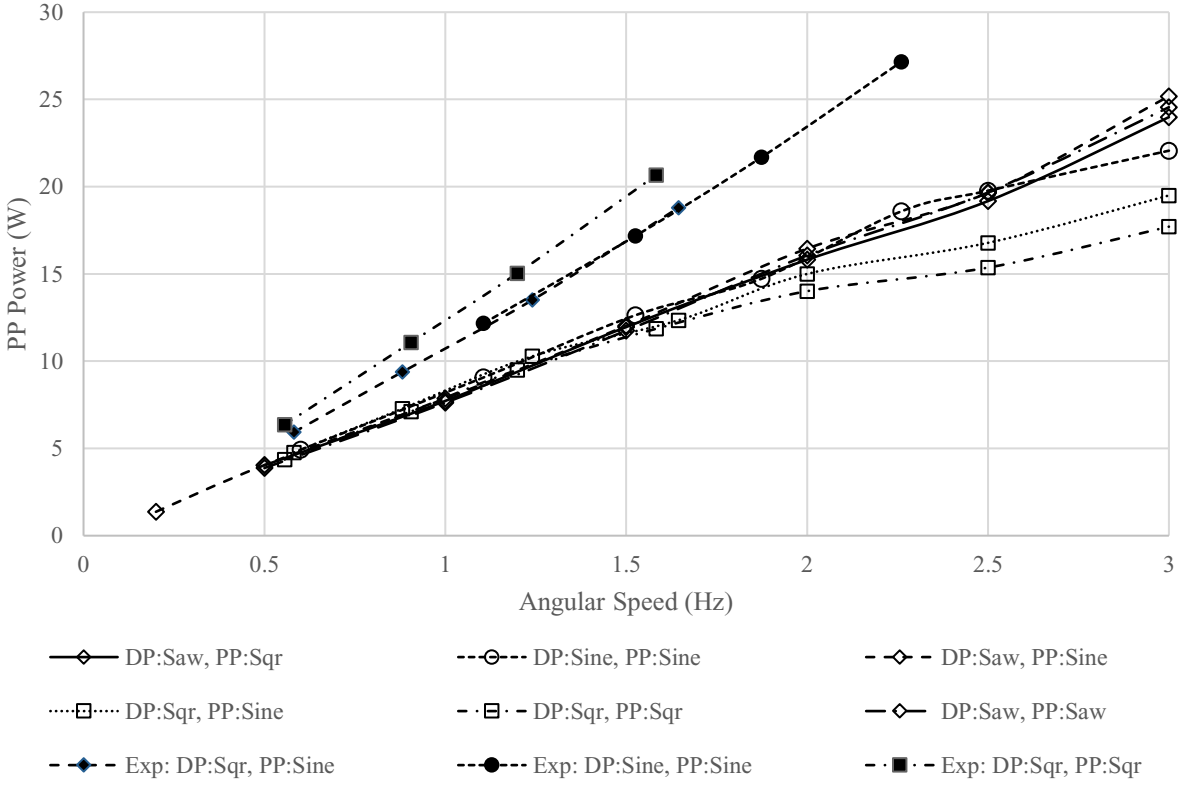


Figure 7.9: MSPM vs experimental power piston indicated work

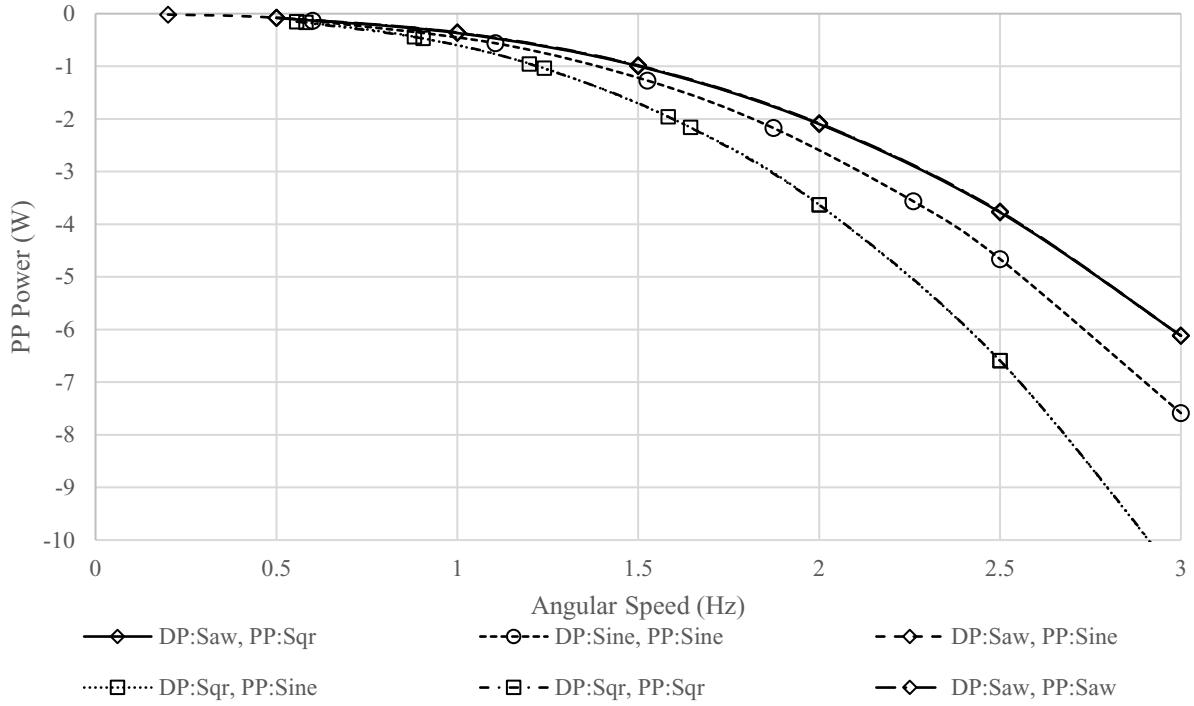


Figure 7.10: MSPM displacer piston indicated work, experimental version not collected

The results show that the highest power output will come from configuration 4, with a saw wave on the displacer and the power piston set to a sinusoidal motion, the lowest power is from the tests that used the dwelled motion for the displacer. The fact that the dwelling motion is such a disadvantage is found by inspecting the indicated work of the displacer piston. The configurations become more distinct at higher speeds, seen by the 2nd order growth of the flow losses at higher speeds.

The clearest change that could be made to improve the correlation of the simulation with the experiment is to modify the bellows. By observing the indicator diagram, the pressure swing of the simulation is proportional to the compression of the power piston. The effect of compression is tested in a second set of tests in which the stroke is reduced to 84.3% of its original value. This value was determined by assuming that pressure is inversely related to volume and given that the pressure swing was $18.7 \pm 1.4\%$ among the 12 tests. Dead volume is also increased by 7.8% of original stroke to account for bellow expansion and contraction at stroke extremes. A sample result appears in Figure 7.11 below. Only the 12 comparison experiments were repeated.

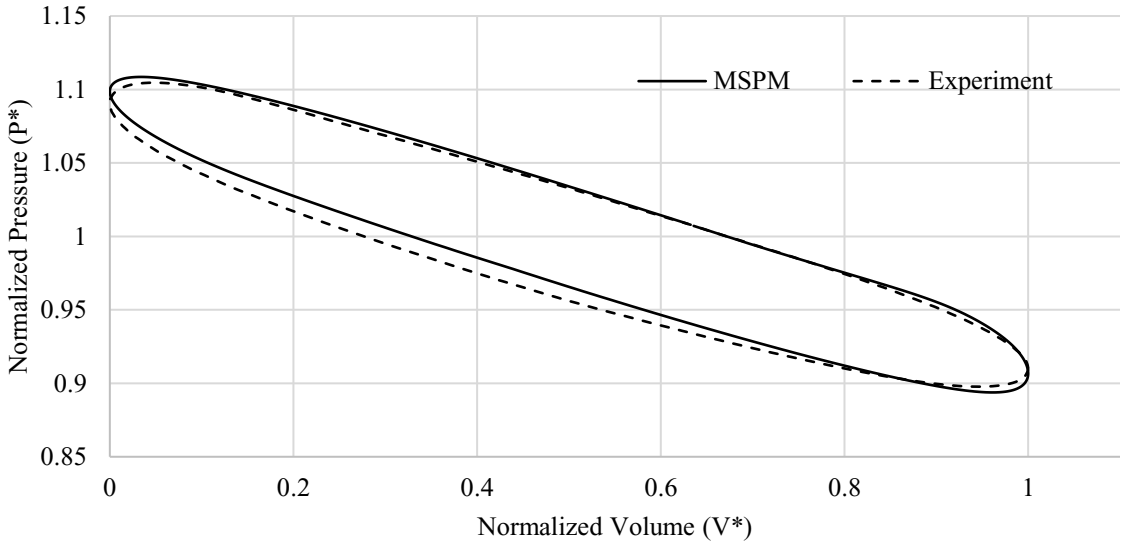


Figure 7.11: Indicator diagram comparison between EPM-1 experiments and simulations with reduction in stroke by 15.7% and increase in dead volume equivalent to 7.8% of stroke. (test: Standard-Standard at 1.1055 Hz shown)

The resulting error in non-dimensional pressure is decreased to an average discrepancy of 21.9% (from 30.6%) and maximum error of 35.2% (from 43.1%) over the 12 modified tests. The discrepancy in pressure maximums appears to be completely corrected, indicating that the property of indicator diagrams is strongly dependent on volume in the regime of interest. Remarkably the broadness in the Sinusoidal cases is also very close with the 4 sinusoidal tests (test set 1) providing an average error of 19.0% with a maximum of 28.5%. The error in the set with the sinusoidal power piston and dwelling displacer provided an average of 24.0% and the set with both pistons dwelling provided an average error of 31.5%. The error of MSPM increased with dwelling cycles, it is possible that this is due to overestimating the flow losses in the heat exchangers. The overall error appears systematic, indicating that it is likely a problem with an equation used to calculate heat transfer, flow losses or even turbulence; as turbulence was originally designed for mostly sinusoidal motions.

7.2.2 In Cycle Speed Variations

As a complement to the above studies the dynamic response portion of the code was evaluated against actual in-cycle velocity variations for 4 tests. These represent the actual conditions of the tests that were compared against previously, where the simulation was set to a constant speed. These tests are outlined in Table 7.4:

Table 7.4: Velocity variation experiment. "B" is a reference to the "Box" / square wave. "0" refers to the standard / sinusoidal trial (Elliptical factor of 0).

Test	Properties:
Fast_0, 0	**PP**: Standard **DP**: Standard **Average Speed**: 1.918805 Hz
Fast_B, B	**PP**: 1/5 Elliptical for square wave **DP**: 1/5 Elliptical for square wave **Average Speed**: 1.346884 Hz
Slow_0, 0	**PP**: Standard **DP**: Standard **Average Speed**: 1.130698 Hz
Slow_0, 0	**PP**: 1/5 Elliptical for square wave **DP**: 1/5 Elliptical for square wave **Average Speed**: 0.602163 Hz

Here a new non-dimensional number is introduced, the velocity ratio ($r_V = \frac{\omega_{min}}{\omega_{max}}$). This ratio is equal to the minimum instantaneous speed (ω_{min}) divided by the maximum instantaneous speed (ω_{max}). A comparison of the angular velocity curves between the EPM-1 tests and MSPM under the above scenarios is found in Figure 7.12 below, it is also presented in an alternative form in Figure 7.13:

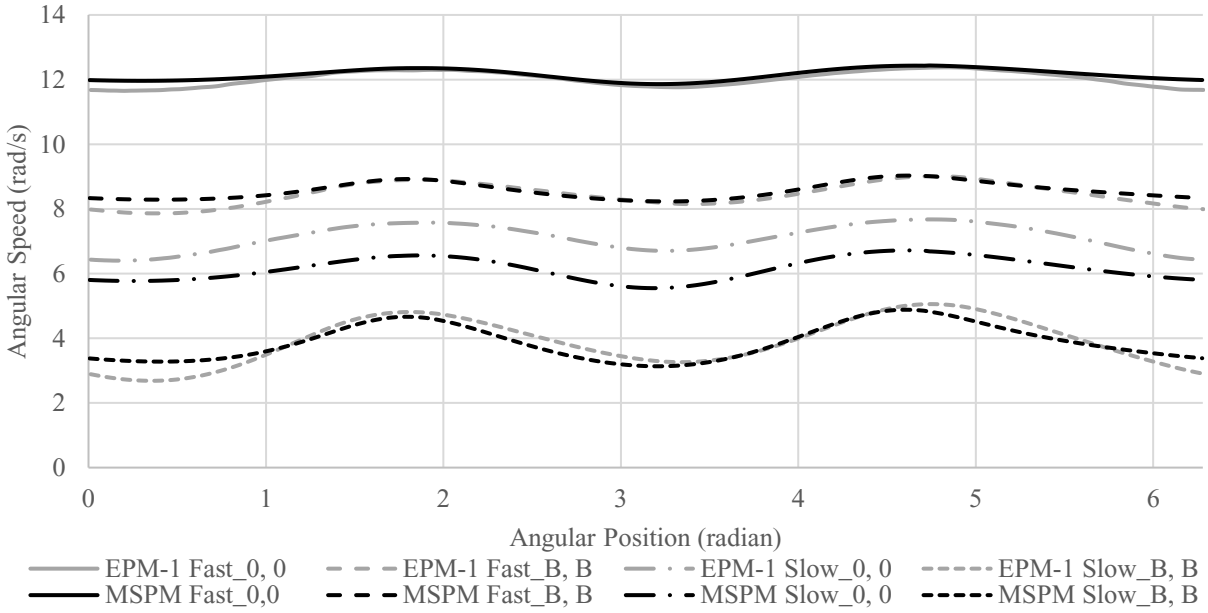


Figure 7.12: Instantaneous angular velocity for one cycle for both the EPM-1 physical tests and MSPM simulations.

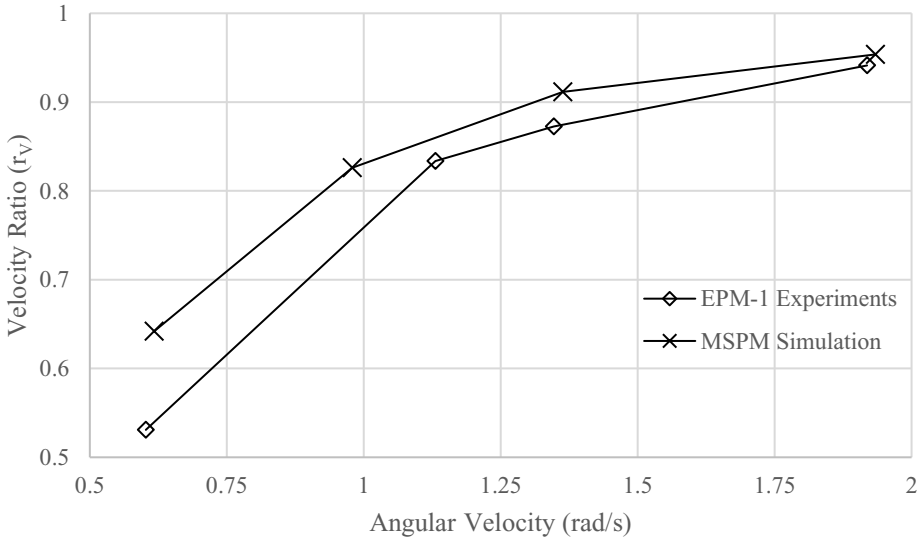


Figure 7.13: Velocity ratio results for experiment and simulation for 4 different velocities

This result indicates that MSPM follows the same trend as the experimental simulations and is within a close margin on the error, on the 3 tests which line up closely in speed, due to is asymptotic nature the error is calculated based on the difference between the speed ratio and the ratio of 1: $(1 - r_V)$, the error in this value is largest at the highest speed with a value of 30.6%.

The differences in velocity variations may be caused by various factors, including the differences when and how much power is entering the mechanism at any one time, which is indicated in the differences between the experimental and modelled indicator diagrams. These differences are caused by a variety of effects. Firstly, are flow losses, which would be different in the true heat exchangers. Secondly, leaks and displacer by-passing which are assumed negligible in the model and may be associated with lower power produced by the experimental engine. Thirdly, as the mechanism frictions were not included in these experiments, their effect, specifically, their intermittent and phase dependent effects are not captured. The actual experiment used a set of 3D printed elliptical gears to define the motion of the pistons for both the sinusoidal and dwelled tests which may have inconsistent loss characteristics. While the model maintains its ability to model friction as an angularly varying loss, it was outside the scope of this thesis to determine what these values were in the experimental engine.

7.2.3 Sensitivity Studies

A set of sensitivity studies were performed on the EP-1 model (filled at atmospheric pressure, and using sinusoidal motions for both pistons) and the change in the pressure-volume diagram was observed. These studies were performed on a test at 0.5 Hz and a test running at 2 Hz. A summary of the changed properties can be found in Table 7.5 below.

Table 7.5: Sensitivity Studies (results are colored based on absolute value, -50% uses backwards difference, +50% uses forward difference, ±2% uses central difference for slope calculation)

	0.5 Hz Test, 7.824 J/cycle			2 Hz Test, 1.707 J/cycle		
	Slope (J/cycle/%)			Slope (J/cycle/%)		
Change	-50%	±2%	+50%	-50%	±2%	+50%
Heat Exchanger Nusselt	8.10E-02	5.35E-02	3.84E-02	8.20E-02	7.10E-02	5.86E-02
Regenerator Nusselt	1.16E-02	8.00E-03	7.40E-03	8.20E-03	6.75E-03	6.40E-03
All Friction Factors	-1.60E-03	-1.50E-03	-1.60E-03	-1.56E-02	-1.53E-02	-1.58E-02
All Solid Conduction	-1.16E-02	-7.50E-03	-5.60E-03	-1.66E-02	-1.18E-02	-1.00E-02
Axial Mixing Coefficient	-1.00E-03	-7.50E-04	-8.00E-04	-6.00E-03	-5.00E-04	-6.00E-03

The property that has the strongest response is the heat exchanger Nusselt number. In both the slow and fast trials reducing the convection coefficient resulted in a drop of roughly 4 Joules per cycle. Increasing it increased the power output by a smaller margin. The increase was more significant on the faster trial, presumably as this trial existed farther down the arctan shaped

response curve for Nusselt number. The effect was similar when the regenerator including that the up and down values were closer together in magnitude on the fast trial. Increasing/decreasing the solid conductance and axially Nusselt number was more significant on the fast trials, possibly due to the heat exchangers being less capable of compensating for any drops in temperature. The increased effect of viscous friction is inline with the close to order of magnitude increase in friction losses. A sensitivity study like this can help to guide the designer in identifying where improvements may lie with respect to the running conditions of the engine.

7.3 Comparison with SAGE

7.3.1 In High-Temperature, High Speed Context

To assess the model performance against published literature the paper by Hoegel et al [44] was selected. This work was selected because it provided geometry details and results for a set of different engines and included several tests at with lower source temperatures. The premise of the referenced work was to compare optimized designs between low and high-temperature alpha type Stirling engine using the commercial software SAGE, the MSPM model of this engine is shown below:

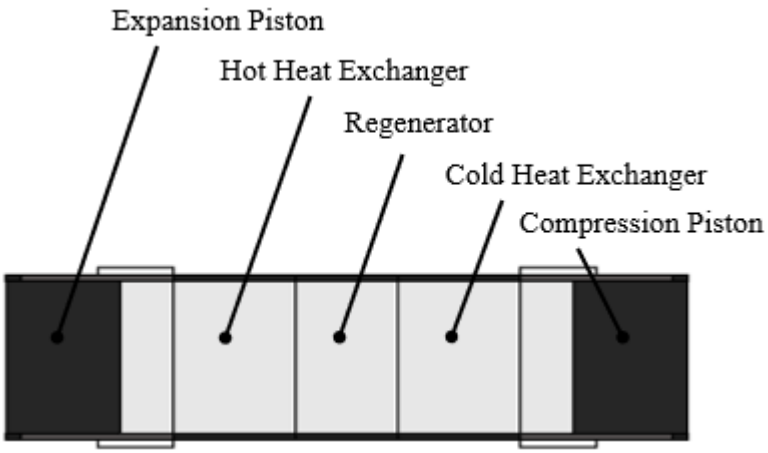


Figure 14: Annotated alpha engine for Phase 135°, Source 150 °C test as shown in MSPM

For the purposes of comparison SAGE is correct, however this is not necessarily true as SAGE is not perfect, and the given results do not provide an experimental validation. The model parameters of the tested opposed piston alpha type engine are shown in Table 7.6.

Table 7.6: Alpha engine geometrical properties for SAGE comparison [44]

Component	Value	Unit
Material (heat conductors and regenerator)	Steel	
Bore	0.2	m
Stroke	0.1	m
Phase Angle	Test Dependent	degrees
Angular Speed	16.7	Hz
Heat Source Temperature	Test Dependent	°C
Heat Sink Temperature	40	°C
Mean Pressure	5,000,000	Pa
Working Fluid	Helium	
Heat Exchanger Type	Tube Bundle	
Tube Diameter	0.003	m
Tube Wall Thickness	0.0005	m
Tube Number	Test Dependent	
Heat Exchanger Length	Test Dependent	
Regenerator Cavity Diameter	0.2	m
Regenerator Wall Thickness	0.0075	m
Regenerator Matrix	Random Fibre	
Fibre Diameter	0.00005	m
Porosity	Test Dependent	
Length	Test Dependent	

Table 7.7: Alpha engine test and specific geometrical properties for SAGE comparison [44]

Test All at 16.7 Hz	HX Tube Number	HX Length (m)	Regen. Porosity	Regen. Length	Power (W)
Phase 135°, Source 150 °C	1054	0.1604	0.9686	0.6709	3,630
Phase 165°, Source 150 °C	1042	0.1441	0.9067	0.01441	4,840
Phase 90°, Source 750 °C	Cold: 277 Hot: 398	Cold: 0.2628 Hot: 0.2592	0.7846	0.03220	96,286
Phase 135°, Source 750 °C	Cold: 233 Hot: 401	Cold: 0.2496 Hot: 0.1895	0.6902	0.009823	104,470
Phase 165°, Source 750 °C	Cold: 330 Hot: 510	Cold: 0.1607 Hot: 0.1108	0.7301	0.009823	45,736

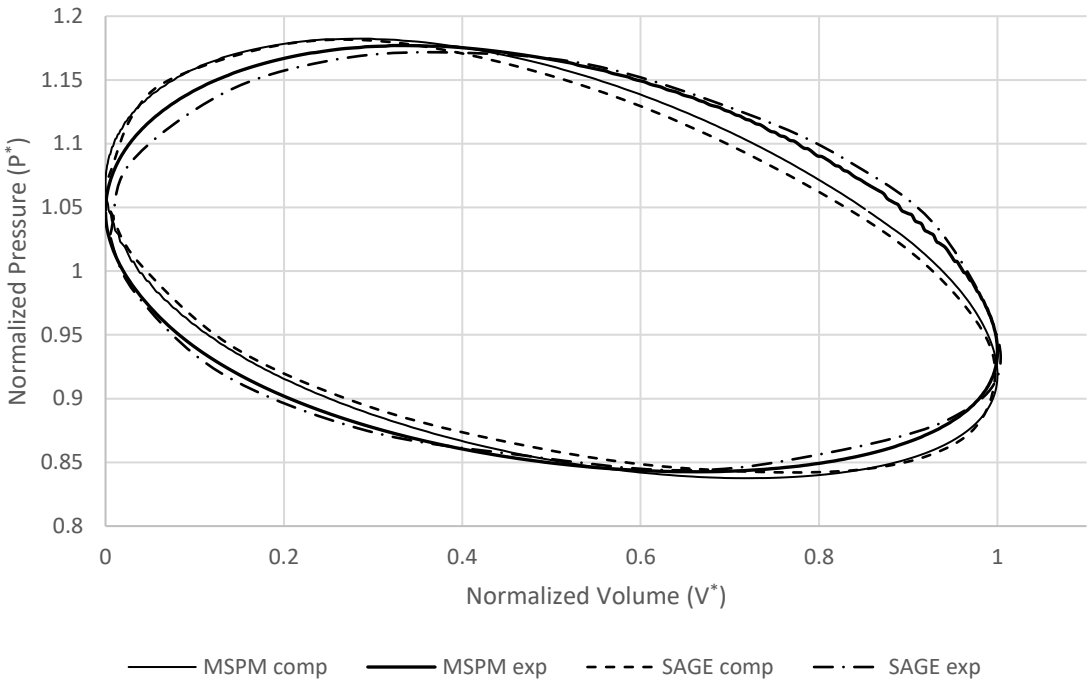
Some information, such as the thickness of the cylinder walls is missing. Therefore, a thickness of 7.5 mm is also selected for those points. All components including pistons and walls are assumed to be steel. The results from the 5 tests conducted are presented in the following table:

Table 7.8: Output power comparison between MSP and SAGE simulations at 16.7 Hz

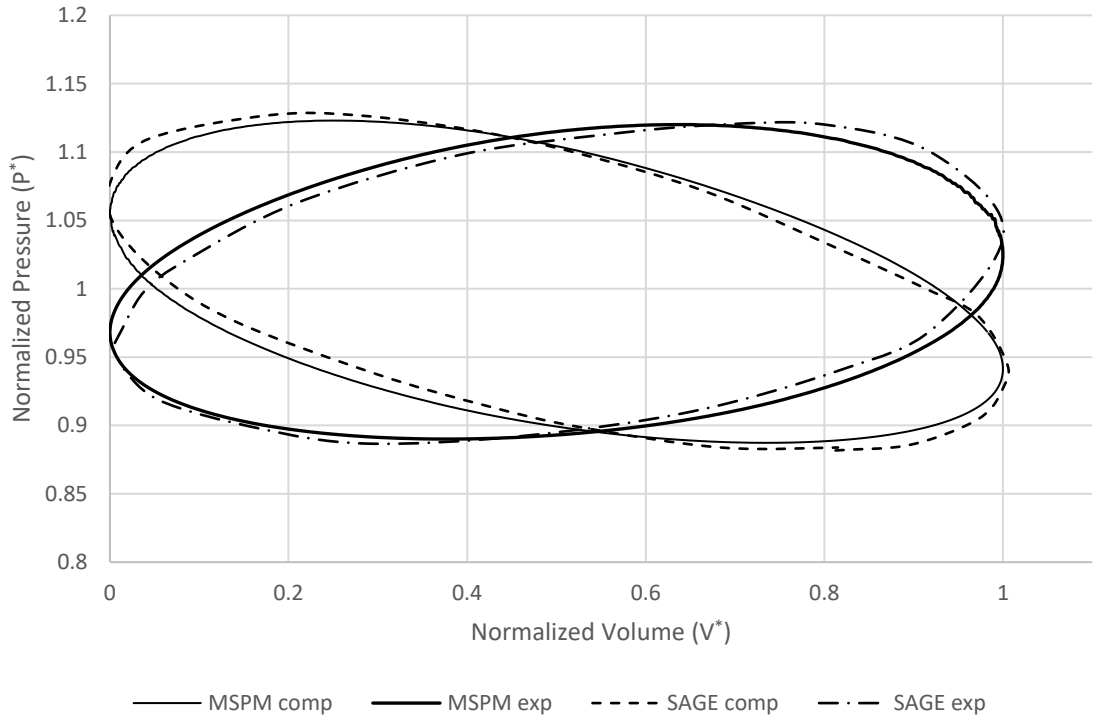
Test	MSPM Output Power (W)	SAGE Output Power (W)	Error (%)
Phase 135°, Source 150 °C	1,484	3,630	59.1%
Phase 165°, Source 150 °C	3,507	4,840	27.5%
Phase 90°, Source 750 °C	73,146	96,286	24.0%
Phase 135°, Source 750 °C	72,478	104,470	30.6%
Phase 165°, Source 750 °C	33,734	45,736	26.2%

The PV diagrams for each of the tests are compared in Figure 7.15. Note that pressures and volumes are converted to their non-dimensional form.

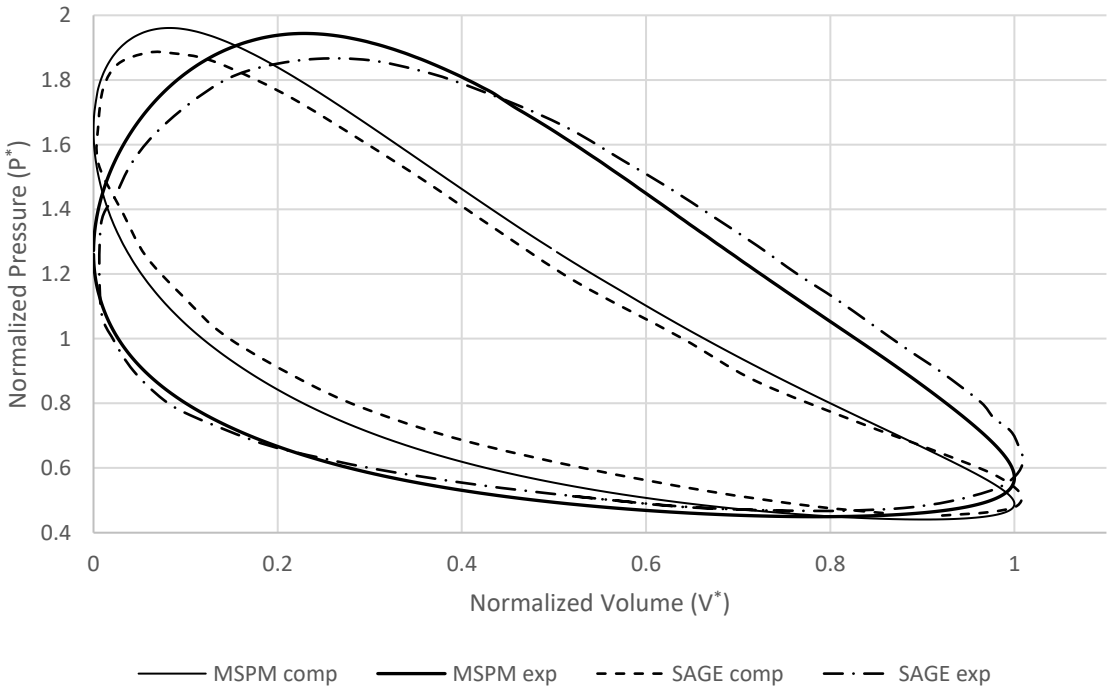
Normalized Pressure: P/P_{mean} Normalized Volume: V/V_{max}



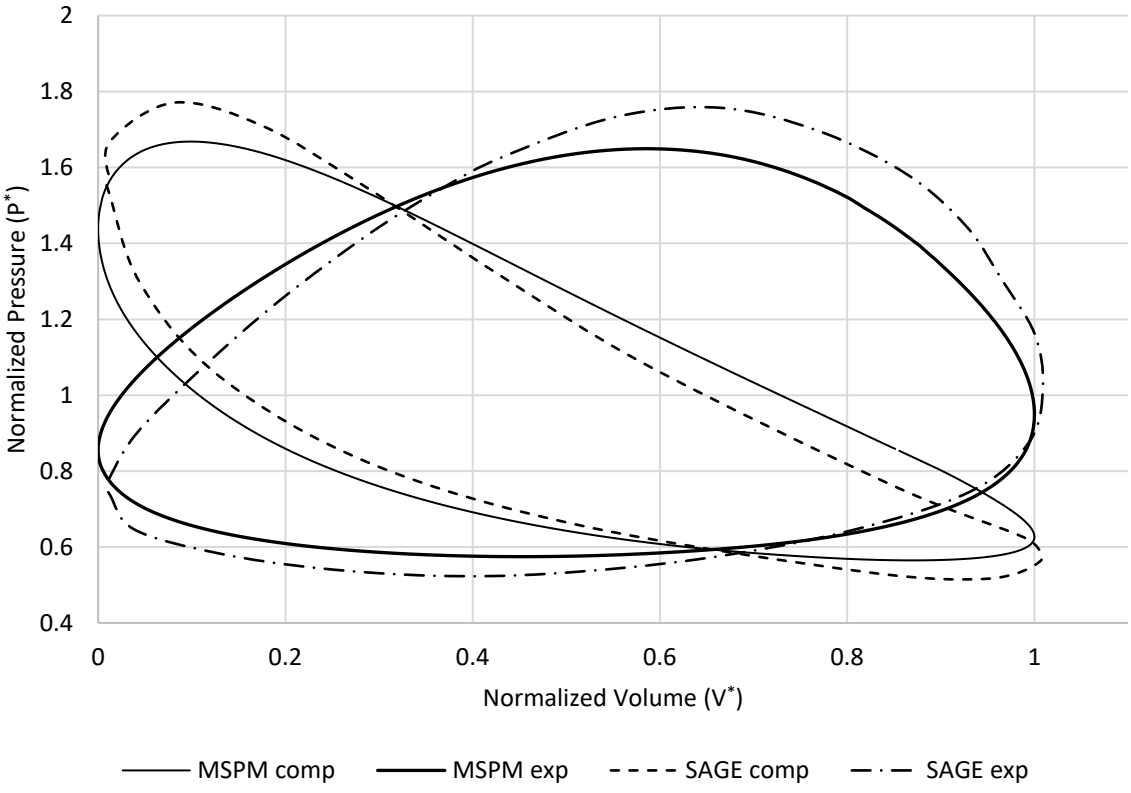
Phase 135°, Source 150 °C



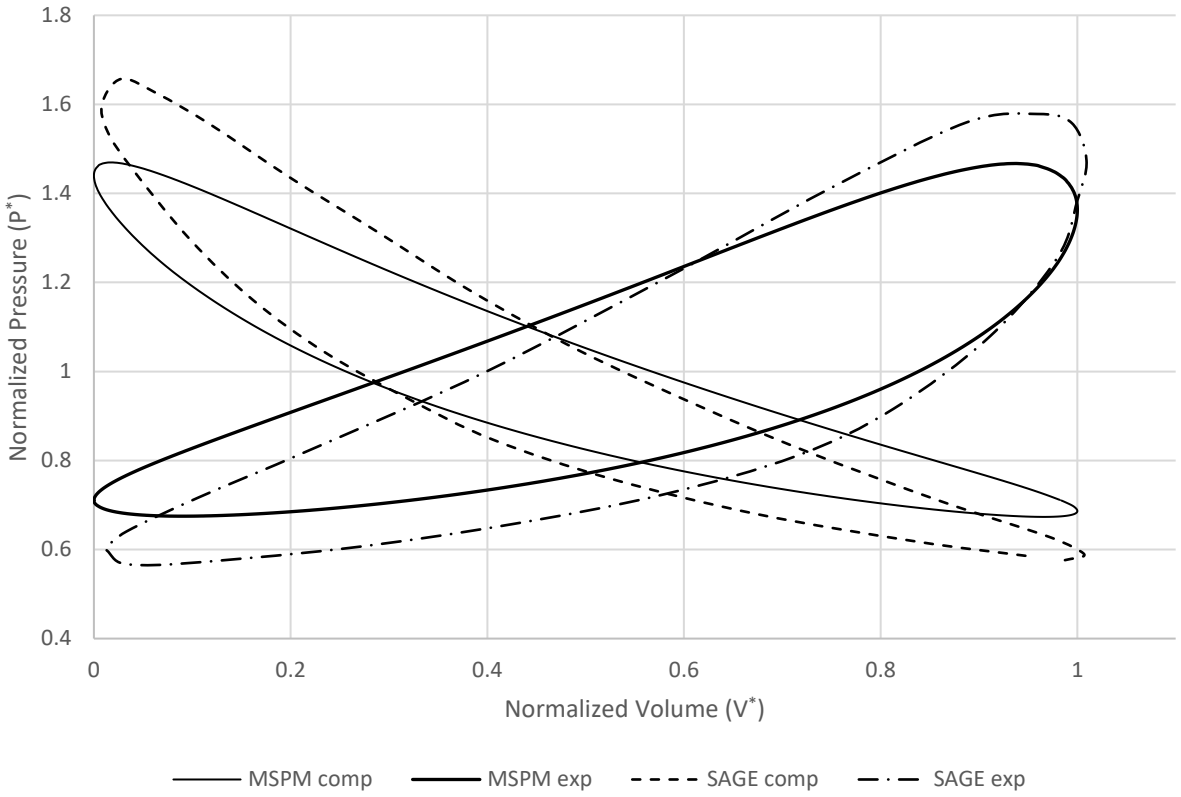
Phase 165°, Source 150 °C



Phase 90°, Source 750 °C



Phase 135°, Source 750 °C



Phase 165°, Source 750 °C

Figure 7.15: Pressure – volume diagram comparison between MSPM and SAGE, data extracted from: [44]

There are several observations that are made about the above figures. Firstly, the pressure maximums are reduced, which indicates that MSPM underpredicts – relative to SAGE – the temperature performance of the engine given that both models should have the same motions. This is likely due to a combination of two things: different Nusselt number correlation in the heat exchangers and the neglection of tortuosity. MSPM uses the same turbulent correlations as SAGE but could not adapt SAGE's complex scheme for determining the laminar Nusselt number of its tube bank heat exchangers which involved compression and advection driven flows [35] in complex form. Also, it is not known what values SAGE uses for minor losses at component transitions as these are not shared in the documentation. In addition, MSPM does not include tortuosity in its analysis, which approximates the curviness of a fluid streamlines through a medium, this alone would result in lower regenerator performance, as incorporating tortuosity would result in a higher effective speed, yet similar residence time in the regenerator. Additionally, SAGE uses a real gas representation [35], which under high pressures approximates the divergence

of real gases from ideal ones, in particular on the higher temperature and higher phase runs where the limiting factor in the short regenerators may be the local Nusselt number.

7.3.2 In Low-Temperature, Low-Speed Context

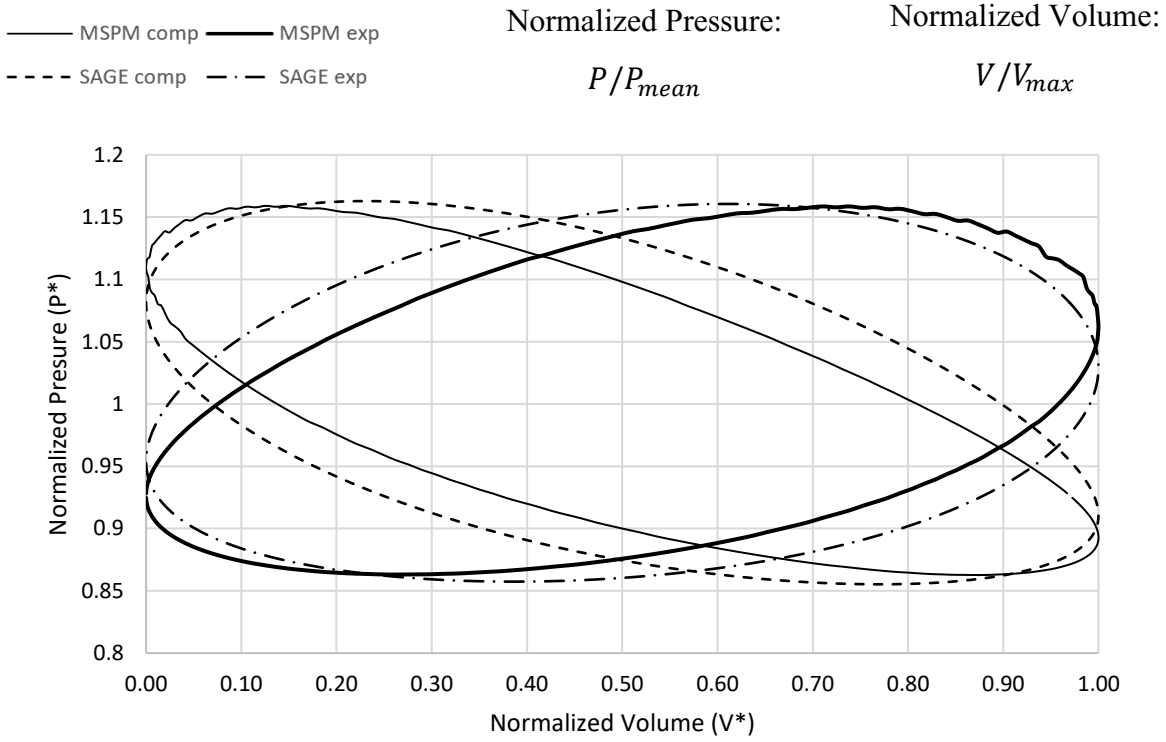
The following tests expand upon the previous tests, which though useful are not running at speeds or temperatures for laboratory engines produced by DTECL which MSPM was designed for. These new experiments feature the following modified properties, properties not listed are the same as those found in Table 7.6. It should be said that, though results are compared against SAGE, it is not clear whether SAGE models correctly the low-temperature, low-speed regime. Results from Table 7.10 indicate that MSPM and SAGE predict a similar trend but diverge at higher speeds.

Table 7.9: Unique properties for low-speed/low-temperature alpha engine SAGE comparisons

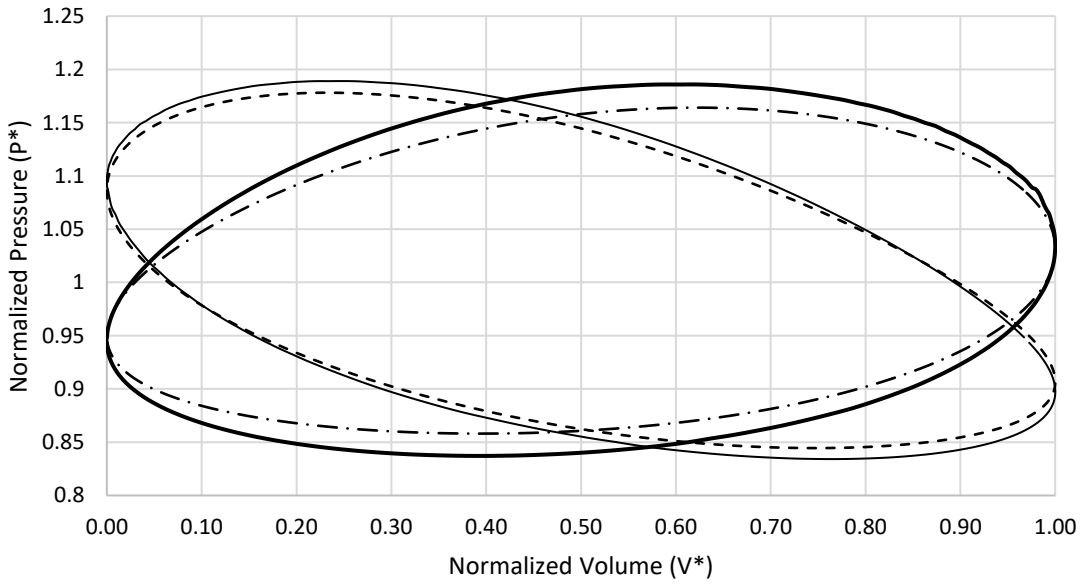
Component	Value	Unit
Phase Angle	160	degrees
Angular Speed	0.5-5	Hz
Heat Source Temperature	95	°C
Heat Sink Temperature	5	°C
Mean Pressure	101325	Pa
HX Tube Number	459.6	
HX Length	0.2348	m
Regenerator Porosity	76.47	%
Regenerator Length	0.001350	m

Table 7.10: Test results for low-speed/low-temperature alpha engine SAGE comparisons

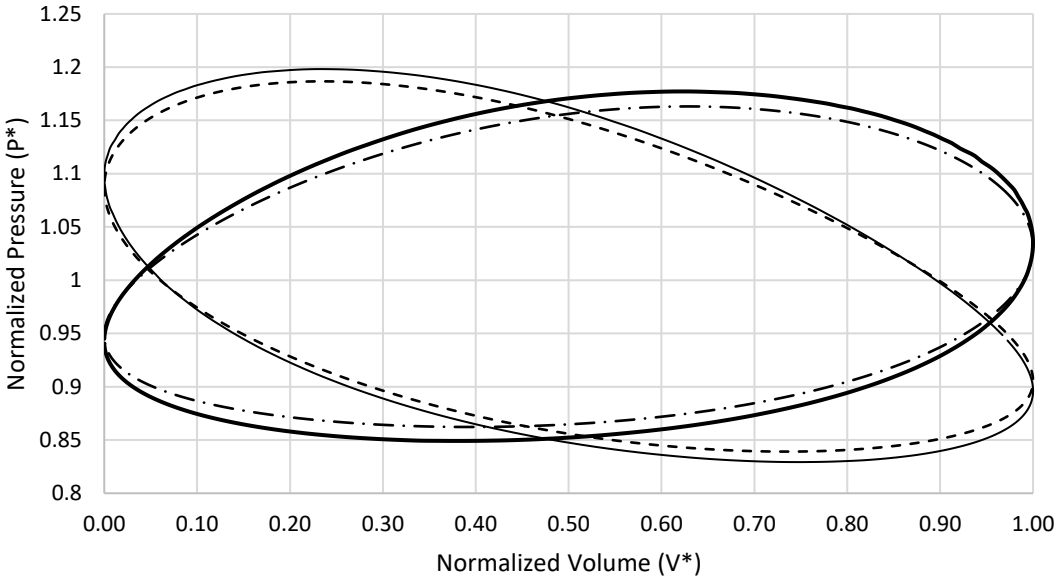
Test	Non-Dimensional Power (W)		Error
(Hz)	SAGE	MSPM	(%)
0.5	0.015	0.006	59.9%
1.0	0.027	0.028	2.5%
1.5	0.053	0.054	3.0%
2.0	0.079	0.083	4.0%
2.5	0.101	0.107	6.3%
3.0	0.111	0.123	10.2%
3.5	0.107	0.125	16.4%
4.0	0.078	0.107	36.9%
4.5	0.016	0.066	301.5%
5.0	-0.077	-0.004	94.3%


MSPM comp
MSPM exp
SAGE comp
SAGE exp
Normalized Pressure:
P/P_{mean}
Normalized Volume:
V/V_{max}
Normalized Presure (P*)
Normalized Volume (V*)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00

(a) 0.5 Hz


Normalized Pressure (P*)
Normalized Volume (V*)
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00

(b) 3 Hz



(c) 5 Hz

Figure 7.16: Pressure – volume diagram comparison between MSPM and SAGE for low-speed, low-temperature, low-pressure case.

The results indicate that MSPM, relative to SAGE, sometimes overestimates the temperature ratio that the gas achieves – via the broadness of the indicator diagram. At the same time MSPM underestimates, by a factor of roughly 2 the pressure loss through the components – via the pressure difference between the peaks of expansion and compression curves. Here the differences between SAGE's representation of the laminar Nusselt and friction loss coefficient are seen to a greater extent.

7.4 Optimization Studies

MSPM was tasked with optimizing a new engine to be created by the laboratory. The proposed engine would be in a beta-style configuration, as shown on Figure 7.17, with the power piston residing on the cold side of the engine. During optimizations only the stroke of the pistons and size of the power piston was kept constant while the diameter of the displacer and heat exchangers was modified. During these tests the target parameter was volumetric power density $\dot{\boldsymbol{e}} = \dot{\boldsymbol{E}}_{\boldsymbol{shaft}}/\boldsymbol{V}_{\boldsymbol{engine}}$ which gave rise to reasonable engines. The properties of the running conditions and heat exchangers for an engine without a regenerator are included in Table 7.11.

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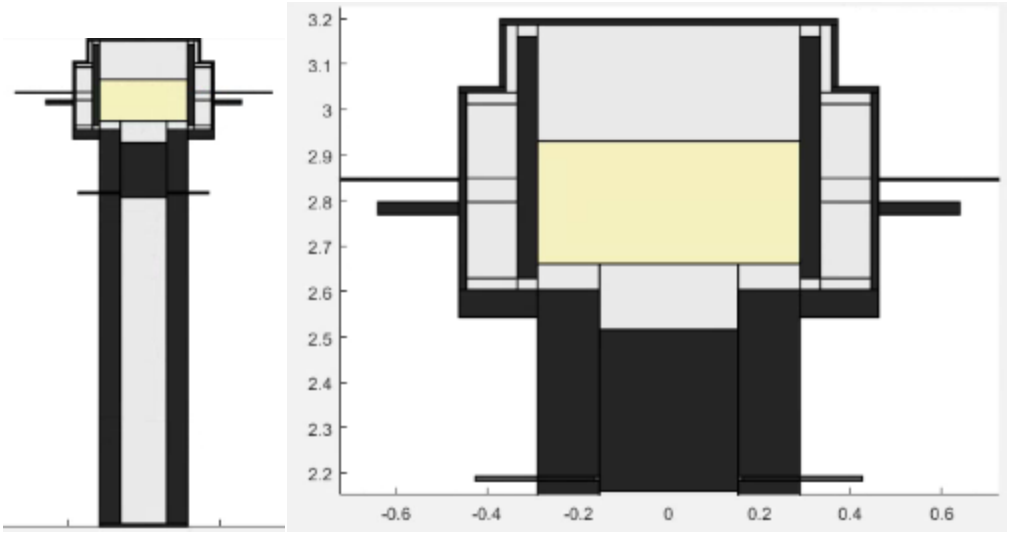

Figure 7.17: Depiction of beta-layout engine to be optimized. Large volume beneath engine represents the crankcase, the additional bodies jutting out of the engine are added to prevent the optimizer from making certain features too small leading to instabilities in the solution. (these bodies will overlap before the gas body becomes too small)

Table 7.11 Test properties for Beta-Engine Optimization

Running Properties	Value
Running Speed	1 Hz
Phase	90°
PP & DP Stroke	0.254 m
PP Diameter	0.3048 m
Fill Pressure	1 → 6 atm
Mechanism Efficiency	0.8 → 0.9
Heat Exchanger Properties	Bell AW450085060
Material	Aluminium Alloy
Air Gap Between Water Channels	0.00635 m
Water Channel Width	0.003175 m
Wall Thickness	0.0008128 m
Surface Roughness	1e-6 m
Fin Period	0.0023314 m
Fin Thickness	0.00021195 m

Table 7.12 Geometrical properties for Beta-Engine Optimization, Optimized for Maximum Power vs Gas Volume (1 Hz, filled with air)

Design Variables	**Post Optimal Values**					
Charge Pressure (atm) / Mechanism Efficiency	Heater / Cooler Volume	Swept / PP Volume	HX / Swept Volume	Compression Ratio	PV Power / Shaft Power	Flow Loss / PV Power
2 atm / 0.8	1.088	5.755	0.434	1.116	0.455	0.058
4 atm / 0.8	1.142	4.010	1.140	1.104	0.475	0.050
6 atm / 0.8	1.179	5.894	1.339	1.065	0.470	0.117
2 atm / 0.9	1.095	5.261	0.696	1.099	0.783	0.090
4 atm / 0.9	1.037	4.879	0.938	1.094	0.755	0.073
6 atm / 0.9	1.178	5.860	1.347	1.091	0.678	0.089
2 atm / 1.0	1.071	5.204	0.824	1.094	0.985	0.085
4 atm / 1.0	1.091	4.760	1.071	1.090	0.986	0.067
6 atm / 1.0	1.069	4.722	1.069	1.090	0.978	0.083

From Table 7.12, it can be observed several clear trends: Optimal Heater/Cooler volume is not strongly related to either mechanism efficiency or fill pressure. Optimal swept volume over power piston volume hovers around 4-6. Optimal heat exchanger volume vs swept volume ratio hovers around 1 at low temperatures. Compression ratio is slightly greater that which is predicted by Kolin [65] equal to 1.082 for temperatures of 95 and 5 Celsius. The ratio of PV power / shaft power is strongly dependent on the mechanism efficiency falling on the line $2.5831\eta_{mech} - 1.5957$ with an R value of 0.999. The extra mechanism losses are due to energy transmitting back and forth to the engine to compress or expand against the pressure regime or fight flow losses. With regards to flow losses, it appears to be good practice to ensure that flow losses never amount to more than 10% of PV.

An improvement was proposed to optimize the engine for maximum efficiency as the above tests featured an average efficiency on the order of 1% and would overload the available heating supply within the test laboratory. As a reference the Carnot Efficiency is on the order of 24%. As the expected range of fill pressures is between 1 to 10 atmospheres an engine will be designed to be optimum at 5 atmospheres. It was determined that a mechanism effectiveness of 80% could be used to conservatively model the mechanism currently in the design phase, though it is likely to be in the range of 85%. The addition of a regenerator and insulation of the engine is known to strongly effect the efficiency. Also, it is proposed that thin, large cross-section heat exchangers are desirable for maintaining good heat exchange without much pressure drop. Thus, the new engine

features a HX stack which is detached from the engine such that the length can be optimized independent of the displacer cylinder length, at the introduction of some additional dead volume. Through previous investigations a regenerator porosity of 95% is expected to be close to the optimum value, the stainless steel randomly oriented fibres are 0.1 mm in diameter, in line with coarse steel wool. The results of these further optimizations are shown on Table 7.13.

Table 7.13 Test properties for Beta-Engine Optimization (listed component volumes are for available gas volume only, heat exchangers have a surface are to volume ratio of about 1.52 m^2/Litre, 1 Hz, 80% efficient mechanism, wire diameter of 0.1 mm in regenerator, HX volume is for heater and cooler only, with air if not otherwise indicated)

Details	Power (W)	Heater / Cooler Volume	HX / Swept Volume	Regen. / Swept Volume	Swept / PP Volume	Eff. (%)
Power Density						
90% porosity regen.	328.4	1.074	0.809	0.0363	6.372	2.18%
95% porosity regen.	336.3	1.054	0.706	0.0680	6.579	2.12%
Insulated, 95% porosity regen.	431.7	1.053	0.660	0.0653	6.673	3.70%
As above with 24” DP	416.0	0.958	0.554	0.0965	5	4.95%
Insulated, offset HX, 95% por. regen.	427.5	1.003	0.478	0.0882	5.462	4.72%
Efficiency						
Insulated, offset HX, 95% por. regen.	407.5	0.9488	0.567	0.142	4.925	5.55%
As above with 24” DP	329.0	0.838	0.842	0.383	5	6.20%
Insulated, offset HX, 95% por. regen. (Optimized with Helium)	486.15	0.930	0.5515	0.180	4.975	8.02%

Based on the results in Table 7.13 several observations can be made. Firstly, efficiency strongly correlates with the size of the regenerator. Secondly, well insulating the engine body can improve the efficiency by several percent and will reduce the requirements on HX size vs swept volume. Relative size of both heat exchangers is consistent among trials. Peak power density and peak efficiency occur at similar but notably different conditions. The final test, which featured an engine filled with helium resulted in increased power with very similar geometry. The power increase is largely attributed to an increase in efficiency from reduced flow losses; 33% lower than the optimal point for air. This is created by reduced viscosity in similarly sized heat exchangers and regenerators.

CHAPTER 8. CONCLUSIONS

8.1 Conclusions

The model presented here predicts the complex phenomenon present in Stirling engines. The following subsections will discuss the model through the lens of the project goals.

8.1.1 Create a Combined Mechanical and Thermodynamic Model for Low-Temperature Stirling Engines

This was accomplished through the alternating coupling of the gas and kinematic mechanical system. The gas system was solved as a one-dimensional pipe network around the assumption of equal gas pressures, which prevented the emergence of acoustic instabilities and allowed each step to be solved using a larger timestep than the compressible simulation would allow. The mechanical system using an alternating coupling allows the mechanical system to respond quickly to changes in the gas system, while allowing the gas network to use deterministic positions and velocities.

8.1.2 Ensure the model is User-Friendly and Intuitive

While not an engineering issue, ease of use is an important component of the selection and further development of any software tool, this model is no exception. To support the user, this model features a graphical user interface (GUI) which allows the user to define engine-geometry in a physically viable context. The model may include as much detail as required, and internally develops the connectivity of the user defined blocks. Other features such as: a drop-down menu for editing object properties, an animation tool for visualizing motions and mesh visualization are included to support the user. Additionally the MSPM software package uses no external MATLAB toolboxes and requires only the MATLAB editor to run.

MSPM natively creates animations of the view-screen after simulation, which are much easier to inspect than data-structures, which it also produces. The user can also place generic point and line sensors in addition to indicator diagram generating sensors. These output features may allow the model to serve as a explanation or presentation tool.

8.1.3 Validate the Model against Experimental and a well Established Numerical Model

The model is tested against a variety of classical experiments to check the correctness of different aspects of the code in isolation. In these tests MSPM matched up well with analytical results, these tests show that the fundamental aspects of the model are correct, and that the numerical method used converges to the expected trend.

When compared against the EP-1 (in lab engine) under-steady-state conditions without calibration, MSPM developed a maximum error of 43.1% with an average error of 30.6% over the 12 tests with speeds ranging from 0.56 to 2.26 Hz. The model was calibrated through modification of the compression to match the observed variance in pressure ranges which reduced the maximum and average error to 35.2% and 21.9% respectively. The remaining error was systematic and consistent among all the speeds, this indicated that the actual error may be in the effectiveness of the heat exchangers to expose the air to actual source temperatures. This fine perspective on the heat exchangers is possible in MSPM but was not explored in detail here.

When compared against SAGE, a well established and accurate numerical code, 5 tests were extracted from Hoegel [44], which modelled an opposed alpha type engine. Over the 5 tests, in which error is calculated relative to SAGE's output indicated power, MSPM developed a maximum discrepancy of 59.1% with an average of 33.5%. The cycle speed for these tests was 16.7 Hz. It was concluded that the error was largely due to differences in convection and the exclusion of tortuosity from MSPM as it stands currently. Each of these tests were tested with different geometrical and phasing parameters.

A second batch of SAGE tests were included, which were modelled in-house but at the reduced speeds and temperatures common to low-temperature Stirling engines. The two models followed a similar trend in power however diverged at higher speeds.

Finally, MSPM was used to optimize a beta engine. The resulting engines displayed consistency in the relative size of certain components and informed the design of a new engine project. The information gained from the model included optimal geometrical sizes, expected power, anticipated supply power and expected losses due to friction.

8.2 Sources of Error

The following sub-sections outline specific areas where for a variety of reasons errors are introduced in the name of simplicity or computational efficiency. The possible sources of error include:

8.2.1 Decoupling of Flow Friction and Volumetric Flow Rate

This will have the effect of incorrectly determining the phase lag and dampening of volumetric flow rates as well as incorrectly determining of the density of the gas.

8.2.2 Constant Properties

Material properties such as solid conductivity, solid heat capacity as gas-constants is assumed constant given that these properties did not vary significantly over the temperature range considered. However, this introduces a bias error for any point that is not equal to the calibration point.

8.2.3 Ideal Gas Representation of the Fill Gas

The ideal gas representation is valid only for low-pressures and high-temperatures. Of course, these statements are relative, and error increases the moment the gas is no longer at the point for which the gas constant was derived. At atmospheric pressure the ideal gas law for air is accurate to within 2% from 100 K with an upper bound exceeding 1000 K, at a pressure of 20 bar, the lower bound rises to 250 K and at a pressure of 100 bar, this range shrinks to within 300 to 350 K, outside of which error increases rapidly [66].

8.2.4 Radiation Heat Transfer is Ignored

In the annular gap in particular radiation heat transfer plays an important role in the heat transfer from 2 surfaces separated by a very small air gap. In MSPM this effect is ignored. This was justified because of the low temperature assumption which states that because the magnitude of radiation is based on temperature to the power of 4, that for tow-temperature Stirling engines the

magnitude would be very small. While very small, the radiation effect would still produce a loss and thus results in a small bias error.

8.2.5 No Contact Resistance

Built into the conduction algorithm is an assumption that all interfaces have zero contact resistance. This is particularly unlikely in cases where a cylinder and wall are closely mated but run against each other, the model assumes that the two surfaces are bonded perfectly, when in reality a thin layer of air and other fluids would offer a measurable resistance.

8.2.6 Nusselt Number is Node Based, not Surface Based

The Nusselt number is intended and derived for convection between a gas and a surface with a particular geometry. This non-dimensional number was expanded to having a single value of Nusselt number per node due to the computational complexity of solving a Nusselt number for each face. This simplification was justified based on the concept that within a Stirling engine surfaces affect each other. Thus, turbulence created by one surface would throw off the Nusselt number calculation for another, therefore a single value from the most dominant surface would be the best guess at a global Nusselt number without ugly area weighted anonymous functions.

8.2.7 Constant Friction Coefficients in Mechanism

Currently, the system takes only normal force in the calculation of friction coefficients. More realistic models would incorporate temperature buildup effects, speed, lubricant film thickness and could introduce drag from the air around the mechanism and flywheel.

8.2.8 One Dimensional Flow Assumption

The one-dimensional flow assumption has its drawbacks, including the inability to evaluate the following:

- Recirculation regions [35] or complexities within open chambers
- Preferential flows [67] either due to offset designs or due to manufacturing inconsistencies

Not modelling these phenomena means that generic approximations are required. Recirculation regions are approximated by a combination of minor loss coefficients and turbulence in variable volume spaces, which are general at best, especially when combined with the mono-Nusselt number assumption. Minor loss coefficients are used out of scope as no minor loss coefficients could be found for annular interfaces. There is no generic approximation for preferential flows as it is assumed that the designer avoids it as much as possible and that features are uniform all the way around the engine, even in cases where a bridge is applied to an offset or side position, the inflow and outflow is assumed to be distributed or smeared all the way around the engine. The problem of preferential flows becomes particularly problematic with thin, HX's, which are optimal with regards to flow losses, but may result in inefficient use of HX volume or lower than expected exit temperatures.

8.2.9 Minor Loss Coefficients are Naively Applied

The model does not incorporate support for laminar minor loss coefficients. Ideally these would be calibrated through CFD or real-world experiments for a range of flow through rates, but likely the designer will be restricted to generalized formulas such as the Hooper 2-K [68] or Darby 3-K [69] which provide loss coefficients for fittings in the laminar regime.

Turbulent minor loss coefficients are calculated simply by determining the change in flow area between one zone and the next. No modifications are made for turns, for the number or distribution of openings or for the effect of annularity.

8.2.10 Fluid Inertia and Acoustics, are Ignored

Neglecting fluid inertia will prevent any inertia effects, such as the pressure increase/decrease in response to the speed of a moving boundary, or acoustic resonance at higher speeds. Neglecting acoustics will have the effect of improving the simulated performance of the engine due to reduced friction losses. Acoustics were neglected here to improve computational efficiency using gas speed instead of sound speed as the timestep limiter and reduce anomalies at low speeds.

8.2.11 Steady-State Convergence

Currently, the model uses the deviation from cycle to cycle as the assessment criterion for convergence to steady state, for particularly large engines it may take a great deal of time to converge. Thus, the model may recognize an engine as converged even if the slope is not asymptotic but slow enough to fall within the tolerance bounds. In these cases, it is recommended that tolerance be reduced until the model shows truly convergent behavior, thankfully any follow up experiments can use the end of the previous experiment, the snapshot, as the starting point.

8.2.12 Calculation Errors

Computers work within a limited scope of possible values, therefore any operations conducted using a computer has limitations. MATLAB natively uses double precision values (15 decimal digits) in its calculations, which results in very little calculation error through basic operations. Therefore, the only meaningful sources of error lie within areas where these values are magnified. These areas are matrix inversion and large values. These areas are often combined, as was the case with the flow rate solving. The error of matrix inversion is said to be on the order of the condition number of the matrix. For a typical matrix in the flow rate solving loop of the EP-1 model the condition number was on the order of $1 \cdot 10^4$ which means that the matrix is somewhat ill-conditioned, and a small error in any of the properties may be magnified by roughly this amount.

8.3 Future Opportunities

8.3.1 Real Gases

Due to the use of Stirling engines in cryogenic fields, under high pressure and with large changes in pressure and temperature it would be beneficial to represent the gas as a non-ideal gas. The Van der Waals or Redlich-Kwong model of gases would be sufficient for this and even would allow prediction of the phase change behavior of the constituent gas.

8.3.2 Interface for Simulating Control System

An improvement would introduce smart valves, localized sensors and modifiable transmission systems driven by a control system designed by the user. Ideally the system would control the mechanism phasing, which would involve a modification of how the mechanism is interpolated, fill pressure through an orifice and source temperatures.

8.3.3 Multi-Phase simulations

Simulating multiphase transport, condensation, evaporation, and mixed properties would allow this to simulate more complex systems. This would involve a condensation / evaporation rate series of equations based on presence of a liquid film and flow properties, thermodynamic properties of mixtures, species transport as particulate, flow due to gravity and assisted liquid transport. Phase change is a promising angle for Stirling engines, typically incorporating phase change reduces the efficiency of a Stirling engine [70] but it is known to increase the power density substantially. With controlled evaporation it may be possible to significantly improve the performance of Stirling engines and with modification, MSPM could assist in that goal.

8.3.4 Source/Sink Simulation

Simulating the temperature regime within the thermal sources and sinks along the length of the heat exchanger might be of interest in cases where significant amounts of heat are transferred. This could involve defining the source fluid path through the heat exchanger and adding more detail to the source's convection behavior, which is currently not defined.

8.3.5 Material Distortion

Within the laboratory, there have been many observations of substantial flexing of members in response to pressure, the two most notable are the 1" thick acrylic blind flange of the EP-1 flexing close to 2 mm in either direction and the flexible bellow expanders which notably balloon outward or collapse under negative pressure. In short, modeling of flexible interfaces could prove valuable in cases where the pressure is contained by soft materials or when the engine body is to be analyzed for structural stability. With material distortion the simulation of more abstract structures may be

possible, including diagrams which are often used as frictionless pistons where high efficiency is required.

8.3.6 Improved modelling of Entrance Turbulence and Swirl in Open Volumes

The current formulation of open space turbulence is extracted from SAGE. It would be of interest to investigate this topic further to ensure that these values are true, as it is known that interfaces between gases and solids support a laminar, near-wall, region which must be accounted for. This is not accounted for in the current implementation.

8.3.7 String or Text File Based Test Set Run Files

To take this code out of the MATLAB environment it would be prudent to add an interface for the construction of test sets or allow the user to submit them as a standard text file.

8.3.8 Modelling of explicit faces

When two regions become exposed to each other the resulting outflow is explosive. Such a flow process would be modelled as a compressible process. After a short period though, if the two regions remain connected this explicit face would continue to slow the simulation down as the flow would oscillate. The solution would be to combine the two regions into one during this connected period and handle the opening or closing event as a regulated transition between the separated and combined states. As such connections where not required for simulation of DTECL's Stirling engines it was not within the scope of this project to implement the projected complexity that this transition system would entail.

8.3.9 Improvements to Geometry Optimizer

The current geometry optimizer does not consider that an improvement might occur through the modification of one or more properties simultaneously where independent modification of those same properties may result in a loss. This would be very common in cases where increasing the diameter of the displacer causes the heat exchangers to shrink simultaneously reducing their effectiveness and inducing more friction losses, while increasing both the displacer and heat

exchangers might result in a gain. To avoid the added cost of gradient calculation, the edits could be designed such that the cross-section of components that are downstream is maintained. This would involve turning on and off relationships, which could be made part of the degree of freedom definition.

In its current state it may be prudent then to optimize in stages, have one model broken up so that features can be as independent as possible, then reassemble into a compact interconnected engine and optimize all the features again.

8.3.10 Parallelization

The program produced as part of this thesis runs entirely on a single core. A parallel implementation could, on a 4-core computer, be capable of operating at speeds close to 4 times as fast. Alternatively, this could allow the code to run more than one simulation at a time.

Alternatively, the model for steady-state cases could be discretized in both the spatial and time grid and a parallel non-linear solver would use to solve the resulting matrix. This would present a much better alternative to solving each step individually as it is done in this model and the resulting matrix updates would be calculated in parallel, preferably on the GPU as with modern CFD simulations. In such simulation the multi-grid consideration would work both in the time and space domain, the snapshot would serve as an initial guess and the steady-state solid temperatures assumption used to increase the convergence rate would replace the nodes deep within the bodies.

8.3.11 Other Programming Languages

MATLAB is primarily a prototyping language and is very strong at vectorizable operations and in matrix operations, in these areas the built-in technology is almost unmatched. However, MATLAB is typically slow at conducted sequential operations, an area where C++ is more suited for. Replacing sections of the code base with C files could offer dramatic improvements.

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Appendices

Appendix A. Mechanisms

The mechanisms described below are only a subset of the myriad of linear to rotational mechanisms proposed for Stirling Engines. Each of them assumes the following:

- A piston force is considered positive if it pushes the piston away from the driveshaft.
- Friction is excluded except for a modification on the output torque which takes the rotational speed and formulates a moment such that the energy loss from each source of friction is represented in the modified torque.
- To ensure that the bearing load on the driveshaft is properly oriented in space the orientation of the mechanism, rotates the coordinate system of the output normal loads before outputting.
- As a piston can be based either as coming from above the cylinder or below, each mechanism has an orientation property, in addition to its rotation, which changes the sign of the piston forces and inverts the returned position offsets.

A.1. Slider-crank Mechanism

Each component of the Slider-crank is solved using Newton's law, resulting in 7 semi-explicit equations.

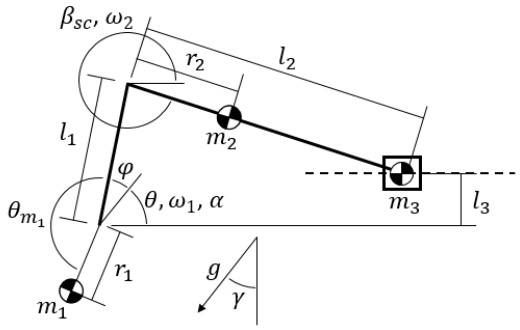


Figure 8.1. Slider-crank Mechanism: dimensions, masses, and gravity

Crank Arm

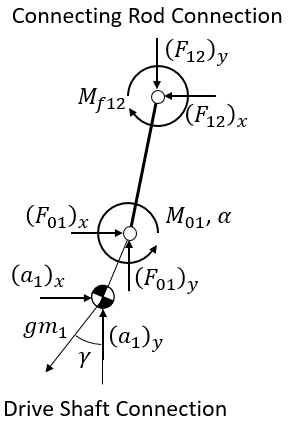


Figure 8.2. Free Body Diagram of Crank Arm

$$\theta_{sc} = \theta + \varphi$$

$$\theta_g = \theta + \varphi + \theta_{m_1}$$

$$I_{m_1} = m_1 r_1^2$$

The moment generated around the driveshaft

$$\sum M = I_{m_1}\alpha = (F_{12})_x l_1 \sin(\theta_{sc}) - (F_{12})_y l_1 \cos(\theta_{sc}) + M_{01} - g m_1 r_1 \cos(\theta_g)$$

Forces in the local x-direction

$$\sum F_x = m_1 (a_1)_x = (F_{01})_x - (F_{12})_x - g m_1 \sin(\gamma)$$

Forces in the local y-direction

$$\sum F_y = m_1 (a_1)_y = (F_{01})_y - (F_{12})_y - g m_1 \cos(\gamma)$$

Linking acceleration to relevant parameters

$$(a_1)_x = \left(-r_1 \cos\left(\theta_{sc} + \theta_{m_1}\right)\right)\omega^2 + \left(-r_1 \sin\left(\theta_{sc} + \theta_{m_1}\right)\right)\alpha = B_{a1x}\omega^2 + C_{a1x}\alpha$$

$$(a_1)_y = \left(-r_1 \sin\left(\theta_{sc} + \theta_{m_1}\right)\right)\omega^2 + \left(r_1 \cos\left(\theta_{sc} + \theta_{m_1}\right)\right)\alpha = B_{a1y}\omega^2 + C_{a1y}\alpha$$

Loss associated with M_{f12}:

$$L = \left| M_{f12}\omega_1(1 - C_{\omega 2}) \right|$$

Connecting Rod

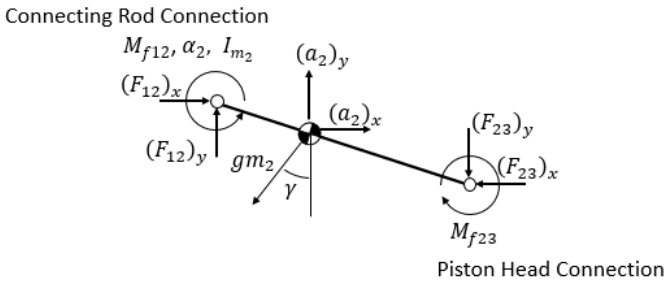


Figure 8.3. Free Body Diagram of Connecting Rod

$$\beta_{sc} = sin^{-1}\left(\frac{l_3 - l_1 sin(\theta_{sc})}{l_2}\right)$$

$$\beta_g = \beta_{sc} + \gamma$$

$$I_{m_2} = m_2 r_2^2$$

The moment generated around Crank Arm – Connecting Rod joint

$$\sum M = I_{m_2}\alpha_2 = (F_{23})_x l_2 \sin(\beta_{sc}) - (F_{23})_y l_2 \cos(\beta_{sc}) - g m_2 r_2 \cos(\beta_g)$$

Forces in the local *x*-direction

$$\sum F_x = m_2 (a_2)_x = (F_{12})_x - (F_{23})_x - g m_2 \sin(\gamma)$$

Forces in the local *y*-direction

$$\sum F_y = m_2 (a_2)_y = (F_{12})_y - (F_{23})_y - g m_2 \cos(\gamma)$$

Linking acceleration to relevant parameters

$$\omega_2 = \left(-\frac{l_1 \cos(\theta_{sc})}{l_2 \cos(\beta_{sc})}\right)\omega_1 = C_{\omega 2}\omega_1$$

$$\alpha_2 = \left(\frac{l_1 \sin(\theta_{sc}) + l_2 \sin(\beta_{sc})\, {C_{\omega 2}}^2}{l_2 \cos(\beta_{sc})}\right)\omega^2 + \left(-\frac{l_1 \cos(\theta_{sc})}{l_2 \cos(\beta_{sc})}\right)\alpha = B_{\alpha_2}\omega^2 + C_{\omega_2}\alpha$$

$$(a_2)_x = \left(-l_1\cos(\theta_{sc}) - r_2\cos(\beta_{sc})\,{C_{\omega 2}}^2 - r_2\sin(\beta_{sc})\,B_{\alpha_2}\right)\omega^2 + \left(-l_1\sin(\theta_{sc}) - r_2\sin(\beta_{sc})\,C_{\omega_2}\right)\alpha = B_{a2x}\omega^2 + C_{a2x}\alpha$$

$$(a_2)_y = \left(-l_1\sin(\theta_{sc}) - r_2\sin(\beta_{sc})\,{C_{\omega 2}}^2 + r_2\cos(\beta_{sc})\,B_{\alpha_2}\right)\omega^2 + \left(l_1\cos(\theta_{sc}) + r_2\cos(\beta_{sc})\,C_{\omega_2}\right)\alpha = B_{a2y}\omega^2 + C_{a2y}\alpha$$

Loss associated with M_{f23}:

$$L = \left|M_{f23}\omega_1 C_{\omega 2}\right|$$

Piston Head

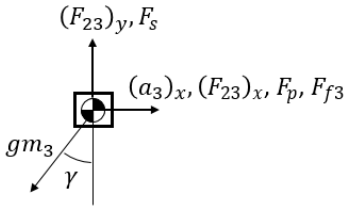


Figure 8.4. Free Body Diagram of Piston Head

Forces in the local *x*-direction

$$\sum F_x = m_3(a_3)_x = F_p + (F_{23})_x - gm_3\sin(\gamma)$$

$$\sum F_y = 0 = (F_{23})_y + F_s - gm_3\cos(\gamma)$$

Linking acceleration to relevant parameters

$$(a_3)_x = \left(-l_1\cos(\theta_{sc}) - l_2\cos(\beta_{sc})\,{C_{\omega 2}}^2 - l_2\sin(\beta_{sc})\,B_{\alpha_2}\right)\omega^2 + \left(-l_1\sin(\theta_{sc}) - l_2\sin(\beta_{sc})\,C_{\omega_2}\right)\alpha = B_{a3x}\omega^2 + C_{a3x}\alpha$$

Piston Motion and position

$$x_p = l_1\cos(\theta_{sc}) + l_2\cos(\beta_{sc}) - \sqrt{(l_2 - l_1)^2 - {l_3}^2}$$

$$v_p = (-l_1\sin(\theta_{sc}) - l_2\sin(\beta_{sc})\,C_{\omega 2})\omega$$

Loss associated with F_{f3}:

$$L = \left|F_{f3} v_p\right|$$

Deriving M_{01}, $(F_{01})_x$ and $(F_{01})_y$ as $F = A\alpha + B\omega^2 + G + E$

$$(F_{23})_x = (m_3 C_{a3x})\alpha + (m_3 B_{a3x})\omega^2 + (g m_3 \sin(\gamma)) - F_p$$

$$= A_1\alpha + B_1\omega^2 + G_1 + E_1$$

$$(F_{12})_x = (m_2 C_{a2x} + A_1)\alpha + (m_2 B_{a2x} + B_1)\omega^2 + (g m_2 \sin(\gamma) + G_1) + (E_1)$$

$$= A_2\alpha + B_2\omega^2 + G_2 + E_2$$

$$(F_{23})_y = \left(\frac{-I_{m_2} C_{\omega_2}}{l_2 \cos(\beta_{sc})} + \tan(\beta_{sc})\, A_1\right)\alpha + \left(\frac{-I_{m_2} B_{\alpha_2}}{l_2 \cos(\beta_{sc})} + \tan(\beta_{sc})\, B_1\right)\omega^2 + \left(\frac{-g m_2 r_2 \cos(\beta_g)}{l_2 \cos(\beta_{sc})} + \tan(\beta_{sc})\, G_1\right) + (\tan(\beta_{sc})\, E_1)$$

$$= A_3\alpha + B_3\omega^2 + G_3 + E_3$$

$$(F_{12})_y = \left(m_2 C_{a2y} + A_3\right)\alpha + \left(m_2 B_{a2y} + B_3\right)\omega^2 + \left(g m_2 \cos(\beta_g) + G_3\right) + (E_3)$$

$$= A_4\alpha + B_4\omega^2 + G_4 + E_4$$

$$(F_{01})_x = (m_1 C_{a1x} + A_2)\alpha + (m_1 B_{a1x} + B_2)\omega^2 + (g m_1 \sin(\gamma) + G_2) + (E_2)$$

$$= A_5\alpha + B_5\omega^2 + G_5 + E_5$$

$$(F_{01})_y = \left(m_1 C_{a1y} + A_4\right)\alpha + \left(m_1 B_{a1y} + B_4\right)\omega^2 + (g m_1 \cos(\gamma) + G_4) + (E_4)$$

$$= A_6\alpha + B_6\omega^2 + G_6 + E_6$$

Output Variables (converted to global coordinates)

Torque from the driveshaft to the slider-crank mechanism

$$\sum M = I_{m_1}\alpha = (F_{12})_x l_1 \sin(\theta_{sc}) - (F_{12})_y l_1 \cos(\theta_{sc}) + M_{01} - g m_1 r_1 \cos(\theta_g)$$

$$M_0 = (I_{m1} - l_1 \sin(\theta_{sc})\, A_2 + l_1 \cos(\theta_{sc})\, A_4)\alpha + (-l_1 \sin(\theta_{sc})\, B_2 + l_1 \cos(\theta_{sc})\, B_4)\omega^2 + \left(g m_1 r_1 \cos(\theta_g) - l_1 \sin(\theta_{sc})\, G_2 + l_1 \cos(\theta_{sc})\, G_4\right) + \left(F_p l_1 (\cos(\theta_{sc}) \tan(\beta_{sc}) - \sin(\theta_{sc}))\right) = A_M \alpha + B_M \omega^2 + G_M + E_M$$

Horizontal force as felt by the driveshaft.

$$F_x = (-\cos(\gamma)\, A_5 + \sin(\gamma)\, A_6)\alpha + (-\cos(\gamma)\, B_5 + \sin(\gamma)\, B_6)\omega^2 + (-\cos(\gamma)\, G_5 + \sin(\gamma)\, G_6) + (-\cos(\gamma)\, E_5 + \sin(\gamma)\, E_6) = A_x \alpha + B_x \omega^2 + G_x + E_x$$

Vertical force as felt by the driveshaft.

$$F_y = (-\sin(\gamma)\, A_5 - \cos(\gamma)\, A_6)\alpha + (-\sin(\gamma)\, B_5 - \cos(\gamma)\, B_6)\omega^2 + (-\sin(\gamma)\, G_5 - \cos(\gamma)\, G_6) + (-\sin(\gamma)\, E_5 - \cos(\gamma)\, E_6) = A_y \alpha + B_y \omega^2 + G_y + E_y$$

Losses:

$$M_{Loss} = \left|M_{f12}(F_{12x}, F_{12y})\omega_1(1 - C_{\omega 2})\right| + \left|M_{f23}(F_{23x}, F_{23y})\omega_1 C_{\omega 2}\right| + \left|F_{f3}(F_{23y})v_p\right|$$

A.2. Rhombic Drive Mechanism

Half of the Rhombic Drive mechanism is very similar to the slider-crank mechanism except that the friction for the piston is only a product of side-load free seal friction. Also, half of the bearing load on the shaft is placed on an auxiliary shaft that can be entirely contained in the engine body without a seal.

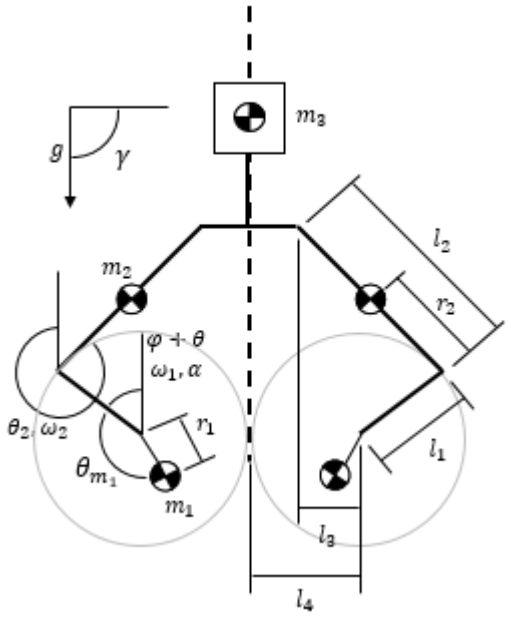


Figure 8.5: Rhombic Drive Mechanism: dimensions, masses, and gravity

Output Variables (converted to global coordinates)

Torque from the driveshaft to a slider-crank mechanism

$$M_0 = (I_{m1} - l_1 \sin(\theta_{sc})\, A_2 + l_1 \cos(\theta_{sc})\, A_4)\alpha + (-l_1 \sin(\theta_{sc})\, B_2 + l_1 \cos(\theta_{sc})\, B_4)\omega^2 + \left(g m_1 r_1 \cos(\theta_g) - l_1 \sin(\theta_{sc})\, G_2 + l_1 \cos(\theta_{sc})\, G_4\right) + \left(F_p l_1 (\cos(\theta_{sc}) \tan(\beta_{sc}) - \sin(\theta_{sc}))\right) = A_M \alpha + B_M \omega^2 + G_M + E_M$$

Horizontal force as felt by the driveshaft.

$$F_x = 0.5\big((-\cos(\gamma)\, A_5 + \sin(\gamma)\, A_6)\alpha + (-\cos(\gamma)\, B_5 + \sin(\gamma)\, B_6)\omega^2 + (-\cos(\gamma)\, G_5 + \sin(\gamma)\, G_6) + (-\cos(\gamma)\, E_5 + \sin(\gamma)\, E_6)\big) = A_x \alpha + B_x \omega^2 + G_x + E_x$$

Vertical force as felt by the driveshaft.

$$F_y = 0.5((-\sin(\gamma)\,A_5 - \cos(\gamma)\,A_6)\alpha + (-\sin(\gamma)\,B_5 - \cos(\gamma)\,B_6)\omega^2 + (-\sin(\gamma)\,G_5 - \cos(\gamma)\,G_6) + (-\sin(\gamma)\,E_5 - \cos(\gamma)\,E_6)) = A_y\alpha + B_y\omega^2 + G_y + E_y$$

Losses:

$$M_{Loss} = \left|2M_{f12}\left(\frac{F_{12x}}{2}, \frac{F_{12y}}{2}\right)\omega_1(1 - C_{\omega 2})\right| + \left|2M_{f23}\left(\frac{F_{23x}}{2}, \frac{F_{23y}}{2}\right)\omega_1 C_{\omega 2}\right| + \left|F_{f3}(0)v_p\right| + \left|F_{aux}(F_x, F_y)\omega_1\right| + \left|F_{gear}\left(\omega_1 \frac{M_0}{2}\right)\right|$$

A.3. Scotch Yoke Mechanism

Crank Arm

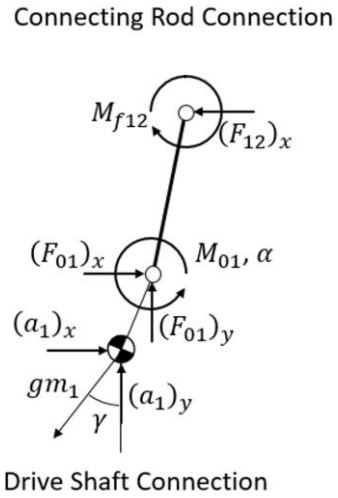


Figure 8.6. Free Body Diagram of Crank Arm

$$\theta_{sy} = \theta + \varphi$$

$$\theta_g = \theta + \varphi + \theta_{m_1}$$

The moment generated around the driveshaft

$$\sum M = I_{m_1}\alpha = (F_{12})_x l_1 \sin(\theta_{sy}) - (F_{12})_y l_1 \cos(\theta_{sy}) + M_{01} - gm_1 r_1 \cos(\theta_g)$$

Forces in the local *x*-direction

$$\sum F_x = m_1(a_1)_x = (F_{01})_x - (F_{12})_x - gm_1 \sin(\gamma)$$

Forces in the local *y*-direction

$$\sum F_y = m_1(a_1)_y = (F_{01})_y - gm_1 \cos(\gamma)$$

Linking acceleration to relevant parameters

$$(a_1)_x = \left(-r_1 \cos(\theta_{sy} + \theta_{m_1})\right)\omega^2 + \left(-r_1 \sin(\theta_{sy} + \theta_{m_1})\right)\alpha = B_{a1x}\omega^2 + C_{a1x}\alpha$$

$$(a_1)_y = \left(-r_1 \sin(\theta_{sy} + \theta_{m_1})\right)\omega^2 + \left(r_1 \cos(\theta_{sy} + \theta_{m_1})\right)\alpha = B_{a1y}\omega^2 + C_{a1y}\alpha$$

Loss associated with M_{f12}:

$$L = \left|M_{f12}\omega_1(1 - C_{\omega 2})\right|$$

Piston Assembly

The piston for the scotch yoke mechanism is supported by a linear bearing assembly, which has a moment dependent and constant component to friction loss. The forces in the local *x*-direction are as follows:

$$\sum F_x = m_p(a_p)_x = F_p + (F_{12})_x$$

$$\sum F_y = (F_{BAsm})_y - gm_p\cos(\gamma)$$

$$\sum M = 0 = M_{BAsm} - (F_{12})_x l_1 \sin(\theta_{sy}) - gm_p \sin(\gamma)$$

Where:

$$x_p = C_{offset} + l_1\cos(\theta_{sy})$$

$$v_p = -l_1\omega\sin(\theta_{sy})$$

$$a_p = -l_1\alpha\sin(\theta_{sy}) - l_1\omega^2\cos(\theta_{sy})$$

Thus:

$$(F_{12})_x = -m_p l_1(\alpha\sin(\theta_{sy}) + \omega^2\cos(\theta_{sy})) - F_p$$

$$(F_{BAsm})_y = gm_p\cos(\gamma)$$

$$M_{BAsm} = -(m_p l_1^2\sin^2(\theta_{sy})\alpha + m_p l_1^2\cos(\theta_{sy})\sin(\theta_{sy})\omega^2 + l_1^2\sin^2(\theta_{sy})F_p) - gm_p\sin(\gamma)$$

$$(F_{01})_x = m_1(a_1)_x + (F_{12})_x + gm_1\sin(\gamma)$$

$$(F_{01})_x = m_1(B_{a1x}\omega^2 + C_{a1x}\alpha) - m_p l_1(\alpha\sin(\theta_{sy}) + \omega^2\cos(\theta_{sy})) - F_p + gm_1\sin(\gamma)$$
$$= A_1\alpha + B_1\omega^2 + E_1F_p + G_1$$

$$(F_{01})_y = m_1(a_1)_y + gm_1\cos(\gamma)$$

$$(F_{01})_y = m_1 B_{a1y}\omega^2 + m_1 C_{a1y}\alpha + g m_1 \cos(\gamma) = A_2\alpha + B_2\omega^2 + G_2$$

$$M_{01} = I_{m_1}\alpha + \left(m_p l_1^2 \sin^2(\theta_{sy})\,\alpha + m_p l_1^2 \cos(\theta_{sy}) \sin(\theta_{sy})\,\omega^2 + l_1^2 \sin^2(\theta_{sy})\,F_p\right) + g m_1 r_1 \cos(\theta_g) = -A_M\alpha - B_M\omega^2 - E_M F_p - G_M$$

Torque from the driveshaft to a slider-crank mechanism

$$M_0 = A_M\alpha + B_M\omega^2 + G_M + E_M$$

$$A_M = -I_{m_1} - m_p l_1^2 \sin^2(\theta_{sy})$$

$$B_M = -m_p l_1^2 \cos(\theta_{sy}) \sin(\theta_{sy})$$

$$G_M = -g m_1 r_1 \cos(\theta_g)$$

$$E_M = -l_1^2 \sin^2(\theta_{sy})$$

Horizontal force as felt by the driveshaft.

$$F_x = \big((-\cos(\gamma)\,A_1 + \sin(\gamma)\,A_2)\alpha + (-\cos(\gamma)\,B_1 + \sin(\gamma)\,B_2)\omega^2 + (-\cos(\gamma)\,G_1 + \sin(\gamma)\,G_2) + (-\cos(\gamma)\,E_1)\big) = A_x\alpha + B_x\omega^2 + G_x + E_x$$

$$A_x = -\cos(\gamma)\left(m_1 C_{a1x} - m_p l_1 \sin(\theta_{sy})\right) + \sin(\gamma)\left(m_1 C_{a1y}\right)$$

$$B_x = -\cos(\gamma)\left(m_1 B_{a1x} - m_p l_1 \cos(\theta_{sy})\right) + \sin(\gamma)\left(m_1 B_{a1y}\right)$$

$$G_x = 0$$

$$E_x = \cos(\gamma)$$

Vertical force as felt by the driveshaft.

$$F_y = ((-\sin(\gamma)\,A_1 - \cos(\gamma)\,A_2)\alpha + (-\sin(\gamma)\,B_1 - \cos(\gamma)\,B_2)\omega^2 + (-\sin(\gamma)\,G_1 - \cos(\gamma)\,G_2) + (-\sin(\gamma)\,E_1)) = A_y\alpha + B_y\omega^2 + G_y + E_y$$

$$A_y = -\sin(\gamma)\left(m_1 C_{a1x} - m_p l_1 \sin(\theta_{sy})\right) - \cos(\gamma)\left(m_1 C_{a1y}\right)$$

$$B_y = -\sin(\gamma)\left(m_1 B_{a1x} - m_p l_1 \cos(\theta_{sy})\right) - \cos(\gamma)\left(m_1 B_{a1y}\right)$$

$$G_y = g(m_1 + m_p)$$

$$E_y = \sin(\gamma)$$

A.4. Ideal Sinusoidal Mechanism

The ideal sinusoidal mechanism is simply a simplified Scotch Yoke mechanism

$$\theta_{sc} = \theta + \varphi$$

The moment generated around the driveshaft

$$\sum M = I_{m_1}\alpha = (F_{12})_x l_1 \sin(\theta_{sc}) + M_{01}$$

Forces in the local *x*-direction

$$\sum F_x = 0 = (F_{01})_x - (F_{12})_x - gm_1 \sin(\gamma)$$

Forces in the local *y*-direction

$$\sum F_y = 0 = (F_{01})_y - gm_1 \cos(\gamma)$$

Piston

$$\sum F_x = \alpha_p m_p = (F_{12})_x + F_p - gm_p \sin(\gamma)$$

$$\sum F_y = 0 = (F_3)_y - gm_p \cos(\gamma)$$

$$x_p = l_1 \cos(\theta_{sc}) + C$$

$$v_p = -l_1 \sin(\theta_{sc})\, \omega_{sc}$$

$$a_p = -l_1 \cos(\theta_{sc})\, \omega_{sc}^2 - l_1 \sin(\theta_{sc}) \alpha_{sc}$$

Separating the root forces F_{01} and M_0

$$(F_{12})_x = -m_p l_1 \cos(\theta_{sc}) \omega_{sc}^2 - m_p l_1 \sin(\theta_{sc})\, \alpha_{sc} + gm_p \sin(\gamma) - F_p$$

$$(F_{01})_x = -m_p l_1 \cos(\theta_{sc}) \omega_{sc}^2 - m_p l_1 \sin(\theta_{sc})\, \alpha_{sc} + gm_p \sin(\gamma) + gm_1 \sin(\gamma) - F_p$$

$$(F_{01})_y = gm_1 \cos(\gamma)$$

$$M_{01} = I_{m_1}\alpha_{sc} + m_p l_1^2 \cos(\theta_{sc}) \sin(\theta_{sc})\, \omega_{sc}^2 + m_p l_1^2 \sin^2(\theta_{sc})\, \alpha_{sc} + F_p l_1 \sin(\theta_{sc}) - g m_p l_1 \sin(\gamma) \sin(\theta_{sc})$$

$$A_x = -\cos(\gamma)\left(-m_p l_1 \sin(\theta_{sc})\right)$$

$$B_x = -\cos(\gamma)\left(-m_p l_1 \cos(\theta_{sc})\right)$$

$$G_x = 0$$

$$E_x = -\cos(\gamma)\left(-F_p\right)$$

$$A_y = -\sin(\gamma)\left(-m_p l_1 \sin(\theta_{sc})\right)$$

$$B_y = -\sin(\gamma)\left(-m_p l_1 \cos(\theta_{sc})\right)$$

$$G_y = g\left(m_1 + m_p\right)$$

$$E_y = -\sin(\gamma)\left(-F_p\right)$$

$$A_M = \left(I_{m_1} + m_p l_1^2 \sin^2(\theta_{sc})\right)$$

$$B_M = m_p l_1^2 \cos(\theta_{sc}) \sin(\theta_{sc})$$

$$G_M = -g m_p l_1 \sin(\gamma) \sin(\theta_{sc})$$

$$E_M = F_p l_1 \sin(\theta_{sc})$$

A.5. Custom Profile Mechanism

The following mathematics determines a generic representation of a custom profile mechanism.

The custom motion mechanism is simply a modified Scotch Yoke mechanism

$$\theta' = \theta + \varphi$$

Forces in the local *x*-direction

$$\sum F_x = m_p a_p \cos(\gamma) = -F_{x,DS} - g\left(m_1 + m_p\right)\sin(\gamma) + F_p \cos(\gamma)$$

$$F_{x,DS} = -g\left(m_1 + m_p\right)\sin(\gamma) + \left(F_p - m_p a_p\right)\cos(\gamma)$$

Forces in the local *y*-direction

$$\sum F_y = m_p a_p \sin(\gamma) = -F_{y,DS} - g\left(m_1 + m_p\right)\cos(\gamma) + F_p \sin(\gamma)$$

$$F_{y,DS} = -g\left(m_1 + m_p\right)\cos(\gamma) + \left(F_p - m_p a_p\right)\sin(\gamma)$$

Inertia of piston

$$KE = \frac{1}{2} m_p v_p^2, \qquad \frac{dKE}{dt} = m_p v_p a_p = \omega T_p$$

$$T_p = \frac{v_p}{\omega} m_p a_p$$

This torque is positive concerning the driveshaft when the acceleration is opposite to the current velocity, as in kinetic energy is leaving the piston and being transmitted to the driveshaft. When the velocity and acceleration have the same sign, this should be negative. Thus:

$$T_{p,DS} = -\frac{v_p}{\omega} m_p a_p$$

Work against forces

$$\frac{dE}{dt} = \left(F_p - g\sin(\gamma)\, m_p\right) v_p = \omega T_f$$

$$T_f = \frac{v_p}{\omega}\left(F_p - g\sin(\gamma)\, m_p\right)$$

This torque is positive when the force is in the same direction as the velocity, thus:

$$T_{f,DS} = -\frac{v_p}{\omega}\left(F_p - g\sin(\gamma)\, m_p\right)$$

Work into rotating inertia

$$\frac{dE}{dt} = I_{m_1}\alpha$$

When acceleration is positive will reduce the torque sent to the driveshaft.

$$T_{m,DS} = -I_{m_1}\alpha$$

Moment around driveshaft

$$M_{DS} = -I_{m_1}\alpha - \frac{v_p}{\omega}m_p a_p + \frac{v_p}{\omega}\left(F_p - g\sin(\gamma)\, m_p\right)$$

The Piston Motion

$$x_p = x(\theta)$$

$$v_p = \omega\frac{dx}{d\theta}$$

$$a_p = \alpha\frac{dx}{d\theta} + \omega^2\frac{d^2x}{d\theta^2}$$

Separating the root forces F_{01}

$$F_{x,DS} = -g\left(m_1 + m_p\right)\sin(\gamma) + \left(F_p - m_p a_p\right)\cos(\gamma)$$

$$F_{x,DS} = -m_p\left(\alpha\frac{dx}{d\theta} + \omega^2\frac{d^2x}{d\theta^2}\right)\cos(\gamma) - g\left(m_1 + m_p\right)\sin(\gamma) + F_p\cos(\gamma)$$

$$F_{y,DS} = -g\left(m_1 + m_p\right)\cos(\gamma) + \left(F_p - m_p a_p\right)\sin(\gamma)$$

$$F_{y,DS} = -m_p\left(\alpha\frac{dx}{d\theta} + \omega^2\frac{d^2x}{d\theta^2}\right)\sin(\gamma) - g\left(m_1 + m_p\right)\cos(\gamma) + F_p\sin(\gamma)$$

$$M_{DS} = -I_{m_1}\alpha + \frac{dx}{d\theta}\left(F_p - g\sin(\gamma)\, m_p - m_p\left(\alpha\frac{dx}{d\theta} + \omega^2\frac{d^2x}{d\theta^2}\right)\right)$$

$$A_x = -\cos(\gamma)\left(m_p \frac{dx}{d\theta}\right) \tag{121}$$

$$B_x = -\cos(\gamma)\left(m_p \frac{d^2x}{d\theta^2}\right) \tag{122}$$

$$G_x = 0 \tag{123}$$

$$E_x = \cos(\gamma)\left(F_p\right) \tag{124}$$

$$A_y = -\sin(\gamma)\left(m_p \frac{dx}{d\theta}\right) \tag{125}$$

$$B_y = -\sin(\gamma)\left(m_p \frac{d^2x}{d\theta^2}\right) \tag{126}$$

$$G_y = g\left(m_1 + m_p\right) \tag{127}$$

$$E_y = \sin(\gamma)\left(F_p\right) \tag{128}$$

$$A_M = -I_{m_1} - m_p \left(\frac{dx}{d\theta}\right)^2 \tag{129}$$

$$B_M = -m_p \frac{dx}{d\theta}\frac{d^2x}{d\theta^2} \tag{130}$$

$$G_M = -g\sin(\gamma)\, m_p \frac{dx}{d\theta} \tag{131}$$

$$E_M = F_p \frac{dx}{d\theta} \tag{132}$$

Appendix B. Property Correlations, Surface Area & Resistance of Matrix Elements

Table 8.1: User inputs and correlations for various properties based on regenerator type. Correlations from (Gedeon, SAGE users manual [35]**).**

	Regenerator Type			
	Woven Screen	Random Fiber	Packed Sphere	Stacked Foil
Inputs	Porosity (β) Wire Diameter (d_o)	Porosity (β) Wire Diameter (d_o)	Porosity (β) Sphere Diameter (d_o)	Gap Width (l_g) Thickness (l_t) Roughness (l_r)
Hydraulic Diameter (d_h)	$\frac{d_o}{1-\beta}$	$\frac{d_o}{1-\beta}$	$\frac{d_o.\beta}{6(1-\beta)}$	$2l_g$
Laminar Friction Factor (N_f)	$\frac{129}{N_{Re}}+\frac{2.91}{N_{Re}^{0.103}}$	$\frac{25.7c+79.8}{N_{Re}}+\frac{0.146c+3.76}{N_{Re}^{0.00283c+0.0748}}+\frac{5.15}{N_{Re}^{0.137}}$	$\left(\frac{157}{N_{Re}}\right)\left(\frac{\beta}{0.39}\right)^{3.48}$	$\frac{96}{N_{Re}}$
Laminar Nusselt Number (N_{Nu})	$\left(1+0.99{N_{Pe}}^{0.66}\right)\beta^{1.79}$	$1+0.186c{N_{Pe}}^{0.55}$	$1+0.48{N_{Pe}}^{0.65}$	8.23
Laminar Conduction Enhancement Factor (N_k)	$1+\frac{{N_{Pe}}^{0.66}}{2\beta^{2.91}}$	$1+{N_{Pe}}^{0.55}$	$1+3{N_{Pe}}^{0.65}$	1
Turbulent Friction Factor (N_f)	---	---	---	$0.121\left(\frac{l_r}{d_h}+\frac{68}{N_{Re}}\right)^{0.25}$
Turbulent Nusselt Number (N_{Nu})	---	---	---	$0.025N_{Re}^{0.79}.N_{Pr}^{0.33}$
Turbulent Conduction	---	---	---	$0.022N_{Re}^{0.75}.N_{Pr}$

Enhancement Factor (N_k)			
Extra Equations:	$N_{Pe} = N_{Re}.N_{Pr}$	$c = \frac{\beta}{1-\beta}$	$\beta = \frac{l_g}{l_g + l_t}$

WOVEN SCREEN & RANDOM FIBER REGENERATORS

For a long cylindrical element

Surface Area = $2\pi rL$

Volume = $\pi r^2 L$

Average Radius = $\frac{\int_0^r 2\pi r^2 dr}{\pi r^2} = \frac{\frac{2}{3}\pi r^3}{\pi r^2} = \frac{2}{3}r$

Resistance from Surface to Average Radius = $\frac{\ln\left(\frac{r}{\frac{2}{3}r}\right)}{2\pi Lk} = \frac{\ln\left(\frac{3}{2}\right)}{2\pi Lk}$

Surface Area per unit Volume = $(1-\beta)\frac{2}{r} = 4\frac{(1-\beta)}{d_w}$

Resistance times Area = $\frac{\ln\left(\frac{3}{2}\right)r}{k} = \frac{\ln\left(\frac{3}{2}\right)d_w}{2k}$

PACKED SPHERE REGENERATORS

For spherical elements

Surface Area = $4\pi r^2$

Volume = $\frac{4}{3}\pi r^3$

Average Radius = $\frac{\int_0^r 4\pi r^3 dr}{\frac{4}{3}\pi r^3} = \frac{\frac{4}{4}\pi r^4}{\frac{4}{3}\pi r^3} = \frac{3}{4}r$

Resistance from Surface to Average Radius = $\frac{r\left(1-\frac{3}{4}\right)}{4\pi k\left(\frac{3}{4}\right)r^2} = \frac{1}{12\pi kr}$

Surface Area per unit Volume = $(1-\beta)\frac{4\pi r^2}{\frac{4}{3}\pi r^3} = 6\frac{(1-\beta)}{d_s}$

Resistance times Area = $\frac{4\pi r^2}{12\pi kr} = \frac{d_s}{6k}$

STACKED FOIL REGENERATORS

For Planar Elements

Surface Area = $2dxdy$

Volume = $dxdy(l_t + l_g)$

Average Radius = $\frac{1}{4}l_t$

Resistance from Surface to Average Radius = $\frac{\frac{1}{4}l_t}{k2dxdy} = \frac{l_t}{8kdxdy}$

Surface Area per unit Volume = $\frac{2}{l_t+l_g}$

Resistance times Area = $\frac{l_t 2dxdy}{8kdxdy} = \frac{l_t}{4k}$

Table 8.2: User inputs and correlations for various properties based on heat exchanger type: Fin Enhanced Surface, Fin Connected Channels. Correlations from [35] **unless otherwise indicated.**

	Heat Exchanger Type		
	Fin Enhanced Surface	Fin Connected Channels (Rectangular)	Fin Connected Channels (Triangular)
Inputs	Fin Separation (l_g) Fin Thickness (l_{th}) Roughness (l_r) Surface to build off of	Gas space between source channels ($l_{c,g}$) Source channel width ($l_{c,w}$) Source channel wall thickness ($l_{c,wth}$) Surface roughness (l_r) Base Width / Fin Separation ($l_{f,g}$) Fin Thickness (l_{th})	
Porosity (β)	$\frac{l_g}{l_g + l_{th}}$	$\frac{l_f}{l_f + l_{c,w}} \frac{l_{f,g}}{l_{f,g} + l_{th}}$	$\frac{l_{c,g}}{l_{c,g} + l_{c,w}} \frac{l_{f,g}}{l_{f,g} + l_{eff}}$
Hydraulic Diameter (d_h)	$\frac{2l_g}{1 + \frac{l_g}{l_f}}$	$\frac{2l_{f,g}}{1 + \frac{l_{f,g}}{l_f}}$	$\frac{0.5l_{f,g}}{1+\sqrt{1+\frac{1}{\tan^2 \Phi}}}$*
Laminar Friction Factor (N_f)	$\frac{-43.94\alpha^3+123.2\alpha^2-118.31\alpha+96}{N_{Re}}$*		$\frac{-6.1181\Phi^2+8.8371\Phi+49.433}{N_{Re}}$*
Laminar Nusselt Number (N_{Nu})	8.23		$2.66\theta\Phi^5 - 12.19\Phi^4 + 21.63\Phi^3 - 19.9\Phi^2 + 8.92\Phi + 0.956$**
Lam. Cond. Enhancement Factor (N_k)	1		
Turbulent Friction Factor (N_f)	$(-0.0086c^3 + 0.0223c^2 - 0.0247c + 0.121)\left(\frac{l_r}{d_h} + \frac{68}{N_{Re}}\right)^{0.25}$*		$(-0.0184\theta^2 + 0.0414\theta + 0.0847)\left(\frac{l_r}{d_h} + \frac{68}{N_{Re}}\right)^{0.25}$*
Turbulent Nusselt Number (N_{Nu})	$0.025N_{Re}^{0.79}.N_{Pr}^{0.33}$		$\frac{\left(\frac{N_f}{8}\right)N_{Re}.N_{Pr}}{1.07+12.7\left(N_{Pr}^{\frac{2}{3}}-1\right)\sqrt{\frac{N_f}{8}}}$***
Turbulent Conduction Enhancement Factor (N_k)	$0.022N_{Re}^{0.75}N_{Pr}$		
Extra Equations:	Depending on the orientation of the fin, Fin Length (l_f) is $\begin{cases} x_o - x_i \\ or \\ \min(y_{o\theta} - y_{i\theta}) \end{cases}$ $c = \min\left(\frac{l_f}{l_g}, \frac{l_g}{l_f}\right)$	$l_f = l_{c,g} - l_{th}$ $c = \min\left(\frac{l_{f,g}}{l_f}, \frac{l_f}{l_{f,g}}\right)$	$l_f = l_{c,g} - l_{th}$ $\Phi = \tan^{-1}\left(\frac{0.5l_{f,g}}{l_f}\right)$ $l_{eff} = \frac{l_{th}}{\cos(\Phi)}$

*Polynomial Fit to Table Data of weights [71] multiplied onto equation for circular pipe [35]
**Constant Wall Temperature inflow and peripheral directions [72]
***Gnielinski correlation [73]

Table 8.3: User inputs and correlations for various properties based on heat exchanger type: Tube and Plate Heat Exchangers.

	Continuously Finned
	Staggered – always turbulent
Inputs	Spacing Perpendicular to Flow (l_{perp}) Spacing Parallel to Flow (l_{para}) Fin Thickness (l_{th}) Fin Separation (l_g) Tube Outer Diameter (d_o) Tube Inner Diameter (d_i)
Porosity (β)	$\left(1-\frac{\frac{\pi}{4}d_o^2}{l_{perp}.l_{para}}\right)\left(\frac{l_g}{l_g+l_{th}}\right)$
Hydraulic Diameter (d_h)	$\frac{4\beta.l_{perp}.l_{para}.l_{th}.l_g}{\pi.d_o.l_g+2\left(l_{perp}.l_{para}-\pi.d_o\right)}$
Friction Factor (N_f)	$c_4'.N_{Re}^{-0.521}+c_5'\left(\frac{d_o}{d_h}.N_{Re}\right)^{-0.18}$ *
Nusselt Number (N_{Nu})	If $N_r \geq 4$ $0.14\left(\frac{l_{para}}{l_{perp}}\right)^{0.502}\left(\frac{l_g}{d_o}\right)^{0.031}N_{Re}^{0.672}.N_{Pr}^{0.333}$ * Else $c_2.N_{Re}^{c_3}.N_{Pr}^{0.333}$ *
Conduction Enhancement Factor (N_k)	1
Extra Equations:	$N_r = \frac{\text{total streamwise distance}}{l_{para}}$ $c_1 = 0.14\left(\frac{l_{para}}{l_{perp}}\right)^{0.502}\left(\frac{l_g}{d_o}\right)^{0.031}$ $c_2 = c_1 0.991\left(2.24\left(\frac{4}{N_r}\right)^{0.031}\right)^{(-0.607(4-N_r))}$ $c_3 = 1+(-0.092*0.607(4-N_r)-0.328$ $c_4 = \frac{S_f}{S_{tube}+S_f}$ $c_5 = (1-c_4)(1-\beta_f)$ $c_4' = 2.032c_4\left(\frac{l_{para}}{d_o}\right)^{1.318}$ $c_5' = 4c_5\left[\left(\frac{l_{perp}}{l_{para}}\right)^2 \quad \frac{l_{perp}}{l_{para}} \quad 1\right]\begin{bmatrix}-0.108 & 0.730 & -0.213\\ 0.314 & -1.296 & 0.561\\ -0.234 & 1.034 & -0.747\end{bmatrix}.\left[\left(\frac{l_{para}}{d_o}\right)^2 \quad \frac{l_{para}}{d_o} \quad 1\right]$**

* [74]

** Combined formula of [74], with component representing pressure drop of bare staggered tube banks derived from data of [75].

Table 8.4: User inputs and correlations for various properties based on heat exchanger type: Individually Finned Tube Heat Exchangers.

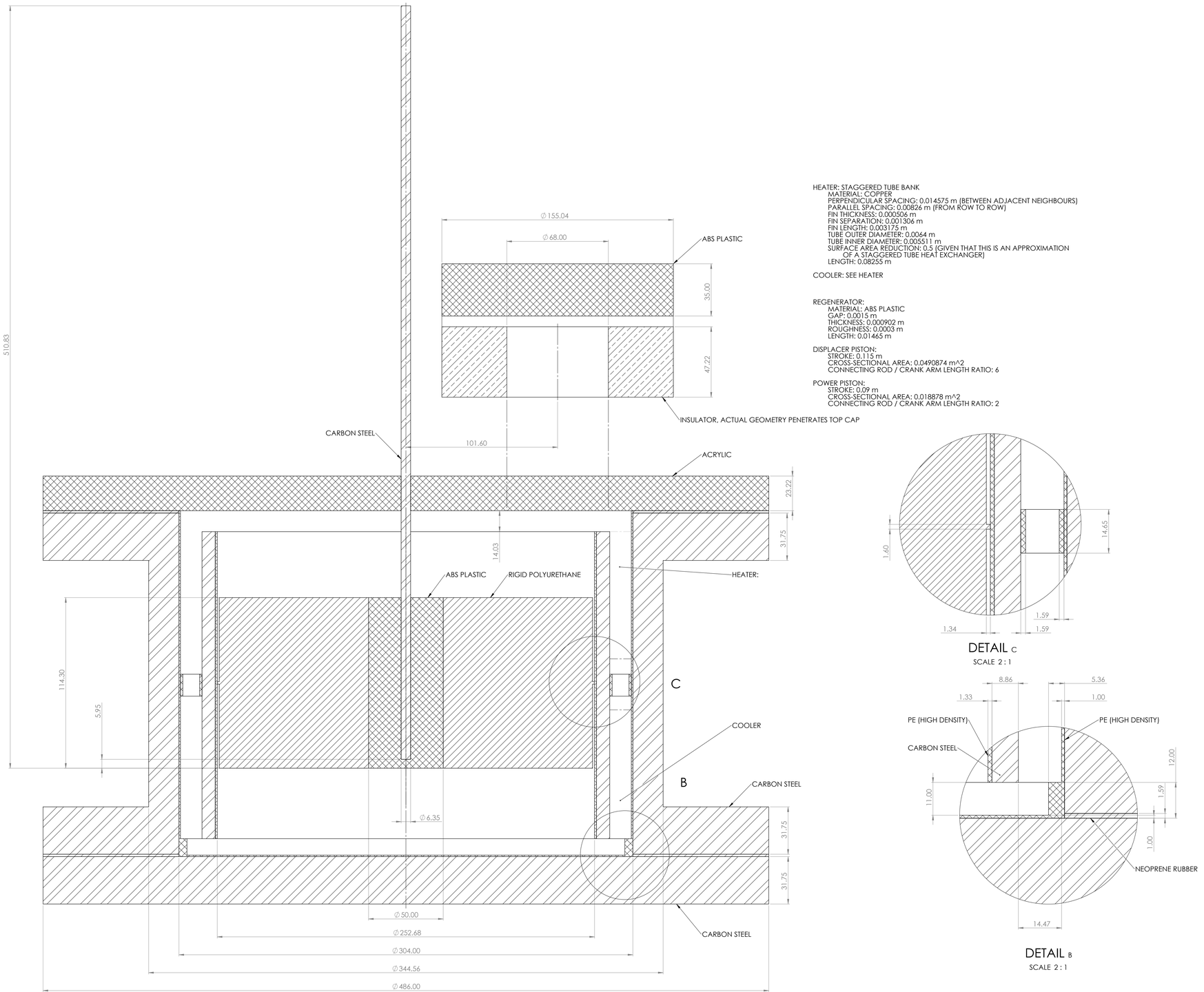
	Individually Finned
	Staggered
Inputs	Fin Length (l_f)
Porosity (β)	$1-\pi\dfrac{\left(\frac{d_o}{2}+l_f\right)^2-\left(\frac{l_g}{l_{th}+l_g}\right)\left(\left(\frac{d_o}{2}+l_f\right)^2-\left(\frac{d_o}{2}\right)^2\right)}{l_{perp}.l_{para}}$
Hydraulic Diameter (d_h)	$\dfrac{4\beta.l_{perp}.l_{para}.l_{th}.l_g}{\pi.d_o.l_g+2\pi\left(\left(\frac{d_o}{2}+l_f\right)^2-\left(\frac{d_o}{2}\right)^2\right)+\pi.l_f(d_o+l_f)}$
Laminar Friction Factor (N_f)	Assumed to be always turbulent
Laminar Nusselt Number (N_{Nu})	Assumed to be always turbulent
Laminar Conduction Enhancement Factor (N_k)	$1+0.5(0.5113^{-2.91}(N_{Re}N_{Pr})^{0.66})$
Turbulent Friction Factor (N_f)	If $l_f/d_o<0.09$ (Low Finned Tubes) $\dfrac{4\left(1.748\left(\frac{l_f.d_o}{lg.lpara}\right)^{0.1738}\left(\frac{d_o}{lperp}\right)^{0.599}\right)}{N_{Re}^{0.233}}$* Else (High Finned Tubes) $\dfrac{4\left(9.465\left(\frac{d_o}{l_{perp}}\right)^{0.927}\left(\frac{l_{perp}}{\sqrt{l_{perp}^2+l_{para}^2}}\right)^{0.515}\right)}{N_{Re}^{0.316}}$**
Turbulent Nusselt Number (N_{Nu})	If $l_f/d_o<0.09$ (Low Finned Tubes) $0.255\left(\frac{2l_f+d_o}{l_g}\right)N_{Re}^{0.7}.N_{Pr}^{0.333}$*** Else (High Finned Tubes) $0.134\left(\frac{l_g}{l_f}\right)^{0.2}\left(\frac{l_g}{l_{th}}\right)^{0.11}N_{Re}^{0.681}.N_{Pr}^{0.333}$**
Turbulent Conduction Enhancement Factor (N_k)	1

* Chai [76]
** Webb [74]
*** Ganguli & Yilmaz [77]

Table 8.5: User inputs and correlations for various properties based on heat exchanger type: Bare Tube Banks (internal). Correlations from [35] **unless otherwise indicated.**

	Bare Tube Banks (internal)
	Staggered
Inputs	Tube Spacing ($l_{tube,s}$) (Circle Packed Arrangement) Tube Outer Diameter (d_o) Tube Inner Diameter (d_i)
Porosity (β)	$\frac{\pi . d_i^2}{\sqrt{3} l_{tube,s}^2}$
Hydraulic Diameter (d_h)	d_i
Laminar Friction Factor (N_f)	$\frac{64}{N_{Re}}$
Laminar Nusselt Number (N_{Nu})	6.0
Laminar Conduction Enhancement Factor (N_k)	1
Turbulent Friction Factor (N_f)	$0.11\left(\frac{\epsilon}{d_h}+\frac{68}{N_{Re}}\right)^{0.25}$
Turbulent Nusselt Number (N_{Nu})	$0.036\left(\frac{L}{d_h}\right)^{-0.055} N_{Re}^{0.8} . N_{Pr}^{0.33}$
Turbulent Conduction Enhancement Factor (N_k)	$0.022 N_{Re}^{0.75} . N_{Pr}$

Appendix C. EP-1 Geometry



HEATER: STAGGERED TUBE BANK
- MATERIAL: COPPER
- PERPENDICULAR SPACING: 0.014575 m (BETWEEN ADJACENT NEIGHBOURS)
- PARALLEL SPACING: 0.00826 m (FROM ROW TO ROW)
- FIN THICKNESS: 0.000506 m
- FIN SEPARATION: 0.001306 m
- FIN LENGTH: 0.003175 m
- TUBE OUTER DIAMETER: 0.0064 m
- TUBE INNER DIAMETER: 0.005511 m
- SURFACE AREA REDUCTION: 0.5 (GIVEN THAT THIS IS AN APPROXIMATION OF A STAGGERED TUBE HEAT EXCHANGER)
- LENGTH: 0.08255 m

COOLER: SEE HEATER

REGENERATOR:
- MATERIAL: ABS PLASTIC
- GAP: 0.0015 m
- THICKNESS: 0.000902 m
- ROUGHNESS: 0.0003 m
- LENGTH: 0.01465 m

DISPLACER PISTON:
- STROKE: 0.115 m
- CROSS-SECTIONAL AREA: 0.0490874 m^2
- CONNECTING ROD / CRANK ARM LENGTH RATIO: 6

POWER PISTON:
- STROKE: 0.09 m
- CROSS-SECTIONAL AREA: 0.018878 m^2
- CONNECTING ROD / CRANK ARM LENGTH RATIO: 2

DETAIL C
SCALE 2 : 1

DETAIL B
SCALE 2 : 1

Appendix D. Motion Profile Mathematics for EP-1 Studies

For all elliptical profiles the following equations convert the number of lobes (n) and the Elliptical Factor (e) and lobe phase (ϕ_{lobe}) into the resulting series of angles for input into the attached slider crank.

$$C = \frac{\sqrt{1 + (n^2 - 1)(1 - e^2)} + e}{n(1 - e)}$$

$$\theta' = \text{atan}\big(C.tan\big(\theta + \phi_{off}\big)\big) + \phi_{lobe}$$

For all of the following profiles the conversion of the translated angle is as follows. This converts it into the distorted harmonic motion produced by slider crank mechanisms.

$$\theta_2' = \text{asin}\left(-\frac{l_{cr}\sin(\theta')}{l_{con}}\right)$$

$$x = l_{con}(\cos(\theta_2') - 1) + l_{cr}(\cos(\theta') + 1)$$

The final profile is shifted numerically post calculation.

Motion	Number of Lobes (n)	Elliptical Factor (e)	Phase Shift (ϕ_{off})	Lobe Phase (ϕ_{lobe})
Sinusoidal	1	0	0	0
1/5 Elliptical for Square Wave	2	0.2	$\frac{\pi}{2}$	$\frac{\pi}{2}$
1/5 Elliptical for Saw Wave	2	0.2	π	0
Extreme Square Wave	2	0.8	$\frac{\pi}{2}$	$\frac{\pi}{2}$
Extreme Saw Wave	Due to the extreme necking that occurs with a highly elliptical set of gears set into the saw wave configuration, a synthesized version was created, which was originally seeded as a pure saw wave, followed by several iterations of smoothing filter.			

The Extreme Saw Wave is defined by a smoothed and normalized saw wave to avoid the extreme necking that occurs when a saw wave is constructed from a set of highly elliptical gears. The non-phase-shifted profiles are displayed below.

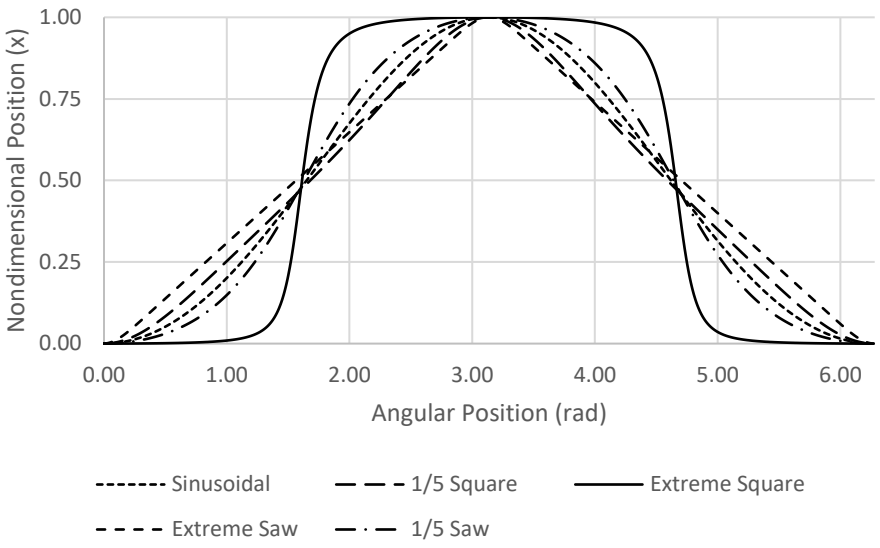


Figure D.1: Different motion profiles tested – using a connecting arm to crank arm ratio of 6.

When the mechanism orientation is stated as downwards the profile will appear inverted as well.

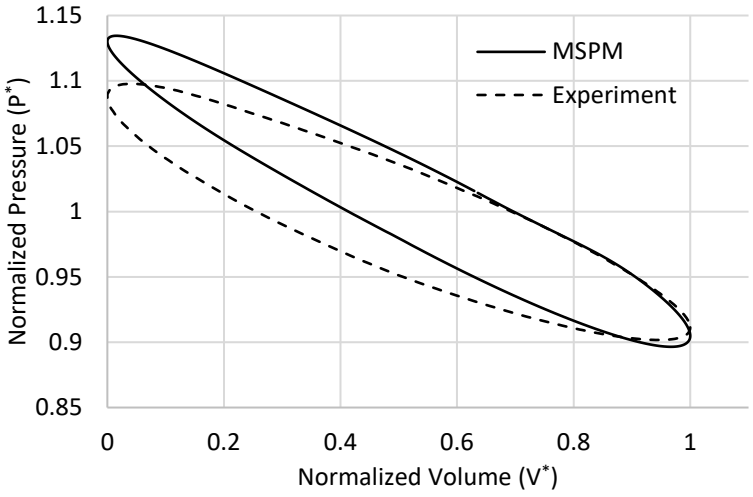
Appendix E. EP-1 Studies PV Diagrams

Included in the power curves produced for each mechanical arrangement, a series of simulations were taken to line up with experiments conducted by Nicol-Seto [61]. These test cases and the simulation-experiment percent error are as follows. The percent error is calculated by comparing the area under the curve associated with the power piston, that is, the pressure measured at the power piston, plotted against the volume of the power piston.

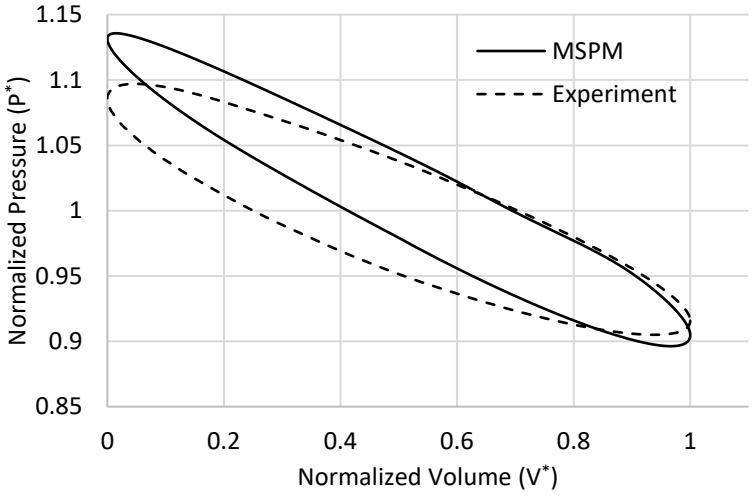
Test #	Gearing (DP, PP)	Speed (Hz)	Exp. Normalized Cycle Energy	MSPM: Normalized Cycle Energy	Power Piston PV error (%)
1	Sinusoidal Sinusoidal	1.1055	11.01	8.21	25.4%
2		1.5257	11.26	8.27	26.6%
3		1.8735	11.57	7.83	32.3%
4		2.2606	12.01	8.13	32.3%
5	1/5 Elliptical for Square Wave Sinusoidal	0.582	10.21	8.14	20.3%
6		0.8818	10.65	8.21	22.9%
7		1.2407	10.89	8.24	24.3%
8		1.6444	11.43	7.46	34.7%
9	1/5 Elliptical for Square Wave 1/5 Elliptical for Square Wave	0.5558	11.45	7.79	32.0%
10		0.9051	12.24	7.80	36.3%
11		1.1992	12.54	7.83	37.6%
12		1.5825	13.05	7.43	43.1%

The following plots include the simulated as well as experimental PV diagrams for the 12 tests.

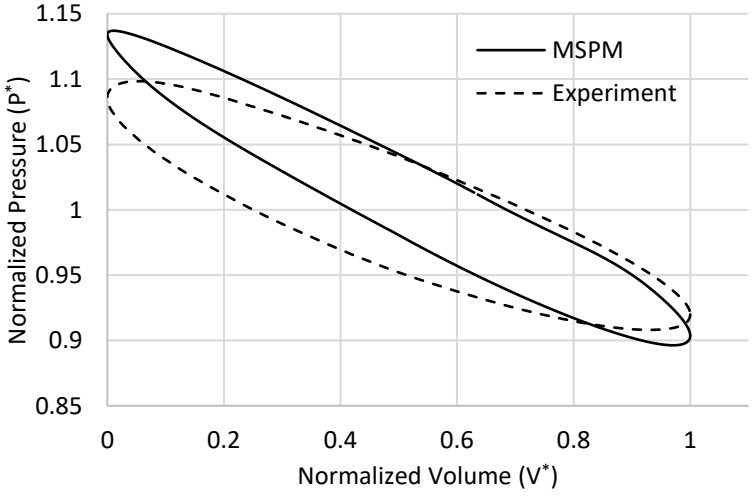
Test 1:



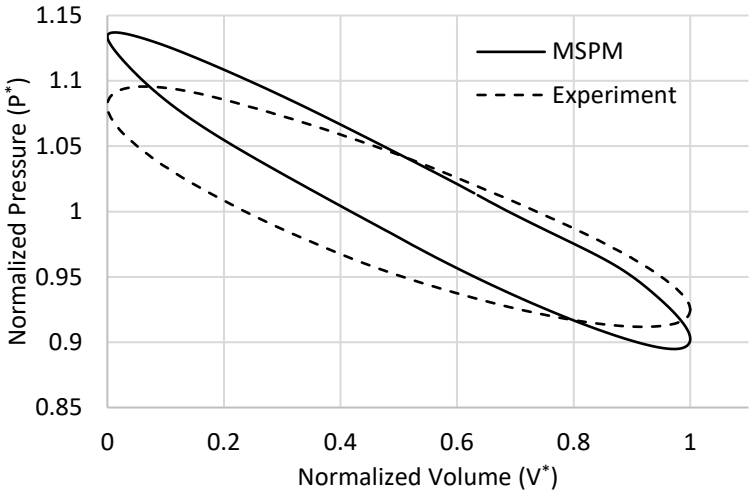
Test 2:



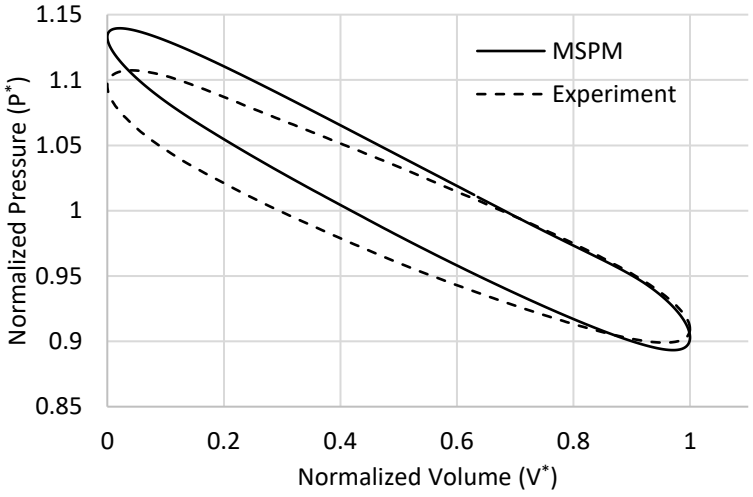
Test 3:



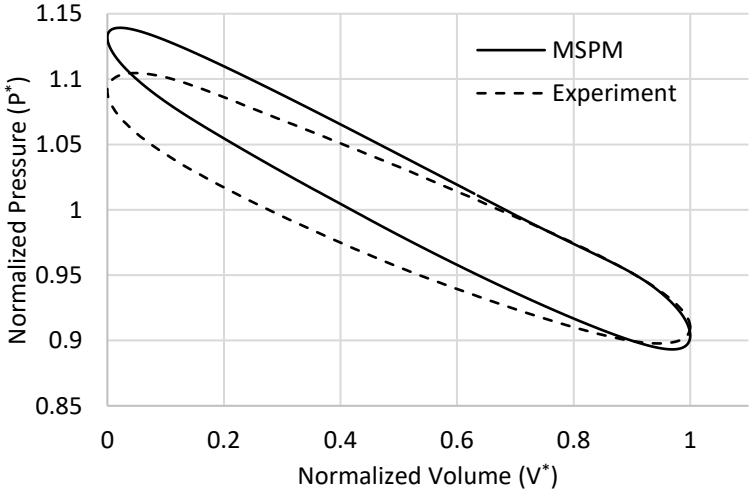
Test 4:



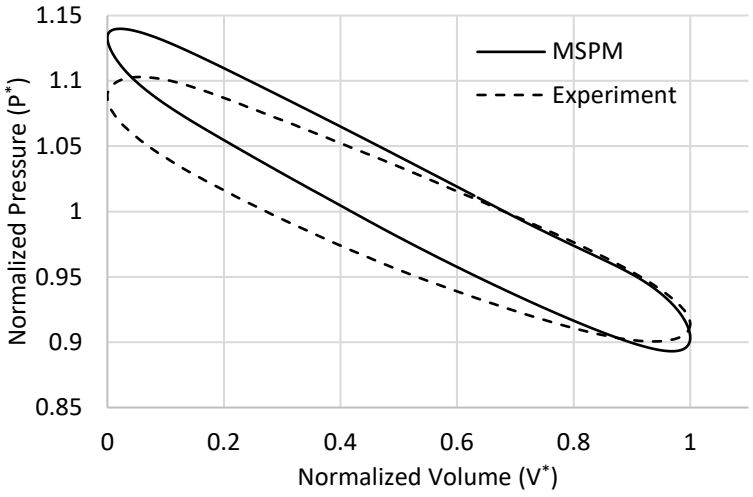
Test 5:



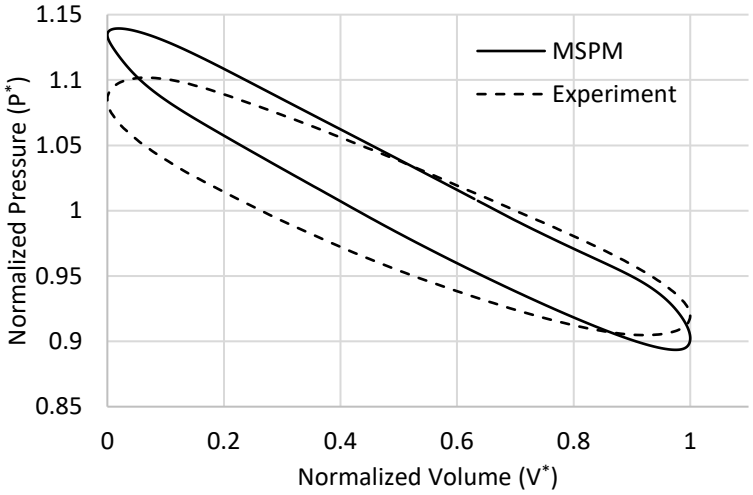
Test 6:



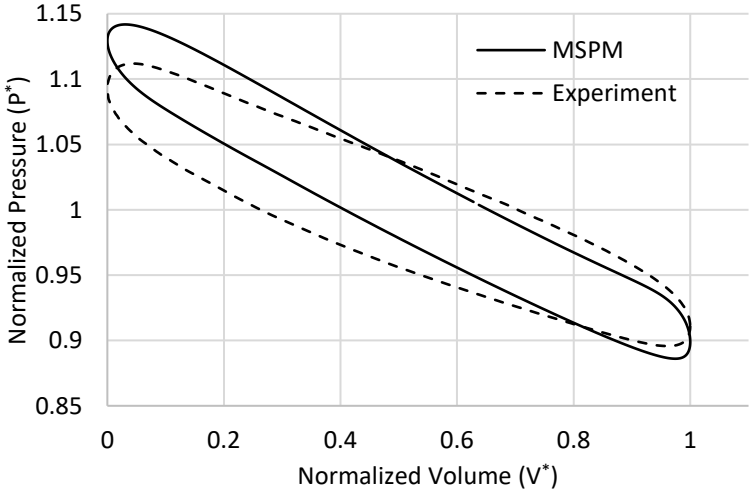
Test 7:



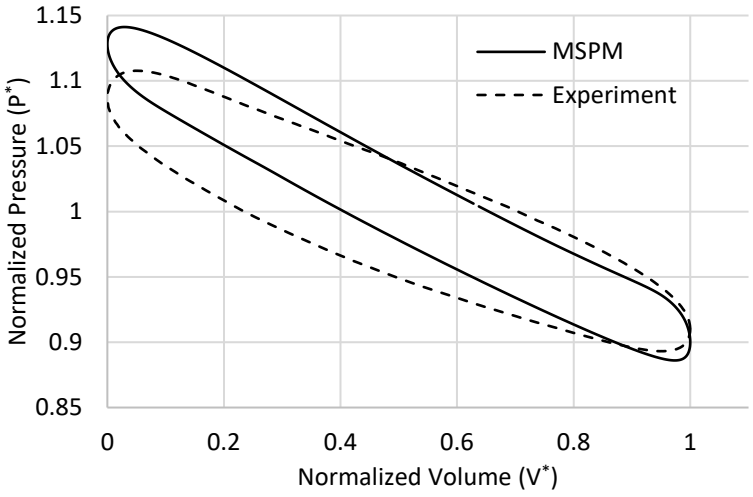
Test 8:



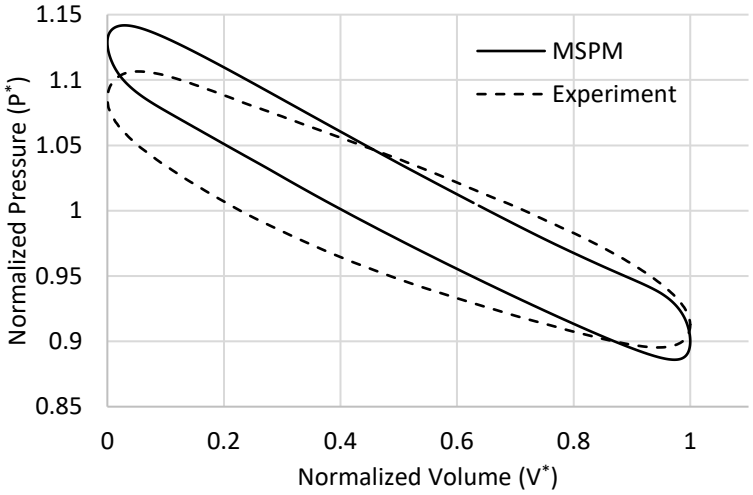
Test 9:



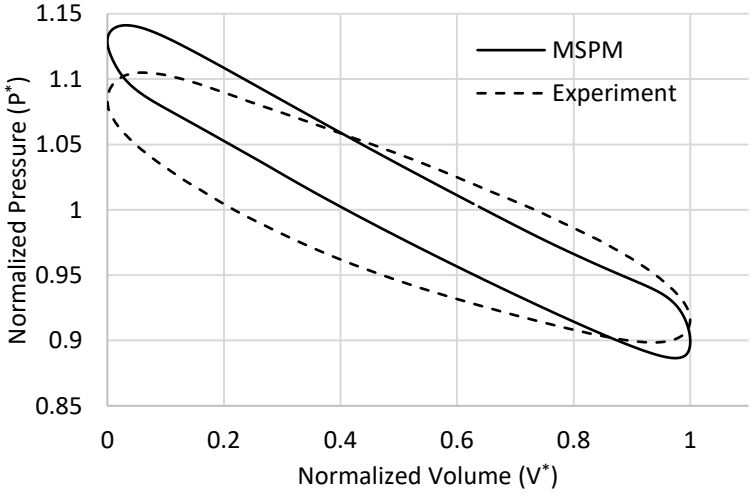
Test 10:



Test 11:



Test 12:



Appendix F. Mesh Sensitivity

G.1. EPM-1 Model

A correctly performed mesh independency test should capture a series of tests in which the model decays on a predictable, mono-directional rate towards the exact value (given the assumptions made to construct the model). Sensitivity of the results on the mesh are plotted on Figure G.1.

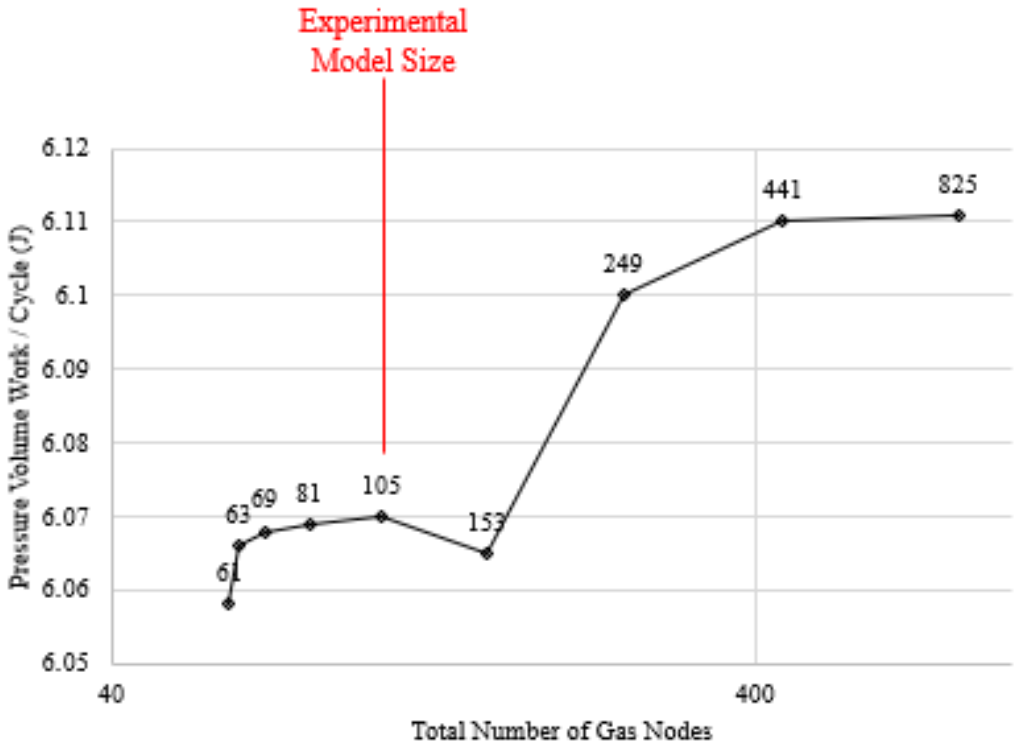


Figure G.1: Sensitivity of indicated cycle energy on Test Set 1 at 1 Hz

The amount of error between the highest mesh size and the mesh which was used for the experiments is equal to 0.8%. The final order of convergence, p, is equal to 3.84. This is calculated via the following formula:

$$p = \frac{\ln\left(\frac{y_N - y_{N-1}}{y_{N-1} - y_{N-2}}\right)}{\ln\left(\frac{x_{N-1}}{x_N}\right)} = 3.84$$

A value in the range of 3 would be expected, given that MSPM uses a 3rd order polynomial for interpolation.

Appendix G. MATLAB CODE

The MATLAB code can found in this appendix or hosted on GITHUB.

G.1. GUI

Simulation Interface V5

The following code is the main GUI of the software, this is paired with the actual controls which are stored as a .fig file. There are several main sections of this code:

1. Required Header Components

2. Insert, Select, Delete and Animate buttons, which all use the “GUI_ButtonDownFcn” under different modes to provide different functionality.

3. Green Highlighting of active buttons and initialization of the modes is handled by ButtonCore

4. Save, Load Functionality

5. Show Option set of functions

6. Box & Recenter Zooms

7. Recording & Animation Options

8. Other Simulation Options

9. Run Options (Run & Run Test Set)

```
function varargout = SimulationInterfaceV5(varargin)
% SIMULATIONINTERFACEV5 MATLAB code for SimulationInterfaceV5.fig
%      SIMULATIONINTERFACEV5, by itself, creates a new SIMULATIONINTERFACEV5 or raises the
existing
%      singleton*.
%
%      H = SIMULATIONINTERFACEV5 returns the handle to a new SIMULATIONINTERFACEV5 or the handle
to
%      the existing singleton*.
%
%      SIMULATIONINTERFACEV5('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in SIMULATIONINTERFACEV5.M with the given input arguments.
%
%      SIMULATIONINTERFACEV5('Property','Value',...) creates a new SIMULATIONINTERFACEV5 or
raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before SimulationInterfaceV5_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to SimulationInterfaceV5_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help SimulationInterfaceV5

% Last Modified by GUIDE v2.5 16-Oct-2020 09:07:43

% Begin initialization code - DO NOT EDIT
```

```
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
    'gui_Singleton',  gui_Singleton, ...
    'gui_OpeningFcn', @SimulationInterfaceV5_OpeningFcn, ...
    'gui_OutputFcn',  @SimulationInterfaceV5_OutputFcn, ...
    'gui_LayoutFcn',  [] , ...
    'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before SimulationInterfaceV5 is made visible.
function SimulationInterfaceV5_OpeningFcn(hObject, ~, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to SimulationInterfaceV5 (see VARARGIN)

% UIWAIT makes SimulationInterfaceV5 wait for user response (see UIRESUME)
% uiwait(handles.figure1);

%% Choose default command line output for SimulationInterfaceV5
handles.output = hObject;

%% Generate space for mouse events
handles.MODE = '';
handles.SelectCon = Connection.empty;
handles.IndexC = 1;
handles.SelectBod = Body();
handles.IndexB = 1;
handles.SelectGroup = Group.empty;
handles.IndexG = 1;

%% Set Initial Values for Display Options
handles.InterGroupDistance = 0.05;
handles.ClickTolerance = 0.1;

%% Generate Default Model
handles.Model = Model();
handles.Model.AxisReference = handles.GUI;
handles.corner_points = [];
handles.SimulationParameters = cell(0);
DistributeGroup(handles);
show_Model(handles);

%% Object Properties
handles.SData = SelectionListData();
handles.SData.Code = '';
handles.SData.ListObjs = ListObj.empty;
handles.DropDownMode = '';
updateSelectionList(handles);

%% Optimization Stuff
handles.OptimizationStudyIndex = 0;

%% Show Options
set(handles.showGroups,'Value',handles.Model.showGroups);
set(handles.showBodies,'Value',handles.Model.showBodies);
set(handles.showConnections,'Value',handles.Model.showConnections);
set(handles.showLeaks,'Value',handles.Model.showLeaks);
set(handles.showBridges,'Value',handles.Model.showBridges);
set(handles.showInterConnections,'Value',handles.Model.showInterConnections);
set(handles.showEnvironmentConnections,'Value',handles.Model.showEnvironmentConnections);
```

```
set(handles.showNodes,'Value',handles.Model.showNodes);
set(handles.showSensors,'Value',handles.Model.showSensors);
set(handles.showRelations,'Value',handles.Model.showRelations);
set(handles.RelationMode,'String','On')
handles.Model.RelationOn = true;

%% Update handles structure
guidata(hObject, handles);

% --- Outputs from this function are returned to the command line.
function varargout = SimulationInterfaceV5_OutputFcn(hObject, ~, handles) %#ok<INUSL>
% Get default command line output from handles structure
varargout{1} = handles.output;

%% General button codes
function GUI_ButtonDownFcn(hObject, ~, h)
C = get(hObject,'Currentpoint');
C = C(1,1:2);
if isempty(h.Model.ActiveGroup)
    % Select the group based on where the user clicked
    h.Model.FindGroup(C);
end
switch h.MODE
    case 'InsertBody'
        % Select 4 connections
        switch get(gcf,'SelectionType')
            case 'normal'
                L = true;
            case 'alt'
                L = false;
            case 'extend'
                L = false;
            otherwise
                L = true;
        end
        found = false;
        %% Get round specific information
        switch h.IndexC
            case 1
                DIR = enumOrient.Vertical;
                prompt = 'New Body Inner Radius 1: ';
                OFFSET = 0;
            case 2
                OFFSET = h.SelectCon(1).x;
                if h.SelectCon(1).Orient == enumOrient.Vertical
                    DIR = enumOrient.Vertical;
                    prompt = 'New Body Radial Thickness: ';
                else
                    DIR = enumOrient.Horizontal;
                    prompt = 'New Body Vertical Thickness: ';
                end
            case 3
                OFFSET = 0;
                if h.SelectCon(2).Orient == enumOrient.Vertical
                    DIR = enumOrient.Horizontal;
                    prompt = 'New Body Lower Vertical Position: ';
                else
                    DIR = enumOrient.Vertical;
                    prompt = 'New Body Inner Radius: ';
                end
            case 4
                OFFSET = h.SelectCon(3).x;
                if h.SelectCon(2).Orient == enumOrient.Vertical
                    DIR = enumOrient.Horizontal;
                    prompt = 'New Body Thickness: ';
                else
                    DIR = enumOrient.Vertical;
                    prompt = 'New Body Radial Thickness: ';
                end
            otherwise % We are done here
                found = true;
```

```
end

%% Find connection at click
if L && found == false % Left Click
    if h.IndexC == 1
        h.SelectCon(h.IndexC) = ...
            h.Model.ActiveGroup.FindConnection(C);
        found = true;
        fprintf(['Selected Connection: ' ...
            h.SelectCon(h.IndexC).name '.\n']);
    else
        Con = h.Model.ActiveGroup.FindConnection(...
            C,DIR,h.SelectCon(h.IndexC-1));
        if ~isempty(Con)
            h.SelectCon(h.IndexC) = Con;
            fprintf(['Selected Connection: ' ...
                h.SelectCon(h.IndexC).name '.\n']);
            found = true;
        else
            found = false;
        end
    end
end

%% Get user Input
if found == false
    % Get User Radius Submission
    DIM = '';
    while ~isnumeric(DIM)
        answer = inputdlg(prompt,'Specify Dimension Window');
        if ~isempty(answer)
            DIM = str2double(answer{1});
        else
            return;
        end
    end
    % If this does not match any Group Connection then CreateNew
    found = false;
    for iCon = h.Model.ActiveGroup.Connections
        if iCon.Orient == DIR && iCon.x == DIM+OFFSET
            h.SelectCon(h.IndexC) = iCon;
            found = true;
        end
    end
    if ~found
        h.SelectCon(h.IndexC) = Connection(DIM+OFFSET,DIR,h.Model.ActiveGroup);
    end
end

%% Iterate or finish up
if h.IndexC == 4
    % Define the body
    matl = [];
    show_Model(h);
    while isempty(matl)
        [matl, tf] = listdlg(...
            'PromptString','Select a material type for this new body:',...
            'SelectionMode','single',...
            'ListString',Material.Source);
    end
    if tf
        newBody = Body(...
            h.Model.ActiveGroup,...
            h.SelectCon,...
            Material(Material.Source{matl}));
%             if handles.Model.ActiveGroup.isOverlaping(newBody)
%                 fprintf('XXX New Body overlaps, creation cancelled XXX\n');
%                 handles.Model.clearHighLighting();
%             else
                h.Model.ActiveGroup.addBody(newBody);
%             end
```

```
            else
                fprintf('XXX You must select a material, creation cancelled XXX\n');
                h.Model.clearHighLighting();
            end
            h.IndexC = 1;
        else
            h.Model.HighLight(h.SelectCon(1:h.IndexC));
            h.IndexC = h.IndexC + 1;
        end
    case 'InsertGroup'
        % Will simply define a vertical Group at the next slot
        % Determine where the user clicked
        C = get(gca,'Currentpoint'); C = C(1,1:2);
        h.Model.addGroup(Group(h.Model,Position(C(1),0,pi/2),[]));
        h.Model.distributeGroup(h.InterGroupDistance);
    case 'InsertBridge'
        % Select 2 horizontal connections and 2 bodies
        if h.IndexC == 1
            if h.IndexB == 1
                % Picking the first Connection
                if isempty(h.Model.ActiveGroup)
                    ChangeGroup_Callback(hObject, [], h);
                end
                Con = h.Model.ActiveGroup.FindConnection(C);
                if ~isempty(Con)
                    h.SelectCon(h.IndexC) = Con;
                    h.Model.HighLight(Con);
                    h.IndexC = 2;
                    set(h.message,'String','[click] Select the Foundation Body');
                end
            end
        elseif h.IndexC == 2
            if h.IndexB == 1
                % Picking the first Body
                Bod = h.SelectCon(1).findConnectedBody(C);
                if ~isempty(Bod)
                    h.SelectBody(h.IndexB) = Bod;
                    h.Model.HighLight(Bod);
                    h.IndexB = 2;
                    set(h.message,'String','[click] Select the Connection for the other body (the
Body that may shift)');
                end
            else
                % Picking the second Connection
                ChangeGroup_Callback(hObject, [], h);
                Con = h.Model.ActiveGroup.FindConnection(C);
                if ~isempty(Con)
                    h.SelectCon(h.IndexC) = Con;
                    h.Model.HighLight(Con);
                    h.IndexC = 3;
                    set(h.message,'String','[click] Select the associated body');
                end
            end
        else
            if h.IndexB == 2
                % Picking the second Body
                Bod = h.SelectCon(2).findConnectedBody(C);
                if ~isempty(Bod)
                    % Finish and Create
                    if h.SelectCon(1).Orient == h.SelectCon(2).Orient
                        if h.SelectCon(1).Orient == enumOrient.Vertical
                            prompt = 'Select the height adjustment for body 2 as it is placed
around body 1';
                            [~,~,defaultval,~] = h.SelectBody(1).limits(enumOrient.Vertical);
                        else
                            prompt = 'Select the radial offset distance';
                            defaultval = 0;
                        end
                    else
                        prompt = 'Select the vertical center offset for the horizontal face to be
up the vertical face';
```

```
                        if h.SelectCon(1).Orient == enumOrient.Vertical
                            [~,~,defaultval,~] = h.SelectBody(1).limits(enumOrient.Vertical);
                        else
                            [~,~,defaultval,~] = h.SelectBody(2).limits(enumOrient.Vertical);
                        end
                    end
                    x = inputdlg(prompt,'Specify Bridge Offset',[1 35],{num2str(defaultval)});
                    % Define the Bridge
                    if ~isempty(x)
                        h.SelectBody(h.IndexB) = Bod;
                        h.Model.HighLight(Bod);
                        h.Model.addBridge(Bridge(...
                            h.SelectBody(1),h.SelectBody(2),...
                            h.SelectCon(1),h.SelectCon(2),str2double(x{1})));
                        h.IndexC = 1;
                        h.IndexB = 1;
                        set(h.message,'String','---');
                    end
                end
            end
        end
    case 'InsertLeakConnection'
        % Select 2 horizontal connections and 2 bodies/Environments
    case 'InsertSensor'
        % Select a group
        C = C(1,1:2);
        % Select a body
        [~, objects] = h.Model.findNearest(C,h.ClickTolerance);
        if ~isempty(objects)
            for obj = objects
                if isa(obj{1},'Body')
                    h.Model.HighLight(obj{1});
                    h.Model.addSensor(Sensor(h.Model,obj{1}));
                end
            end
        end
    case 'InsertPVoutput'
        % Find, within a radius of confidence, the nearest Body
        C = C(1,1:2);
        [~, objects] = h.Model.findNearest(C,h.ClickTolerance);
        if ~isempty(objects)
            for obj = objects
                if isa(obj{1},'Body')
                    if obj{1}.matl.Phase == enumMaterial.Gas
                        h.Model.addPVoutput(PVoutput(obj{1}));
                        set(h.message,'String',['PVoutput added to Body: ' obj{1}.name]);
                    else
                        set(h.message,'String','Must select a Gas Body');
                    end
                end
            end
        end
    case 'InsertNonConnection'
        % Select 2 horizontal connections and 2 bodies
        Bod = Body.empty;
        if h.IndexB == 1
            % Picking the first Body
            [~, objects] = h.Model.findNearest(C,h.ClickTolerance);
            for obj = objects; if isa(obj{1},'Body'); Bod = obj{1}; break; end; end
            if ~isempty(Bod)
                h.SelectBody(h.IndexB) = Bod;
                h.Model.HighLight(Bod);
                h.IndexB = 2;
                set(h.message,'String','[click] Select the second body, or click in open space to
select the environment');
            end
        elseif h.IndexB == 2
            % Picking the first Body
            [~, objects] = h.Model.findNearest(C,h.ClickTolerance);
            for obj = objects; if isa(obj{1},'Body'); Bod = obj{1}; break; end; end
            if Bod ~= h.SelectBody(1)
```

```
            if ~isempty(Bod)
                h.SelectBody(h.IndexB) = Bod;
                h.Model.HighLight(Bod);
                set(h.message,'String','---');
                h.Model.addNonConnection(...
                    NonConnection(h.SelectBody(1),h.SelectBody(2)));
            end
            return;
        end
        % No object was selected, select the environment instead
        set(h.message,'String','---');
        h.Model.addNonConnection(...
            NonConnection(h.SelectBody(1),h.Model.Surroundings));
    end
case 'InsertCustomMinorLoss'
    % Find, within a radius of confidence, the nearest body
    C = C(1,1:2);
    [~, objects] = h.Model.findNearest(C,h.ClickTolerance);
    if ~isempty(objects)
        for obj = objects
            if isa(obj,'Body')
                h.SelectBody(h.IndexB) = obj;
                if (h.IndexB == 2)
                    % Finalize Custom Minor Loss
                    h.IndexB = 1;
                    h.Model.AddCustomMinorLoss(...
                        CustomMinorLoss(...
                        h.SelectBody(1),...
                        h.SelectBody(2)));
                end
                h.IndexB = 2;
            end
        end
    end
case 'Select'
    % Find, within a radius of confidence, the nearest...
    %   Body, Group, Connection, Bridge and Leak Connection
    C = C(1,1:2);
    [names, objects] = h.Model.findNearest(C,h.ClickTolerance);
    if ~isempty(names)
        if length(names) > 1
            [index,tf] = listdlg(...
                'PromptString','Which Object did you select?',...
                'ListString',names,...
                'SelectionMode','single',...
                'ListSize',[400 100]);
        else
            index = 1;
            tf = true;
        end
        if tf
            h.Model.switchHighLighting(objects{index});
        end
    end
case 'MultiSelect'
    % Find, within a radius of confidence, the nearest...
    %   Body, Group, Connection, Bridge and Leak Connection
    C = C(1,1:2);
    [names, objects] = h.Model.findNearest(C,h.ClickTolerance);
    if ~isempty(names)
        if length(names) > 1
            [index,tf] = listdlg(...
                'PromptString','Which Object did you select?',...
                'ListString',names,...
                'SelectionMode','single',...
                'ListSize',[400 100]);
        else
            index = 1;
            tf = true;
        end
        if tf
```

```
            h.Model.HighLight(objects{index});
        end
    end
case 'InsertRelation'
    % Find, within a radius of confidence, the nearest connection
    C = C(1,1:2);
    [~, objects] = h.Model.findNearest(C,h.ClickTolerance);
    if ~isempty(objects)
        for objcll = objects
            obj = objcll{1};
            if isa(obj,'Connection')
                if h.IndexC == 1 || ...
                        (obj.Orient == h.SelectCon(1).Orient && ...
                        obj.Group == h.SelectCon(1).Group)
                    h.SelectCon(h.IndexC) = obj;
                    if (h.IndexC == 2)
                        % Finalize the new relation
                        % Ask the user about the type
                        names = {
                            'Constant Offset', ...
                            'Cross-Section Maintaining', ...
                            'Zero x Based Scale', ...
                            'Smallest x Based Scale', ...
                            'Width Set'};
                        if obj.Orient == enumOrient.Horizontal
                            names{end+1} = 'Defines Stroke Length';
                            names{end+1} = 'Defines Piston Length';
                        end
                        for RMan = obj.Group.RelationManagers
                            if RMan.Orient == obj.Orient; break; end
                        end
                        if ~isempty(RMan)
                            [Type, tf] = listdlg(...
                               'PromptString','What type of relationship?',...
                               'ListString',names,...
                               'SelectionMode','single',...
                               'ListSize',[400 100]);
                           switch names{Type}
                               case 'Constant Offset'
                                   EnumType = enumRelation.Constant;
                               case 'Cross-Section Maintaining'
                                   EnumType = enumRelation.AreaConstant;
                               case 'Zero x Based Scale'
                                   EnumType = enumRelation.Scaled;
                               case 'Smallest x Based Scale'
                                   EnumType = enumRelation.LowestScaled;
                               case 'Width Set'
                                   EnumType = enumRelation.Width;
                               case 'Defines Stroke Length'
                                   EnumType = enumRelation.Stroke;
                               case 'Defines Piston Length'
                                   EnumType = enumRelation.Piston;
                           end
                           if tf
                               Label = RMan.getLabel(EnumType, ...
                                   h.SelectCon(1), h.SelectCon(2));
                               if isempty(Label)
                                   Label = getProperName([names{Type} ' Relation']);
                               end
                               if isempty(Label); return; end
                               if EnumType == enumRelation.Stroke || ...
                                       EnumType == enumRelation.Piston
                                   % Ask which mechanism?
                                   objs = h.Model.Converters;
                                   mecs = cell(0);
                                   for index = length(objs):-1:1
                                       mecs{index} = objs(index).name;
                                   end
                                   index = listdlg(...
                                       'ListString',mecs,...
                                       'SelectionMode','single');
```

```
                                    if isempty(index)
                                        break;
                                    else
                                        Mech = objs(index).Frames(1);
                                    end
                                end
                                switch EnumType
                                    case {enumRelation.Constant, ...
                                            enumRelation.AreaConstant, ...
                                            enumRelation.Scaled, ...
                                            enumRelation.LowestScaled, ...
                                            enumRelation.Width}
                                        success = RMan.addRelation(...
                                            Label, ...
                                            EnumType, ...
                                            h.SelectCon(1), ...
                                            h.SelectCon(2));
                                    case {enumRelation.Stroke, ...
                                            enumRelation.Piston}
                                        % Ask which mechanism?
                                        success = RMan.addRelation(...
                                            Label, ...
                                            EnumType, ...
                                            h.SelectCon(1), ...
                                            h.SelectCon(2), ...
                                            Mech);
                                    otherwise
                                        msgbox(['Selected relation type' ...
                                            ' is not implemented']);
                                        h.IndexC = 1;
                                        break;
                                end
                                if ~success
                                    msgbox(['Relationship was not ' ...
                                        'added successfully']);
                                end
                                h.IndexC = 1;
                            end
                        end
                        h.IndexC = 1;
                    end
                    h.IndexC = 2;
                else
                    msgbox(['The two connections must have the ' ...
                        'same orientation.']);
                end
            end
        end
    end
otherwise
end
show_Model(h);
hP = pan(h.output);
hP.ModeHandle.Blocking = false;
hP.Enable = 'off';
updateSelectionList(h);
guidata(hObject,h);
drawnow(); pause(0.05);

function objs = getButtonObjs(handles)
    objs = [...
            handles.InsertBody ...
            handles.InsertGroup ...
            handles.InsertBridge ...
            handles.InsertLeakConnection ...
            handles.InsertSensor ...
            handles.InsertPVoutput ...
            handles.NonConnection ...
            handles.CustomMinorLoss ...
            handles.InsertRelation ...
            handles.SelectObjects ...
```

```
            handles.MultiSelectObjects];

function ButtonCore(hObject,Mode,handles,message)
    inactivated = hObject.UserData(1) == 0;
    handles = clearButtons(handles);
    if inactivated
        handles.MODE = Mode;
        show_Model(handles);
        set(handles.message,'String',message);
        hObject.BackgroundColor = [0.33 0.67 0.33];
        hObject.UserData(1) = 1;
    else

    end
    show_Model(handles);
    updateSelectionList(handles);
    guidata(hObject, handles);
    drawnow(); pause(0.05);

function handles = clearButtons(handles)
    hObjects = getButtonObjs(handles);
    handles.Model.clearHighLighting();
    set(handles.message,'String','---');
    handles.MODE = '';
    for obj = hObjects
        if obj.UserData(1) == 1
            obj.UserData(1) = 0;
            obj.BackgroundColor = [0.94 0.94 0.94];
            break;
        end
    end
    handles.IndexC = 1;
    handles.IndexG = 1;
    handles.IndexB = 1;
    handles.SelectCon = Connection.empty;
    handles.SelectBody = Body.empty;

%% Individual button codes
function InsertBody_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function InsertBody_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertBody',handles,{'[left click] To select a connection.','[right click] to
prescribe a dimension.'});

function InsertGroup_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function InsertGroup_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertGroup',handles,'[click] To select a position to place a new group.');

function InsertBridge_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function InsertBridge_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertBridge',handles,'[click] To select the connection associated with the
foundation body');

function InsertLeakConnection_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function InsertLeakConnection_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertLeakConnection',handles,'[click] To select Connection 1');

function SelectObjects_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function SelectObjects_Callback(hObject, ~, handles)
ButtonCore(hObject,'Select',handles,'[click] To select a single object');

function MultiSelectObjects_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function MultiSelectObjects_Callback(hObject, ~, handles)
ButtonCore(hObject,'MultiSelect',handles,'[click] To add to select objects');

function InsertSensor_CreateFcn(hObject, ~, ~)
```

```
hObject.UserData(1) = 0;
function InsertSensor_Callback(hObject,~,handles)
ButtonCore(hObject,'InsertSensor',handles,'[click] To select a body');

function InsertPVoutput_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function InsertPVoutput_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertPVoutput',handles,'[click] To select a body');

function CustomMinorLoss_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function CustomMinorLoss_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertCustomMinorLoss',handles,'[click] To select a body');

function NonConnection_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function NonConnection_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertNonConnection',handles,'[click] To select a body');

function InsertRelation_CreateFcn(hObject, ~, ~)
hObject.UserData(1) = 0;
function InsertRelation_Callback(hObject, ~, handles)
ButtonCore(hObject,'InsertRelation',handles,'[click] To select a connection');

function ChangeGroup_Callback(hObject, ~, handles)
[x,y] = ginput(1);
Pnt = [x y];
backupMessage = get(handles.message,'String');
set(handles.message,'String','[click] Select A group');
handles.Model.switchHighLightedGroup(...
    handles.Model.findNearestGroup(Pnt,handles.ClickTolerance^2) );
set(handles.message,'String',backupMessage);
guidata(hObject,handles);
drawnow(); pause(0.05);

%% Selection Properties
function updateSelectionList(h,index)
switch h.DropDownMode
    case ''
        if nargin == 2
            if index > length(h.SData.ListObjs) || index < 1
                fprintf('Index Exceeds Matrix Dimensions: This may be caused by severe lag');
                return;
            else
                if strcmp(h.SData.ListObjs(index).MODE,'Deleteobj')
                    % Close all
                    Code = '';
                else
                    Code = MakeCode(h.SData.ListObjs,index);
                end
            end
        else
            Code = MakeCode(h.SData.ListObjs);
            Code = ResetCode(Code);
        end
        n = 1  + length(h.Model.Selection);
        SelectedObjs(n,1) = ListObj();
        for Obj = [h.Model.Selection {h.Model}]
            SelectedObjs(n) = ListObj('Expandobj',0,[],Obj{1});
            n = n - 1;
        end
        h.SData.ListObjs = ReadCode(Code, SelectedObjs);
        ListString = cell(length(h.SData.ListObjs),1);
        for i = 1:length(h.SData.ListObjs)
            ListString{i} = h.SData.ListObjs(i).getString();
        end
        if nargin < 2; index = get(h.SelectionProps,'Value'); end
        set(h.SelectionProps,'Value',max([1 min([index length(ListString)])]));
        set(h.SelectionProps,'String',ListString);
    case 'Optimizer'
        h.DropDownMode = '';
```

```
        if h.OptimizationStudyIndex == 0
            % Create a new study
            h.Model.OptimizationSchemes(end+1) = ...
                OptimizationScheme(h.Model);
            h.OptimizationStudyIndex = ...
                h.Model.OptimizationSchemes(end).ID;
        end
        % This appends the object and field to the optimization study
        if h.OptimizationStudyIndex > 0
            for scheme = h.Model.OptimizationSchemes
                if h.OptimizationStudyIndex == scheme.ID
                    break;
                end
            end
            if scheme.ID == h.OptimizationStudyIndex
                if nargin > 1
                    obj = h.SData.ListObjs(index).Parent;
                    child = h.SData.ListObjs(index).Child;
                    if isa(obj,'Connection')
                        scheme.AddObj(obj,'x');
                    elseif isa(child,'LinRotMechanism')
                        scheme.AddObj(child,'Stroke');
                    elseif isa(child,'Connection')
                        scheme.AddObj(child,'x');
                    end
                end
            end
        end
end

function SelectionProps_Callback(hObject, ~, h)
% The user has clicked on the SelectionProp's listbox
index = get(hObject,'Value');
if index <= length(h.SData.ListObjs)
    h.SData.ListObjs(index).on_click();
end
updateSelectionList(h,index);

function SelectionProps_CreateFcn(hObject, ~, ~)
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

%% Optimization
function SwitchDropdownMode_Callback(hObject, ~, h)
% Interfaces with the drop down menu when selecting parameters
if strcmp(h.DropDownMode,'')
    h.DropDownMode = 'Optimizer';
    set(h.DropDownModeUI,'String',h.DropDownMode);
else
    h.DropDownMode = '';
    set(h.DropDownModeUI,'String',h.DropDownMode);
end
guidata(hObject,h);

% --- Executes on button press in SwitchOptimizationStudy.
function SwitchOptimizationStudy_Callback(hObject, ~, h)
% Find the optimization scheme after the current one
% Find the current one
if h.OptimizationStudyIndex == 0
    if ~isempty(h.Model.OptimizationSchemes)
        h.OptimizationStudyIndex = h.Model.OptimizationSchemes(1).ID;
        set(h.OptStudyName,'String',h.Model.OptimizationSchemes(1).name);
    else
        set(h.OptStudyName,'String','Create New Study');
    end
    guidata(hObject,h);
    return;
end
for i = 1:length(h.Model.OptimizationSchemes)
    if h.Model.OptimizationSchemes(i).ID == ...
```

```
            h.OptimizationStudyIndex
        set(h.OptStudyName,'String',h.Model.OptimizationSchemes(i).name);
    end
end
i = i + 1;
if i > length(h.Model.OptimizationSchemes)
    h.OptimizationStudyIndex = 0;
    set(h.OptStudyName,'String','Create New Study');
else
    h.OptimizationStudyIndex = h.Model.OptimizationSchemes(i).ID;
end
guidata(hObject,h);

function RunStudy_Callback(~,~,h)
if h.OptimizationStudyIndex ~= 0
    found = false;
    for i = 1:length(h.Model.OptimizationSchemes)
        if h.Model.OptimizationSchemes(i).ID == h.OptimizationStudyIndex
            found = true;
            break;
        end
    end
    if found
        History = GradientAscent(h.Model,h.OptimizationStudyIndex);
        if ~isempty(History)
          save([h.Model.OptimizationSchemes(i).name ' - History','History']);
        end
    end
end


%% Visual Appearance
function DistributeGroup(handles)
% Look at handles.Model.Bridges
%  Simultaneously minimize the distance that things move, as well as the
%  bridge horizontal distance
handles.Model.distributeGroup(handles.InterGroupDistance);
show_Model(handles);

function GUI_CreateFcn(hObject,~,handles) %#ok<INUSD>
%% Create a figure that has zoom & pan capabilities
set(hObject,'NextPlot','add');
% pan off;
% mouse_figure(gcf);

%% Dynamics
function CreateMechanism_Callback(hObject, eventdata, handles)  %#ok<INUSL>
% Open up user form asking for
% ... Type from Source (mechanism type)
% ... ... Stroke (m) (double)
% ... ... Weight (kg) (double)
% ... ... Phases (rad) (double)
% ... ... TiltAngle (rad) (double)
% ... ... MaximumCrankArmAngle (rad) (double)
% ... ... CustomProfile Fcn
Data = Holder({});
[h] = CreateMechanismInterface(Data);
uiwait(h);
handles.Model.addConverter(LinRotMechanism(handles.Model,...
    Data.vars{1},Data.vars{2}));

% --- Executes on button press in Animate.
function Animate_Callback(hObject, ~, handles)
% Temporarily turn off connections, ghosts, groups... etc.
if handles.Model.isAnimating
    hObject.BackgroundColor = [0.94 0.94 0.94];
    handles.Model.isAnimating = false;
    if handles.ViewOptionBackup(1); showConnections_Callback(handles.showConnections, 0,
handles); end
    if handles.ViewOptionBackup(2); showBodyGhosts_Callback(handles.showBodyGhosts, 0, handles);
end
```

```
    show_Model(handles);
else
    hObject.BackgroundColor = [0.33 0.67 0.33];
    handles.ViewOptionBackup = false(2,1);
    handles.ViewOptionBackup(1) = handles.Model.showConnections;
    handles.ViewOptionBackup(2) = handles.Model.showBodyGhosts;
    if handles.ViewOptionBackup(1); showConnections_Callback(handles.showConnections, 0,
handles); end
    if handles.ViewOptionBackup(2); showBodyGhosts_Callback(handles.showBodyGhosts, 0, handles);
end
    handles.Model.isAnimating = true;
    guidata(hObject,handles);
    drawnow(); pause(0.05);
    handles.Model.Animate(); % ANIMATE IT!
    if handles.Model.isAnimating
        hObject.BackgroundColor = [0.94 0.94 0.94];
        handles.Model.isAnimating = false;
        if handles.ViewOptionBackup(1); showConnections_Callback(handles.showConnections, 0,
handles); end
        if handles.ViewOptionBackup(2); showBodyGhosts_Callback(handles.showBodyGhosts, 0,
handles); end
        show_Model(handles);
    end
end

% --- Executes on button press in Delete.
function Delete_Callback(~, ~, handles)
% Delete Selection
if length(handles.Model.Selection) == 1
   if handles.Model.ActiveGroup == handles.Model.Selection{1}
      handles.Model.ActiveGroup(:) = [];
      handles.Model.Selection{1}.deReference();
      handles.Model.Selection = cell(0);
      return;
   end
end
for obj = handles.Model.Selection
    if ~isa(obj{1},'Group')
        obj{1}.deReference();
    end
end
handles.Model.Selection = cell(0);
% For all the selected items

% --- Executes on button press in Revive.
function Revive_Callback(hObject, eventdata, handles)  %#ok<INUSD>
% Open up the recycle bin, Full of Bodies and Special Components that
% have handles and dependencies

%% Save Functionality
function save_Callback(~, ~, handles)
saveModel(false,handles);
function saveas_Callback(~,~,handles)
saveModel(true,handles);
function saveModel(savenew,h)
% The Model name is by default used, if the model name is blank, then the
% userform asks for a name.
if isempty(h.Model.name) || savenew

    notdone = true;
    while notdone
        if ~isempty(h.Model.name)
            name = inputdlg('Save as...','Save Model',1,{h.Model.name});
        else
            name = inputdlg('Save as...','Save Model');
        end
        if isempty(name); return; else; name = name{1}; end
        if ~isempty(regexp(name,'[/\*:?"<>|]','once'))
            fprintf(['XXX Invalid File name, a file name cannot contain ' ...
                'the characters [/*:?"<>|] XXX\n']);
        else
```

```
            if all(ismember(name(1),'0123456789'))
                fprintf(['XXX Invalid File name, a file name cannot start ' ...
                    'with a number. XXX\n']);
            else
                notdone = false;
            end
        end
    end
    if length(name) > 4 && strcmp(name(end-3:end),'.mat')
        name = name(1:end-4);
    end
    ogname = name;
else
    name = h.Model.name;
    ogname = name;
end
% If the name is already an existing file, it asks to overwrite, if false,
% then asks for a new name, suggesting a variation.
SavedModels = dir('Saved Files');
start = 3;
dupfound = false;
notdone = true;
naming = true;
while naming
    while notdone
        for i = start:length(SavedModels)
            if strcmp(SavedModels(i).name,[name '.mat'])
                % Devise an alternative
                if strcmp(SavedModels(i).name(end-4),')')
                    offset = 1;
                    while ...
                            all(ismember(SavedModels(i).name(end-4-offset),'0123456789')) ||...
                            SavedModels(i).name(end-4-offset) == '.'
                        offset = offset + 1;
                    end
                    offset = offset - 1;
                    num = str2double(SavedModels(i).name(end-4-offset:end-5));
                    num = num + 1;
                    name = [SavedModels(i).name(1:end-5-offset) num2str(num) ')'];
                    notdone = true;
                    dupfound = true;
                    break;
                else
                    name = [SavedModels(i).name(1:end-4) ' (1)'];
                    dupfound = true;
                end
            end
        end
        if notdone
            notdone = false;
            % Double check that there are no duplicates
            for i = 3:length(SavedModels)
                if strcmp(SavedModels(i).name,[name '.mat'])
                    notdone = true;
                    start = i;
                    break;
                end
            end
        end
    end
    % We have the new unique name
    if dupfound
        switch questdlg(['Do you want to overwrite the existing file: ' ogname])
            case 'Yes'
                name = ogname;
                naming = false;
            case 'No'
                cellname = inputdlg('Name: ',['Rename: ' ogname],1,{name});
                if isempty(cellname); return; end
                newname = cellname{1};
                if strcmp(newname,name)
```

```
                    naming = false;
                else
                    ogname = newname;
                    notdone = true;
                    dupfound = false;
                end
                name = newname;
            case {'Cancel',''}
                return;
        end
    else
        naming = false;
    end
end
h.Model.name = name;
backupAxis = h.Model.AxisReference;
h.Model.AxisReference(:) = [];
newfile = ['Saved Files\' name '.mat'];
Model = h.Model; %#ok<NASGU>
Model.saveME();
h.Model.AxisReference = backupAxis;
fprintf('Model Saved\n');

%% Load Functionality
function h = load_sub(name, h)
newfile = [pwd '\Saved Files\' name];
File = load(newfile,'Model');
h.Model = File.Model;
h.Model.AxisReference = h.GUI;

h.Model.showInterConnections = false;
h.Model.showNodes = false;
h.Model.RelationOn = true; set(h.RelationMode,'String','On');
h.Model.showGroups = get(h.showGroups,'Value');
h.Model.showBodies = get(h.showBodies,'Value');
h.Model.showBodyGhosts = get(h.showBodyGhosts,'Value');
h.Model.showConnections = get(h.showConnections,'Value');
h.Model.showLeaks = get(h.showLeaks,'Value');
h.Model.showBridges = get(h.showBridges,'Value');
h.Model.showSensors = get(h.showSensors,'Value');
h.Model.showRelations = get(h.showRelations,'Value');
h.Model.showInterConnections = get(h.showInterConnections,'Value');
h.Model.showEnvironmentConnections = get(h.showEnvironmentConnections,'Value');
h.Model.showNodes = get(h.showNodes,'Value');

h.Model.showPressureAnimation = get(h.ShowPressureAnimation,'Value');
h.Model.recordPressure = get(h.RecordPressure,'Value');
h.Model.showTemperatureAnimation = get(h.ShowTemperatureAnimation,'Value');
h.Model.recordTemperature = get(h.RecordTemperature,'Value');
h.Model.showVelocityAnimation = get(h.ShowVelocityAnimation,'Value');
h.Model.recordVelocity = get(h.RecordVelocity,'Value');
h.Model.showTurbulenceAnimation = get(h.ShowTurbulenceAnimation,'Value');
h.Model.recordTurbulence = get(h.RecordTurbulence,'Value');
h.Model.recordOnlyLastCycle = get(h.RecordOnlyLastCycle,'Value');
h.Model.outputPath= get(h.OutputPath,'String');
h.Model.warmUpPhaseLength = str2double(get(h.WarmUpPhaseLength,'String'));
h.Model.animationFrameTime = str2double(get(h.AnimationFrameTime,'String'));

cla;
show_Model(h);
drawnow(); pause(0.05);

function load_Callback(hObject, ~, h)
% Asks the user if they want to save the current model
% if True. Call save_Callback.
switch questdlg('Do you want to save the current model?')
    case 'Yes'
        if ~isempty(h.Model.name)
            switch questdlg('Do you want to save as a new Model?')
                case 'Yes'
                    saveModel(true,h);
```

```
                case 'No'
                    saveModel(false,h);
                case {'Cancel',''}
                    return;
            end
        else
            saveModel(true,h);
        end
    case 'No'
        % Do nothing
    case {'Cancel',''}
        return;
end

% Then provide the user with a list of saved models in the Saved Files
% folder.
SavedModels = dir('Saved Files');
names = {SavedModels.name};
i = 1;
while names{i}(1) == '.'
    i = i + 1;
end
[selection, tf] = listdlg('ListString',names(i:end),...
    'SelectionMode','single');
if tf
    name = names{selection+i-1};
else
    return;
end

% if the user selects one, then replace current model with the loaded one
% and reset the userform.
[h] = load_sub(name, h);
guidata(h.load,h);

%% Show Options
function showGroups_Callback(hObject, ~, h) %#ok<*DEFNU>
value = get(hObject,'Value');
if (value ~= h.Model.showGroups)
    h.Model.showGroups = value;
    show_Model(h);
end
function showBodies_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~=h.Model.showBodies)
    h.Model.showBodies = value;
    show_Model(h);
end
function showConnections_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showConnections)
    h.Model.showConnections = value;
    show_Model(h);
end
function showLeaks_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showLeaks)
    h.Model.showLeaks = value;
    show_Model(h);
end
function showBridges_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showBridges)
    h.Model.showBridges = value;
    show_Model(h);
end
function showInterConnections_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showInterConnections)
    h.Model.showInterConnections = value;
    show_Model(h);
```

```
end
function showEnvironmentConnections_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showEnvironmentConnections)
    h.Model.showEnvironmentConnections = value;
    show_Model(h);
end
function showBodyGhosts_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showBodyGhosts)
    h.Model.showBodyGhosts = value;
    show_Model(h);
end
function showNodes_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showNodes)
    h.Model.showNodes = value;
    show_Model(h);
end
function showSensors_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showSensors)
    h.Model.showSensors = value;
    show_Model(h);
end
function showRelations_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showRelations)
    h.Model.showRelations = value;
    show_Model(h);
end

function BoxZoom_Callback(hObject, eventdata, h) %#ok<INUSL>
%handles.corner_points = ginput(2);
show_Model(h,ginput(2));

function show_Model(h,cornerpoints)
h.Model.show();
if nargin == 2
    % Preserve aspect ratio
    axes = gca;
    width = abs(cornerpoints(1,1) - cornerpoints(2,1));
    height = abs(cornerpoints(1,2) - cornerpoints(2,2));
    r_new = width/height;

    % Get current aspect ratio
    r_old = axes.PlotBoxAspectRatio(1)/axes.PlotBoxAspectRatio(2);

    if r_old > r_new
        width = width*r_old/r_new;
    else
        height = height*r_new/r_old;
    end

    % Determine the center
    c_x = 0.5*(cornerpoints(1,1) + cornerpoints(2,1));
    c_y = 0.5*(cornerpoints(1,2) + cornerpoints(2,2));
    % Adjust the axes
    axes.XLim = [c_x-width/2 c_x+width/2];
    axes.YLim = [c_y-height/2 c_y+height/2];
end
drawnow(); pause(0.05);

function RecenterView_Callback(~, ~, h)
axes = gca;
xlim = h.Model.getXLim();
ylim = h.Model.getYLim();
ar = abs(ylim(1)-ylim(2))/abs(xlim(1)-xlim(2));
cur_xlim = axes.XLim;
cur_ylim = axes.YLim;
cur_ar = abs(cur_ylim(1)-cur_ylim(2))/abs(cur_xlim(1)-cur_xlim(2));
```

```
if ar > cur_ar
    % ylim is the base
    cx = mean(xlim);
    dx = 0.5*abs(ylim(1)-ylim(2))/cur_ar;
    xlim = [cx - dx, cx + dx];
else
    % xlim is the base
    cy = mean(ylim);
    dy = 0.5*cur_ar*abs(xlim(1)-xlim(2));
    ylim = [cy - dy, cy + dy];
end
if any(isnan(xlim)) || any(isinf(xlim)); return; end
if any(isnan(ylim)) || any(isinf(ylim)); return; end
axes.XLim = xlim;
axes.YLim = ylim;
show_Model(h);

%% RunTime Show Options
function showLivePV_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showLivePV)
    h.Model.showLivePV = value;
end
function stopSimulation_Callback(~, ~, h)
h.Model.stopSimulation();

function Run_Callback(~, ~, h)
h.Model.Run();

function CreateMechanism_CreateFcn(~, ~, ~)
function Animate_CreateFcn(~, ~, ~)

%% Simulation Options
function Reset_Discretization_Callback(~, ~, h)
h.Model.resetDiscretization();
show_Model(h);
function DispNumbers_Callback(~, ~, h)
h.Model.dispNodeIndexes();
function clearAxes_Callback(~, ~, ~)
cla;

function ShowPressureAnimation_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showPressureAnimation)
    h.Model.showPressureAnimation = value;
end
if value
    set(h.RecordPressure,'Value',value);
    RecordPressure_Callback(h.RecordPressure,[],h);
end
function RecordPressure_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.recordPressure)
    h.Model.recordPressure = value;
end
if ~value
    set(h.ShowPressureAnimation,'Value',value);
    ShowPressureAnimation_Callback(h.ShowPressureAnimation,[],h);
end

function ShowTemperatureAnimation_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showTemperatureAnimation)
    h.Model.showTemperatureAnimation = value;
end
if value
    set(h.RecordTemperature,'Value',value);
    RecordTemperature_Callback(h.RecordTemperature,[],h);
end
function RecordTemperature_Callback(hObject, ~, h)
value = get(hObject,'Value');
```

```
if (value ~= h.Model.recordTemperature)
    h.Model.recordTemperature = value;
end
if ~value
    set(h.ShowTemperatureAnimation,'Value',value);
    ShowTemperatureAnimation_Callback(h.ShowTemperatureAnimation,[],h);
end

function ShowVelocityAnimation_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showVelocityAnimation)
    h.Model.showVelocityAnimation = value;
end
if value
    set(h.RecordVelocity,'Value',value);
    RecordVelocity_Callback(h.RecordVelocity,[],h);
end
function RecordVelocity_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.recordVelocity)
    h.Model.recordVelocity = value;
end
if ~value
    set(h.ShowVelocityAnimation,'Value',value);
    ShowVelocityAnimation_Callback(h.ShowVelocityAnimation,[],h);
end

function ShowTurbulenceAnimation_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showTurbulenceAnimation)
    h.Model.showTurbulenceAnimation = value;
end
if value
    set(h.RecordTurbulence,'Value',value);
    RecordTurbulence_Callback(h.RecordTurbulence,[],h);
end
function RecordTurbulence_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.recordTurbulence)
    h.Model.recordTurbulence = value;
end
if ~value
    set(h.ShowTurbulenceAnimation,'Value',value);
    ShowTurbulenceAnimation_Callback(h.ShowVelocityAnimation,[],h);
end

function ShowConductionAnimation_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.showConductionAnimation)
    h.Model.showTurbulenceAnimation = value;
end
if value
    set(h.RecordConductionFlux,'Value',value);
    RecordConductionFlux_Callback(h.RecordConductionFlux,[],h);
end
function RecordConductionFlux_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.recordConductionFlux)
    h.Model.recordTurbulence = value;
end
if ~value
    set(h.ShowConductionAnimation,'Value',value);
    ShowConductionAnimation_Callback(h.ShowConductionAnimation,[],h);
end

function PressureDropAnimation_Callback(hObject,~,h)
value = get(hObject,'Value');
if (value ~= h.Model.showPressureDropAnimation)
    h.Model.showPressureDropAnimation = value;
end
if value
```

```
    set(h.recordPressureDrop,'Value',value);
    recordPressureDrop_Callback(h.recordPressureDrop,[],h);
end
function recordPressureDrop_Callback(hObject,~,h)
value = get(hObject,'Value');
if (value ~= h.Model.recordPressureDrop)
    h.Model.recordPressureDrop = value;
end
if ~value
    set(h.PressureDropAnimation,'Value',value);
    PressureDropAnimation_Callback(h.PressureDropAnimation,[],h);
end

function RecordOnlyLastCycle_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.recordOnlyLastCycle)
    h.Model.recordOnlyLastCycle = value;
end

function RecordStatistics_Callback(hObject, ~, h)
value = get(hObject,'Value');
if (value ~= h.Model.recordStatistics)
    h.Model.recordStatistics = value;
end

function OutputPath_CreateFcn(~, ~, ~)
function OutputPath_ButtonDownFcn(hObject, ~, h)
value = uigetdir;
set(hObject,'String',value);
h.Model.outputPath = value;

function WarmUpPhaseLength_Callback(hObject, ~, h)
value = get(hObject,'String');
if isempty(value); value = '0'; end
if all(ismember(value,'.0123456789'))
    set(hObject,'UserData',value);
    h.Model.warmUpPhaseLength = str2double(value);
else
    msgbox('The length must be a number, the units are already defined as seconds');
    set(hObject,'String',get(hObject,'UserData'));
end

function WarmUpPhaseLength_CreateFcn(hObject, ~, ~)
set(hObject,'UserData','0');
set(hObject,'String','0');
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function AnimationFrameTime_Callback(hObject, ~, h)
value = get(hObject,'String');
if isempty(value); value = '0.05'; end
if all(ismember(value,'.0123456789'))
    set(hObject,'UserData',value);
    h.Model.animationFrameTime = str2double(value);
else
    msgbox('The length must be a number, the units are already defined as seconds');
    set(hObject,'String',get(hObject,'UserData'));
end

function AnimationFrameTime_CreateFcn(hObject, ~, ~)
set(hObject,'UserData','0.05');
set(hObject,'String','0.05');
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function RecordSnapShot_Callback(~, ~, handles)
if ~isempty(handles.Model.Result)
    name = getProperName( 'SnapShot' );
    handles.Model.Result.getSnapShot(this,handles.Model,name)
```

```
end

function RunTestSet_Callback(~, ~, h)
% Find the Folder "Test_Running"
files = dir('Test_Running');
names = {files.name};
names(1:2) = [];
if ~iscell(names)
    names = {names};
end
for index = size(names,1):-1:1
    names{index} = names{index}(1:end-2);
end
index = listdlg('ListString',names,...
    'SelectionMode','single',...
    'InitialValue',index);
if ~isempty(index)
    if strfind(names{index},'.m')
        func = str2func(names{index}(1:end-2));
    else
        func = str2func(names{index});
    end
    Test_Set = func();

    % Chunk the test set into groups that have the same model
    group_start = 1;
    group_end = 1;
    while group_end <= length(Test_Set)
        Model = Test_Set(group_start).Model;
        while group_end <= length(Test_Set) && ...
                strcmp(Model,Test_Set(group_end).Model)
            group_end = group_end + 1;
        end
        group_end = group_end - 1;
        h = load_sub(Model, h);
        h.Model.Run(Test_Set(group_start:group_end));
        group_start = group_end + 1;
        group_end = group_start;


        % The Model name is the default name used, it overwrites automatically
        %     name = h.Model.name;
        %     newfile = ['Saved Files\' name '.mat'];
        %     Model = h.Model;
        %     save(newfile,'Model');
        %     fprintf('Model Saved.\n');
    end
end

function DerefinementFactor_Callback(hObject, ~, handles)
value = str2double(get(hObject,'String'));
if isnan(value)
    set(hObject,'String','1');
    return;
end
if value >= 0.01 && value <= 100
    handles.Model.deRefinementFactorInput = value;
else
    if value < 0.01
        set(hObject,'String','0.01');
        handles.Model.deRefinementFactorInput = 0.01;
    else
        set(hObject,'String','100');
        handles.Model.deRefinementFactorInput = 100;
    end
end
handles.Model.resetDiscretization();
guidata(hObject,handles);

function DerefinementFactor_CreateFcn(hObject, ~, ~)
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in SwitchRelationMode.
function SwitchRelationMode_Callback(~, ~, handles)
if strcmp(get(handles.RelationMode,'String'),'On')
  set(handles.RelationMode,'String','Off');
  handles.Model.RelationOn = false;
else
  set(handles.RelationMode,'String','On');
  handles.Model.RelationOn = true;
end
```

Create Mechanism Interface

This module pops up when the user creates a new linear to rotational mechanism. The interface includes a type selection drop-down. This dropdown then switches what is displayed in the property editor, in the form of an editable table. The table contains a column for each property and multiple rows in the case where multiple mechanisms attached to the same point, such as a 90 degree gamma or beta type engine.

```
function varargout = CreateMechanismInterface(varargin)
% CREATEMECHANISMINTERFACE MATLAB code for CreateMechanismInterface.fig
%      CREATEMECHANISMINTERFACE, by itself, creates a new CREATEMECHANISMINTERFACE or raises the
existing
%      singleton*.
%
%      H = CREATEMECHANISMINTERFACE returns the handle to a new CREATEMECHANISMINTERFACE or the
handle to
%      the existing singleton*.
%
%      CREATEMECHANISMINTERFACE('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in CREATEMECHANISMINTERFACE.M with the given input arguments.
%
%      CREATEMECHANISMINTERFACE('Property','Value',...) creates a new CREATEMECHANISMINTERFACE or
raises
%      the existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before CreateMechanismInterface_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to CreateMechanismInterface_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help CreateMechanismInterface

% Last Modified by GUIDE v2.5 13-Dec-2018 14:29:58

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @CreateMechanismInterface_OpeningFcn, ...
                   'gui_OutputFcn',  @CreateMechanismInterface_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before CreateMechanismInterface is made visible.
function CreateMechanismInterface_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
% varargin   command line arguments to CreateMechanismInterface (see VARARGIN)

% Choose default command line output for CreateMechanismInterface
handles.output = hObject;
switch length(varargin{1}.vars)
  case 0 % Create New
    handles.iType = [];
    handles.iData = [];
  case 2 % Modify Existing
    % assume it is a "Holder"
    handles.iType = varargin{1}.vars{1};
    handles.iData = varargin{1}.vars{2};
  case 1 % ???
    handles.iType = varargin{1}.vars{1};
    handles.iData = [];
end
handles.outData = varargin{1};
handles.DataEstablished = false;

% Setup MechType
if ~isempty(handles.iType)
  % Find the index
  i = FindStringInCell(LinRotMechanism.Source,handles.iType);
  if i ~= 0
    set(handles.MechType,'Value',i);
  else
    % Type not found, erase handles.iData & handles.iType
    fprintf(['XXX Type not found in registry, make sure to include ' ...
      'support for "' handles.iType '" if you want to use it. XXX\n']);
    handles.iType = [];
    handles.iData = [];
  end
end

% Setup Data
if ~isempty(handles.iData)
  % Make sure iType is valid
  i = FindStringInCell(LinRotMechanism.Source,handles.iType);
  if i ~= 0
    set(handles.PropertiesTable,'Data',handles.iData);
  else
    % Type not found, erase handles.iData & handles.iType
    fprintf(['XXX Type not found in registry, make sure to include ' ...
      'support for "' handles.iType '" if you want to use it. XXX\n']);
    handles.iType = [];
    handles.iData = [];
  end
  handles.DataEstablished = true;
else
  set(handles.PropertiesTable,'Visible','off');
  handles.DataEstablished = false;
end

% Other things
handles.MODE = '';

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes CreateMechanismInterface wait for user response (see UIRESUME)
% uiwait(handles.TheWindow);

% --- Outputs from this function are returned to the command line.
function varargout = CreateMechanismInterface_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
```

```
% contents = cellstr(get(handles.MechType,'String'));
% varargout{1} = contents{get(handles.MechType,'Value')};
% varargout{2} = get(handles.PropertiesTable,'Data');

% --- Executes on selection change in MechType.
function MechType_Callback(hObject, eventdata, handles)
contents = cellstr(get(hObject,'String'));
Type = contents{get(hObject,'Value')};
if ~handles.DataEstablished
  [Data, Instructions] = ...
    LinRotMechanism.GetPropertyTableSource(Type);
  handles.DataEstablished = true;
else
  [Data, Instructions] = ...
    LinRotMechanism.GetPropertyTableSource(...
    Type,...
    get(handles.PropertiesTable,'Data'));
end
set(handles.PropertiesTable,'Visible','on');
set(handles.PropertiesTable,'Data',Data);
handles.PropertiesTable.ColumnEditable = true(1,size(Data,2));
handles.PropertiesTable.ColumnFormat = cell(1,size(Data,2));
set(handles.Instructions,'String',Instructions);
EstablishWidths(handles);
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function MechType_CreateFcn(hObject, eventdata, handles)
set(hObject,'String',LinRotMechanism.Source);
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes during object creation, after setting all properties.
function PropertiesTable_CreateFcn(hObject, eventdata, handles)

% --- Executes when entered data in editable cell(s) in PropertiesTable.
function PropertiesTable_CellEditCallback(hObject, eventdata, handles)
% hObject    handle to PropertiesTable (see GCBO)
% eventdata  structure with the following fields (see MATLAB.UI.CONTROL.TABLE)
%       Indices: row and column indices of the cell(s) edited
%       PreviousData: previous data for the cell(s) edited
%       EditData: string(s) entered by the user
%       NewData: EditData or its converted form set on the Data property. Empty if Data was not
changed
%       Error: error string when failed to convert EditData to appropriate value for Data
% handles    structure with handles and user data (see GUIDATA)
if eventdata.Indices(1) == 1
  Data = get(hObject,'Data');
  Data{eventdata.Indices(1),eventdata.Indices(1)} = eventdata.PreviousData;
  set(hObject,'Data',Data);
  fprintf('XXX You cannot edit column headers, no matter how hard you try. XXX\n');
end

function EstablishWidths(handles)
Source = get(handles.PropertiesTable,'Data');
for col = size(Source,2):-1:1
  Widths{col} = length(Source{1,col})*6;
end
set(handles.PropertiesTable,'ColumnWidth',Widths);

% Sum of widths
totalWidth = 0;
for i = 1:length(Widths)
  totalWidth = totalWidth + Widths{i};
end

PosInst = get(handles.Instructions,'Position');
PosTable = get(handles.PropertiesTable,'Position');
PosFrame = get(handles.PropertiesFrame,'Position');
PosWin = get(handles.TheWindow,'Position');
```

```
% Table Size
PosTable(3) = totalWidth+32;
set(handles.PropertiesTable,'Position',PosTable);

% Instructions Size
PosInst(3) = min([400 PosTable(3)]);
set(handles.Instructions,'Position',PosInst);

% Frame Size
PosFrame(3) = PosTable(3) + 2*PosTable(1);
set(handles.PropertiesFrame,'Position',PosFrame);

% Window Size
PosWin(3) = PosTable(3) + 4*PosTable(1);
set(handles.TheWindow,'Position',PosWin);
guidata(handles.TheWindow, handles);

function Ok_Callback(~, ~, handles)
Types = get(handles.MechType,'String');
Type = Types{get(handles.MechType,'Value')};
Source = get(handles.PropertiesTable,'Data');
handles.outData.vars = {Type, Source};
close(handles.TheWindow);
% Close it.

% --- Executes when selected cell(s) is changed in PropertiesTable.
function PropertiesTable_CellSelectionCallback(hObject, eventdata, handles)
if ~isempty(eventdata.Indices)
  row = eventdata.Indices(1);
  if row ~= 1
    switch handles.MODE
      case 'delete'
        Data = get(handles.PropertiesTable,'Data');
        NewData = cell(size(Data)-[1 0]);
        k = 0;
        for i = 1:size(Data,1)
          if i ~= row
            for j = 1:size(Data,2)
              NewData{i-k,j} = Data{i,j};
            end
          else
            k = 1;
          end
        end
        set(handles.PropertiesTable,'Data',NewData);
      case 'copy'
        Data = get(handles.PropertiesTable,'Data');
        NewData = cell(size(Data)+[1 0]);
        for i = 1:size(Data,1)
          for j = 1:size(Data,2)
            NewData{i,j} = Data{i,j};
          end
        end
        for i = 1:size(Data,2)
          NewData{size(Data,1)+1,i} = Data{row,i};
        end
        set(handles.PropertiesTable,'Data',NewData);
      otherwise
    end
  end
end

% --- Executes on button press in DeleteOnClick.
function DeleteOnClick_Callback(hObject, eventdata, handles)
if strcmp(handles.MODE,'delete')
  handles.MODE = '';
  set(hObject,'BackgroundColor',[0.94 0.94 0.94]);
else
  handles.MODE = 'delete';
  set(hObject,'BackgroundColor',[0 1 0]);
```

```
  set(handles.CopyOnClick,'BackgroundColor',[0.94 0.94 0.94]);
end
guidata(hObject, handles);

% --- Executes on button press in CopyOnClick.
function CopyOnClick_Callback(hObject, eventdata, handles)
if strcmp(handles.MODE,'copy')
  handles.MODE = '';
  set(hObject,'BackgroundColor',[0.94 0.94 0.94]);
else
  handles.MODE = 'copy';
  set(hObject,'BackgroundColor',[0 1 0]);
  set(handles.DeleteOnClick,'BackgroundColor',[0.94 0.94 0.94]);
end
guidata(hObject, handles);

% --- Executes on button press in AddBlankRow.
function AddBlankRow_Callback(hObject, eventdata, handles)
handles.MODE = '';
set(handles.CopyOnClick,'BackgroundColor',[0.94 0.94 0.94]);
set(handles.DeleteOnClick,'BackgroundColor',[0.94 0.94 0.94]);
Data = get(handles.PropertiesTable,'Data');
Data = AddRow(Data,1);
set(handles.PropertiesTable,'Data',Data);
guidata(hObject, handles);
```

G.2. Major Elements

Body

The body is a class that includes:

A creation function

Functions used to append internal lists of other classes.

Function which is called when it is destroyed: to properly disable its dependents.

A get/set interface, used by the property drop-down on the main GUI.

A set of utility functions which calculate the body orientation, sort connections, detect overlaps and update the bodies derived properties. Including its bounds, its validity, its name, translation reference, moving mode, discretization status, default temperatures, default pressures.

A function to discretize it.

A set of functions that get its color from the material, remove it from the figure and add it to the figure.

```
classdef Body < handle
    % body Summary of this class goes here
    %   Detailed explanation goes here

    properties (Constant)
        MaterialUndefinedColor = [1 0.5569 1];
        ActiveColor = [0 1 0];
        NormalColor = [0 0 0];
        InvalidColor = [1 0 0];
    end

    properties (Hidden)
        GUIObjects;
        isStateValid logical = false;
        isStateDiscretized logical = false;
        StateMovingStatus enumMove;
        s_lb_Vert double;
        s_ub_Vert double;
        s_lb_Hor double;
        d_lb_Hor double;
        s_ub_Hor double;
        d_ub_Hor double;
        customTemperature = [];
        customPressure = [];
    end

    properties (Dependent)
        name;
        isValid;
        MovingStatus;
        RefFrame;
        Temperature;
        Pressure;
        isDiscretized;
```

```
end

properties
    customname = '';
    ID;
    nodeIndex int32;
    Group Group;
    Connections Connection;
    PVoutputs PVoutput;
    Sensors Sensor;
    matl Material;
    divides = [1 1]; % [Nx, Ny]
    NuFunc function_handle;
    fFunc function_handle;
    Matrix Matrix;
    Mesher Mesher;
    DiscretizationFunctionRadial;
    DiscretizationFunctionAxial;

    % Boolean Values
    isActive logical = false;
    isChanged logical = true;

    % Discretization
    Nodes Node;
    Faces Face;
end

methods
    %% Constructor
    function this = Body(Group,Connections,matl)
        if nargin == 3
            % Get name from
            this.Group = Group;
            this.Connections = Connections;
            for iCon = this.Connections; iCon.addBody(this); end
            this.isChanged = true;
            this.matl = matl;
            fprintf(['Body created in Group ' Group.name '.\n']);
        end
    end
    function addPVoutput(this,PVoutputToAdd)
        this.PVoutputs = PVoutputToAdd;
    end
    function addSensor(this,SensorToAdd)
        for iS = SensorToAdd
            found = false;
            for i = 1:length(this.Sensors)
                if this.Sensors(i) == iS
                    found = true;
                    break;
                end
            end
            if ~found
                this.Sensors(end+1) = iS;
                this.Group.Model.addSensor(iS);
            end
        end
    end
    function deReference(this)
        % Remove Reference from connections
        for iCon = this.Connections
            for i = length(iCon.Bodies):-1:1
                if iCon.Bodies(i) == this
                    iCon.Bodies(i) = [];
                    iCon.change();
                    break;
                end
            end
        end
        for i = length(this.Connections):-1:1
```

```
        if isempty(this.Connections(i).Bodies)
            this.Connections(i).deReference();
        end
    end
    % Remove Reference from Group
    iGroup = this.Group;
    for i = length(iGroup.Bodies):-1:1
        if iGroup.Bodies(i) == this
            iGroup.Bodies(i) = [];
            iGroup.isChanged = true;
            break;
        end
    end
    % Remove Reference from any Bridges
    iModel = iGroup.Model;
    for i = length(iModel.Bridges):-1:1
        if iModel.Bridges(i).Body1 == this || iModel.Bridges(i).Body2 == this
            iModel.Bridges(i).deReference();
        end
    end
    % Remove Reference from any Leaks
    for i = length(iModel.LeakConnections):-1:1
        if (isa(iModel.LeakConnections(i).obj1,'Body') ...
                && iModel.LeakConnections(i).obj1 == this) ...
                || (isa(iModel.LeakConnections(i).obj2,'Body') ...
                && iModel.LeakConnections(i).obj2 == this)
            iModel.LeakConnections(i).deReference();
        end
    end
    % Remove Reference from any Custom Minor Losses
    for i = length(iModel.CustomMinorLosses):-1:1
        if iModel.CustomMinorLosses(i).Body1 == this || ...
                iModel.CustomMinorLosses(i).Body2 == this
            iModel.CustomMinorLosses(i) = [];
        end
    end
    % Remove Reference from any NonConnections
    for i = length(iModel.NonConnections):-1:1
        if iModel.NonConnections(i).Body1 == this || ...
                iModel.NonConnections(i).Body2 == this
            iModel.NonConnections(i) = [];
        end
    end
    % Remove Reference from any PVoutputs
    for i = length(iModel.PVoutputs):-1:1
        if iModel.PVoutputs(i) == this.PVoutputs
            iModel.PVoutputs(i).deReference();
        end
    end
    % Remove Reference from any Sensors
    for i = length(iModel.Sensors):-1:1
        for j = 1:length(this.Sensors)
            if iModel.Sensors(i) == this.Sensors(j)
                iModel.Sensors(i).deReference();
                break;
            end
        end
    end
    this.Nodes(:) = [];
    this.Faces(:) = [];
    % Remove any visual remenant
    this.removeFromFigure(gca);
    this.delete();
end

%% get/set
function Item = get(this,PropertyName)
    switch PropertyName
        case 'Name'
            Item = this.name;
        case 'Bottom Connection'
```

```
        miny = inf;
        for iCon = this.Connections
            if iCon.Orient == enumOrient.Horizontal && iCon.x < miny
                miny = iCon.x;
                Item = iCon;
            end
        end
    case 'Top Connection'
        maxy = -inf;
        for iCon = this.Connections
            if iCon.Orient == enumOrient.Horizontal && iCon.x > maxy
                maxy = iCon.x;
                Item = iCon;
            end
        end
    case 'Inner Connection'
        minx = inf;
        for iCon = this.Connections
            if iCon.Orient == enumOrient.Vertical && iCon.x < minx
                minx = iCon.x;
                Item = iCon;
            end
        end
    case 'Outer Connection'
        maxx = -inf;
        for iCon = this.Connections
            if iCon.Orient == enumOrient.Vertical && iCon.x > maxx
                maxx = iCon.x;
                Item = iCon;
            end
        end
    case 'Material'
        Item = this.matl;
    case 'Temperature'
        Item = this.Temperature;
    case 'Pressure'
        Item = this.Pressure;
    case 'Radial Divides'
        Item = this.divides(1);
    case 'Axial Divides'
        Item = this.divides(2);
    case 'RefFrame'
        Item = Frame.empty;
        for iCon = this.Connections
            if iCon.Orient == enumOrient.Horizontal && ~isempty(iCon.RefFrame)
                if isempty(Item)
                    Item = iCon.RefFrame;
                else
                    if Item ~= iCon.RefFrame
                        Item = Frame.empty;
                        break;
                    end
                end
            end
        end
    case 'Change Matrix'
        if isempty(this.Matrix)
            Item = Matrix(this); %#ok<PROPLC>
            this.Matrix = Item;
        else
            Item = this.Matrix;
        end
    case 'Expand Matrix'
        Item = this.Matrix;
    case 'Radial Discretization Function'
        Item = this.DiscretizationFunctionRadial;
    case 'Axial Discretization Function'
        Item = this.DiscretizationFunctionAxial;
    otherwise
        fprintf(['XXX Body GET Inteface for ' PropertyName ' is not found XXX\n']);
end
```

```
end
function set(this,PropertyName,Item)
    switch PropertyName
        case 'Name'
            this.customname = Item;
        case 'Radial Divides'
            this.divides(1) = Item;
        case 'Axial Divides'
            this.divides(2) = Item;
        case 'Temperature'
            if Item ~= this.Group.Model.engineTemperature
                this.customTemperature = Item;
            else
                this.customTemperature = [];
            end
        case 'Pressure'
            if Item ~= this.Group.Model.enginePressure
                this.customPressure = Item;
            else
                this.customPressure = [];
            end
        case 'Change Matrix'
            this.Matrix = Item;
            this.Matrix.Body = this;
        case 'Radial Discretization Function'
            this.DiscretizationFunctionRadial = Item;
        case 'Axial Discretization Function'
            this.DiscretizationFunctionAxial = Item;
        case 'RefFrame'
            if isempty(Item)
                for iCon = this.Connections
                    if iCon.Orient == enumOrient.Horizontal
                        iCon.set('RefFrame',Item);
                    end
                end
            else
                for iCon = this.Connections
                    if iCon.Orient == enumOrient.Horizontal
                        if isempty(iCon.RefFrame) || iCon.RefFrame ~= Item
                            iCon.set('RefFrame',Item);
                        end
                    end
                end
            end
        otherwise
            fprintf(['XXX Body SET Inteface for ' PropertyName ' is not found XXX\n']);
            return;
    end
    this.change();
end

%% Utility
function sortConnections(this)
    % Sort the connections in an order that is xmin,xmax,ymin,ymax
    for i = 1:length(this.Connections)-1
        for j = i+1:length(this.Connections)
            if this.Connections(i).Orient == this.Connections(j).Orient
                if this.Connections(i).x > this.Connections(j).x
                    % swap the two
                    tempCon = this.Connections(i);
                    this.Connections(i) = this.Connections(j);
                    this.Connections(j) = tempCon;
                end
            elseif this.Connections(i).Orient == enumOrient.Horizontal
                % swap the two
                tempCon = this.Connections(i);
                this.Connections(i) = this.Connections(j);
                this.Connections(j) = tempCon;
            end
        end
    end
```

```
end
function dir = getBodyDirection(this)
    if this.divides(1) > this.divides(2)
        dir = 1;
    elseif this.divides(2) > this.divides(1)
        dir = 2;
    else
        cons = zeros(1,2);
        for iCon = this.Connections
            switch iCon.Orient
                case enumOrient.Vertical
                    [b1,b2,~,~] = this.limits(enumOrient.Horizontal);
                    for iBody = iCon.Bodies
                        [y1,y2,~,~] = iBody.limits(enumOrient.Horizontal);
                        if ~(all(y1 > b2) || all(y2 < b1))
                            cons(1) = cons(1) + 1;
                        end
                    end
                case enumOrient.Horizontal
                    [b1,b2,~,~] = this.limits(enumOrient.Vertical);
                    for iBody = iCon.Bodies
                        [x1,x2,~,~] = this.limits(enumOrient.Vertical);
                        if ~(all(x1 > b2) || all(x2 < b1))
                            cons(2) = cons(2) + 1;
                        end
                    end
            end
        end
        if cons(1) == 0
            if cons(2) == 0
                dir = 2;
            else
                dir = 2;
            end
        else
            if cons(2) == 0
                dir = 1;
            else
                if cons(1) > cons(2)
                    dir = 1;
                else
                    dir = 2;
                end
            end
        end
    end
end

%% Creation Tests
function isit = overlaps(thisBody,otherBody)
    isit = false;
    if thisBody ~= otherBody
        % Test x-coords
        [ ~, ~, xmin1, xmax1] = thisBody.limits(enumOrient.Vertical);
        [ ~, ~, xmin2, xmax2] = otherBody.limits(enumOrient.Vertical);
        if xmin1 >= xmax2 || xmin2 >= xmax1
            isit = false;
            return;
        end
        [ymin1, ymax1, ~, ~] = thisBody.limits(enumOrient.Horizontal);
        [ymin2, ymax2, ~, ~] = otherBody.limits(enumOrient.Horizontal);
        N = max([1 length(ymin1) length(ymax1)]);
        if N ~= 1
            if (~isscalar(ymin2) && N ~= length(ymin2)) || ...
                    (~isscalar(ymax2) && N ~= length(ymax2))
                otherBody.update();
                [ymin2, ymax2, ~, ~] = otherBody.limits(enumOrient.Horizontal);
            end
        end
        if all(ymin1 >= ymax2) || all(ymin2 >= ymax1)
            isit = false;
```

```
            return;
        end
        isit = true;
    end
end
function [doesit, orient, xmin, xmax, y] = touches(thisBody,otherBody)
  if thisBody.Connections(1) == otherBody.Connections(2) || ...
      thisBody.Connections(2) == otherBody.Connections(1)
    % Vertical Connections
    orient = thisBody.Connections(1).Orient;
    [ ~, ~, xmin1, xmax1] = thisBody.limits(enumOrient.Vertical);
    [ ~, ~, xmin2, xmax2] = otherBody.limits(enumOrient.Vertical);
    xmin = xmin1; xmin(xmin<xmin2) = xmin2(xmin<xmin2);
    xmax = xmax1; xmax(xmax>xmax2) = xmax2(xmax>xmax2);
    if thisBody.Connections(1) == otherBody.Connections(2)
      y = thisBody.Connections(1).x;
    else
      y = thisBody.Connections(2).x;
    end
    doesit = any(xmin<xmax);
  elseif thisBody.Connections(3) == otherBody.Connections(4) || ...
      thisBody.Connections(4) == otherBody.Connections(3)
    % Horizontal Connections
    orient = thisBody.Connections(3).Orient;
    [ymin1, ymax1, ~, ~] = thisBody.limits(enumOrient.Horizontal);
    [ymin2, ymax2, ~, ~] = otherBody.limits(enumOrient.Horizontal);
    xmin = ymin1;
    if isscalar(ymin2)
      xmin(xmin<ymin2) = ymin2;
    else
      if isscalar(ymin1)
        xmin = ymin1*ones(size(ymin2));
      end
      xmin(xmin<ymin2) = ymin2(xmin<ymin2);
    end
    xmax = ymax1;
    if isscalar(ymax2)
      xmax(xmax>ymax2) = ymax2;
    else
      if isscalar(ymin1)
        xmax = ymax1*ones(size(ymax2));
      end
      xmax(xmax>ymax2) = ymax2(xmax>ymax2);
    end
    if thisBody.Connections(3) == otherBody.Connections(4)
      y = thisBody.Connections(3);
    else
      y = thisBody.Connections(4);
    end
    doesit = any(xmin<xmax);
  else
    doesit = false;
    orient = enumOrient.Vertical;
    xmin = inf;
    xmax = inf;
    y = inf;
  end
end

%% Update on Demand
function update(this)
    if isempty(this.ID); this.ID = this.Group.Model.getBodyID(); end
    if isempty(this.Connections)
        this.isChanged = false;
        return;
    end
    if any(~isvalid(this.Sensors))
        this.Sensors = this.Sensors(isvalid(this.Sensors));
    end
    if any(~isvalid(this.PVoutputs))
        this.PVoutputs = this.PVoutputs(isvalid(this.PVoutputs));
```

```
end

if ~isempty(this.Matrix)
    if isempty(this.Matrix.matl) || isempty(this.Matrix.Dh)
        delete(this.Matrix);
        this.Matrix(:) = [];
    elseif ~(this.Matrix.Body == this)
        this.Matrix.Body = this;
    end
end

this.isChanged = false;

% Update Connections
for iCon = this.Connections
    found = false;
    iCon.CleanUpBodies;
    for iBody = iCon.Bodies
        if iBody == this; found = true; end
    end
    if ~found; iCon.addBody(this); end
end

this.sortConnections();
%% Update Limits
% Find vertical connections
nv = 2; nh = 2;
arrConV(2) = Connection();
arrConH(2) = Connection();
for iCon = this.Connections
    if iCon.Orient == enumOrient.Vertical
        arrConV(nv) = iCon; nv = 1;
    else
        arrConH(nh) = iCon; nh = 1;
    end
end
if arrConV(1).x > arrConV(2).x
    this.s_lb_Vert = arrConV(2).x;
    this.s_ub_Vert = arrConV(1).x;
else
    this.s_lb_Vert = arrConV(1).x;
    this.s_ub_Vert = arrConV(2).x;
end
if arrConH(1).x > arrConH(2).x
    this.s_lb_Hor = arrConH(2).x;
    if arrConH(2).get('isStationary')
        this.d_lb_Hor = this.s_lb_Hor;
    else
        this.d_lb_Hor = this.s_lb_Hor + arrConH(2).RefFrame.Positions;
    end
    this.s_ub_Hor = arrConH(1).x;
    if arrConH(1).get('isStationary')
        this.d_ub_Hor = this.s_ub_Hor;
    else
        this.d_ub_Hor = this.s_ub_Hor + arrConH(1).RefFrame.Positions;
    end
else
    this.s_lb_Hor = arrConH(1).x;
    if arrConH(1).isStationary
        this.d_lb_Hor = this.s_lb_Hor;
    else
        this.d_lb_Hor = this.s_lb_Hor + arrConH(1).RefFrame.Positions;
    end
    this.s_ub_Hor = arrConH(2).x;
    if arrConH(2).isStationary
        this.d_ub_Hor = this.s_ub_Hor;
    else
        this.d_ub_Hor = this.s_ub_Hor + arrConH(2).RefFrame.Positions;
    end
end
```

```
%% Update MovingStatus
found = false;
frame = [];
varenum = enumMove.Stretching;
for i = 1:length(this.Connections)
    if ~this.Connections(i).get('isStationary')
        frame = this.Connections(i).RefFrame;
        found = true;
        break;
    end
end
if ~found
    varenum = enumMove.Static;
else
    found = false;
    for j = i+1:length(this.Connections)
        if ~this.Connections(j).get('isStationary') ...
                && this.Connections(i).RefFrame == frame
            varenum = enumMove.Moving;
            found = true;
        end
    end
    if ~found
        varenum = enumMove.Stretching;
    end
end
this.StateMovingStatus = varenum;

%% Update isValid
varb = true;
isSolid = (this.matl.Phase == enumMaterial.Solid);
% Gas bodies do not support multiple dimensions
if isSolid
    % SOLIDS MUST HAVE FINITE VOLUME
    [~,~,dim1, dim2] = limits(this,enumOrient.Vertical);
    if dim1 == dim2
        fprintf(...
            ['Solid volumes must have finite volumes, please ' ...
            'define a x-dimension for ' ...
            this.name '.\n']);
        varb = false;
    end
    [~,~,dim1, dim2] = limits(this,enumOrient.Horizontal);
    if dim1 == dim2
        fprintf(...
            ['Solid volumes must have finite volumes, please ' ...
            'define a y-dimension for ' ...
            this.name '.\n']);
        varb = false;
    end
    % SOLIDS CANNOT STRETCH
    if this.MovingStatus == enumMove.Stretching
        fprintf(...
            ['Solid volumes cannot be stretched, please define ' ...
            'the same frame to both lateral surfaces of ' ...
            this.name '.\n']);
        varb = false;
    end
else
    % GASES CANNOT HAVE MULTIPLE DIMENSIONS
    if min(this.divides) ~= 1
        fprintf(...
            ['Gas volumes are restricted to single dimensional discretization,' ...
            'please review '  this.name  '"s definition.\n']);
        varb = false;
    end
end

% Check with interference from other bodies
if this.Group.isOverlaping(this)
```

```
            varb = false;
        end
        %fprintf(['Update Body: ' this.name '\n']);
        this.isStateValid = varb;
    end
    function resetDiscretization(this)
        for iCon = this.Connections
            iCon.resetDiscretization();
        end
        this.Nodes(:) = [];
        this.Faces(:) = [];
        this.isStateDiscretized = false;
    end
    function change(this)
        this.isChanged = true;
        this.resetDiscretization();
        this.Group.change();
    end
    function name = get.name(this)
        if isempty(this.customname)
            [~,~,x1,x2] = this.limits(enumOrient.Vertical);
            [~,~,y1,y2] = this.limits(enumOrient.Horizontal);
            name = [this.matl.name ' Body ' ...
                '(' num2str(x1) ', ' num2str(x2) ' )' ...
                '(' num2str(y1) ', ' num2str(y2) ' ) vol:' ...
                num2str(pi*(x2^2-x1^2)*(y2(1)-y1(1))) ];
        else
            name = this.customname;
        end
    end
    function [d_lb, d_ub, s_lb, s_ub] = limits(this, Orient)
        if this.isChanged; this.update(); end
        switch Orient
            case enumOrient.Vertical
                d_lb = 0;
                d_ub = 0;
                s_lb = this.s_lb_Vert;
                s_ub = this.s_ub_Vert;
            case enumOrient.Horizontal
                d_lb = this.d_lb_Hor;
                d_ub = this.d_ub_Hor;
                s_lb = this.s_lb_Hor;
                s_ub = this.s_ub_Hor;
        end
    end
    function isValid = get.isValid(this)
        this.update();
%         if this.isChanged; this.update(); end
        isValid = this.isStateValid;
    end
    function frame = get.RefFrame(this)
        if this.isChanged; this.update(); end
        frame = [];
        if this.MovingStatus == enumMove.Moving
            for iCon = this.Connections
                if iCon.Orient == enumOrient.Horizontal && ~iCon.get('isStationary')
                    frame = iCon.RefFrame;
                end
            end
        end
    end
    function MovingStatus = get.MovingStatus(this)
        if this.isChanged; this.update(); end
        MovingStatus = this.StateMovingStatus;
    end
    function Discretized = get.isDiscretized(this)
        if this.isChanged; this.update(); end
        if isempty(this.Nodes)
            this.isStateDiscretized = false;
        end
        Discretized = this.isStateDiscretized;
```

```
end

%% Property Parameters
function Temp = get.Temperature(this)
    if isempty(this.customTemperature)
        Temp = this.Group.Model.engineTemperature;
    else
        Temp = this.customTemperature;
    end
end
function Press = get.Pressure(this)
    if isempty(this.customPressure)
        Press = this.Group.Model.enginePressure;
    else
        Press = this.customPressure;
    end
end

%% Node Generation
function discretize(this)
    this.update();
    if this.isDiscretized % || ~this.isValid
        return;
    end
    isSolid = (this.matl.Phase == enumMaterial.Solid);
    if isSolid; FType = enumFType.Solid; else; FType = enumFType.Gas; end
    if this.isChanged
        this.update();
    end
    %% DETERMINE THE NODE TYPE
    if isSolid
        NType = enumNType.SN; % SN - Solid Node
    else
        % SVGN - Static Volume Gas Node
        % VVGN - Variable Volume Gas Node
        % SAGS - Shearing Annular Gas Node
        switch this.MovingStatus
            case enumMove.Static
                % Decide, is it shearing or just moving?
                % Looking at the two vertical connections
                for iCon = this.Connections
                    NType = enumNType.SVGN;
                    if iCon.Orient == enumOrient.Vertical
                        % Find a body that shares that
                        % connection and scope of x
                        for iBody = this.Group.Bodies
                            if iBody ~= this
                                if ~isempty(iBody.RefFrame)
                                    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                                    %NType = enumNType.SAGN;
                                    %frame = iBody.RefFrame;
                                    break;
                                end
                            end
                        end
                    end
                end
            case enumMove.Moving
                % Decide, is it shearing or just moving?
                % Looking at the two vertical connections
                for iCon = this.Connections
                    NType = enumNType.SVGN;
                    if iCon.Orient == enumOrient.Vertical
                        % Find a body that shares that
                        % connection and scope of x
                        for iBody = this.Group.Bodies
                            if iBody ~= this
                                if isempty(iBody.RefFrame)
                                    NType = enumNType.SAGN;
                                    frame = this.RefFrame;
                                    break;
```

```
                                    end
                                end
                            end
                        end
                    end
                case enumMove.Stretching
                    NType = enumNType.VVGN;
            end
        end

        %% Y LIMITS
        [ymin,ymax,~,~] = this.limits(enumOrient.Horizontal);
        if ~prod(ymax>=ymin) % Will give false if this is not true everywhere
            changed_registered = false;
            for iCon = this.Group.Connections
                if iCon.Orient == this.Connections(3).Orient && ...
                        iCon.x == this.Connections(3).x
                    if length(iCon.RefFrame) ~= length(this.Connections(3).RefFrame)
                        this.Connections(3) = iCon.x;
                        this.update();
                        changed_registered = true;
                    end
                elseif iCon.Orient == this.Connections(4).Orient && ...
                        iCon.x == this.Connections(4).x
                    if length(iCon.RefFrame) > length(this.Connections(4).RefFrame)
                        this.Connections(4).RefFrame = iCon.RefFrame;
                        this.update();
                        changed_registered = true;
                    end
                end
            end
            if changed_registered
                fprintf(...
                    ['XXX A memory error occured for Body ' this.name ...
                    ' in which a connection reference was duplicated,' ...
                    ' this has been mitigated but will require a restart of' ...
                    ' the discretization. XXX\n']);
                return;
            else
                fprintf(...
                    ['XXX Calculated maximum and minimum positions ' this.name ...
                    ' for will result in a case of negative area, consider' ...
                    ' readjusting gas volume or start positions to mitigate' ...
                    ' this overlap. XXX\n']);
                return;
            end
        end
        %% X LIMITS
        [~,~,xmin,xmax] = this.limits(enumOrient.Vertical);
        if isempty(this.DiscretizationFunctionRadial)
            x = transpose(linspace(xmin,xmax,this.divides(1)+1));
        else
            if isSolid
                [x] =
this.DiscretizationFunctionRadial(this,this.Group.Model.Mesher,enumOrient.Vertical);
                if isempty(x); return; end
                deltas = diff(x);
                if ~(all(sign(deltas) > 0) || all(sign(deltas) < 0))
                    fprintf('XXX x generation issue in Body\m');
                    [x] =
this.DiscretizationFunctionRadial(this,this.Group.Model.Mesher,enumOrient.Vertical);
                end
                if x(end,1) < x(1,1); x = flip(x,1); end
            else
                if isempty(this.Matrix)
                    fprintf(...
                        ['XXX Smart Discretization functions currently cannot' ...
                        ' be used for matrixless gas nodes. Problem found in radial direction
of Body:' ...
                        this.name '. XXX\n']);
                    return;
```

```
                    else
                        if this.divides(1) > 1
                            [x] =
this.DiscretizationFunctionRadial(this,this.Group.Model.Mesh,enumOrient.Vertical);
                            if isempty(x); return; end
                            deltas = diff(x);
                            if ~(all(sign(deltas) > 0) || all(sign(deltas) < 0))
                                fprintf('XXX x generation issue in Body\m');
                                [x] =
this.DiscretizationFunctionRadial(this,this.Group.Model.Mesher,enumOrient.Vertical);
                            end
                            if x(end,1) < x(1,1); x = flip(x,1); end
                        else
                            x = [xmin; xmax];
                        end
                    end
                end
            end


            %% Y LIMITS
            LEN = this.divides(2)+1;
            if isempty(this.DiscretizationFunctionAxial)
                if isscalar(ymin)
                    if  isscalar(ymax)
                        % SCALAR-SCALAR CASE
                        y = transpose(linspace(ymin,ymax,LEN));
                    else % only ymin is scalar - stretching
                        y = zeros(LEN,Frame.NTheta);
                        for i = 1:length(ymax)
                            y(:,i) = transpose(linspace(ymin,ymax(i),LEN));
                        end
                    end
                elseif isscalar(ymax) % only ymax is scalar - stretching
                    y = zeros(this.divides(2)+1,Frame.NTheta);
                    for i = 1:length(ymin)
                        y(:,i) = transpose(linspace(ymin(i),ymax,LEN));
                    end
                else % both are stretching or moving
                    y = zeros(this.divides(2)+1,Frame.NTheta);
                    for i = 1:length(ymin)
                        y(:,i) = transpose(linspace(ymin(i),ymax(i),LEN));
                    end
                end
            else
                if isSolid
                    [y] =
this.DiscretizationFunctionAxial(this,this.Group.Model.Mesher,enumOrient.Horizontal);
                    if isempty(y); return; end
                    deltas = diff(y);
                    try
                        if ~(all(all(sign(deltas) > 0)) || all(all(sign(deltas) < 0)))
                            fprintf('XXX y generation issue in Body\m');

this.DiscretizationFunctionAxial(this,this.Group.Model.Mesher,enumOrient.Horizontal);
                        end
                    catch
                        fprintf('err');
                    end
                    if y(end,1) < y(1,1); y = flip(y,1); end
                else
                    if isempty(this.Matrix)
                        fprintf(...
                            ['XXX Smart Discretization functions currently cannot' ...
                            ' be used for matrixless gas nodes. Problem found in axial direction
of Body:' ...
                            this.name '. XXX\n']);
                        return;
                    else
                        if this.divides(2) > 1
```

```
                            [y] =
this.DiscretizationFunctionAxial(this,this.Group.Model.Mesher,enumOrient.Horizontal);
                            if isempty(y); return; end
                            deltas = diff(y);
                            try
                                if ~(all(all(sign(deltas) > 0)) || all(all(sign(deltas) < 0)))
                                    fprintf('XXX y generation issue in Body\m');

this.DiscretizationFunctionAxial(this,this.Group.Model.Mesher,enumOrient.Horizontal);
                                end
                            catch
                                fprintf('err');
                            end
                            if y(end,1) < y(1,1); y = flip(y,1); end
                        else
                            if isscalar(ymin)
                                if  isscalar(ymax)
                                    % SCALAR-SCALAR CASE
                                    y = transpose(linspace(ymin,ymax,LEN));
                                else % only ymin is scalar - stretching
                                    y = zeros(LEN,Frame.NTheta);
                                    for i = 1:length(ymax)
                                        y(:,i) = transpose(linspace(ymin,ymax(i),LEN));
                                    end
                                end
                            elseif isscalar(ymax) % only ymax is scalar - stretching
                                y = zeros(LEN,Frame.NTheta);
                                for i = 1:length(ymin)
                                    y(:,i) = transpose(linspace(ymin(i),ymax,LEN));
                                end
                            else % both are stretching or moving
                                y = zeros(LEN,Frame.NTheta);
                                for i = 1:length(ymin)
                                    y(:,i) = transpose(linspace(ymin(i),ymax(i),LEN));
                                end
                            end
                        end
                    end
                end

                if strcmp(this.matl.name ,'Perfect Insulator') || ...
                    strcmp(this.matl.name ,'Constant Temperature')
                  x = [x(1,:); x(end,:)];
                  y = [y(1,:); y(end,:)];
                end
                divx = size(x,1) - 1;
                divy = size(y,1) - 1;

                this.Nodes = Node.empty;
                this.Faces = Face.empty;

                %% INITIALIZE
                sendtoConnections{4} = NodeContact.empty;
                ncount = divx*divy;
                fcount = (divx-1)*divy + divx*(divy-1);
                %fcount = prod([divx divy]-[1 0])+prod(this.divides-[0 1]);

                %% FOR EACH DISTINCT NODE WITHIN BODY
                for iy = size(y,1) - 1:-1:1
                    % loop initialization
                    starty = y(iy,:);
                    endy = y(iy+1,:);
                    starty = CollapseVector(starty);
                    endy = CollapseVector(endy);

                    for ix = size(x,1) - 1:-1:1
                        %% Define this.Nodes
                        CurrentNode =
Node(NType,x(ix),x(ix+1),starty,endy,Face.empty,Node.empty,this,0);
                        this.Nodes(ncount) = CurrentNode;
```

```
                ncount = ncount - 1;
            end
        end

        for i = 1:length(this.Nodes)
            nd = this.Nodes(i);
            if nd.xmin == xmin
              sendtoConnections{1}(end+1) = ...
                NodeContact(nd,nd.ymin,nd.ymax,FType,this.Connections(1));
            end
            if nd.xmax == xmax
              sendtoConnections{2}(end+1) = ...
                NodeContact(nd,nd.ymin,nd.ymax,FType,this.Connections(2));
            else
              % Make Vertical connection
              this.Faces(fcount) = ...
                  Face([this.Nodes(i+1) nd],FType,enumOrient.Vertical);
              fcount = fcount - 1;
            end
            if nd.ymin(1) == ymin(1)
              sendtoConnections{3}(end+1) = ...
                NodeContact(nd,nd.xmin,nd.xmax,FType,this.Connections(3));
            end
            if nd.ymax(1) == ymax(1)
              sendtoConnections{4}(end+1) = ...
                NodeContact(nd,nd.xmin,nd.xmax,FType,this.Connections(4));
            else
              % Make Horizontal connection
              this.Faces(fcount) = ...
                  Face([this.Nodes(i+divx) nd],FType,enumOrient.Horizontal);
              fcount = fcount - 1;
            end
        end

        %% SEND THE COMPILED LIST TO CONNECTIONS FOR PROCESSING
        for i = 1:length(this.Connections)
            this.Connections(i).addNodeContacts(sendtoConnections{i});
        end

        if ~isempty(this.Matrix) && ~isempty(this.Matrix.Geometry)
            % Pass Nodes to Matrix for generation
            [nodes, faces] = this.Matrix.discretize(this.Nodes);
            this.Nodes = [this.Nodes nodes];
            this.Faces = [this.Faces faces];
        end

        this.isStateDiscretized = true;
        % fprintf(['Body ' this.name ' is discretized, but this.Nodes still need to reference
their this.Faces.\n']);
    end

    %% GRAPHICS FUNCTIONS
    function color = getColor(this)
        if this.isActive
            color = Body.ActiveColor;
        else
            color = Body.NormalColor;
        end
    end
    function updateColor(this)
        if ~isempty(this.GUIObjects)
            for iGraphicsObject = this.GUIObjects
                set(iGraphicsObject,'FaceColor',this.getColor());
            end
        end
    end
    function removeFromFigure(this,AxisReference)
        if ~isempty(this.GUIObjects)
            children = get(AxisReference,'Children');
            for obj = this.GUIObjects
```

```
                    if isgraphics(obj)
                        for i = length(children):-1:1
                            if isgraphics(children(i)) && children(i) == obj
                                children(i).delete;
                                break;
                            end
                        end
                    end
                end
                this.GUIObjects = [];
            end
        end
        function show(this,AxisReference,Inc)
            if this.isChanged; this.update(); end
            % fprintf(['Plotted Body ' this.name '.\n']);
            % Remove object from plot
            % this.removeFromFigure(AxisReference);

            if this.isValid
                if ~isempty(this.matl) && ~isempty(this.matl.Color)
                    fillcolor = this.matl.Color;
                else
                    fillcolor = Body.MaterialUndefinedColor;
                end
            else
                fillcolor = Body.InvalidColor;
            end
            edgecolor = this.getColor();
            % Find the extents of the body and position the rectangle(s)
            % accordingly

            %% Case 1: If it has 6 connections it is a cuboid
            if length(this.Connections) == 6
                % Render as cuboid

                return;
            end

            %% Case 2: It is a cylinder
            % If one connection is vertical and x = 0
            for iConnection = this.Connections
                if iConnection.Orient == enumOrient.Vertical && iConnection.x == 0
                    % Treat it as a cylinder
                    [~, ~,~,maxx] = this.limits(enumOrient.Vertical);
                    if nargin > 2 % Inc Exists
                        [miny, maxy,~,~] = this.limits(enumOrient.Horizontal);
                        if length(miny) > 1; miny = miny(Inc); end
                        if length(maxy) > 1; maxy = maxy(Inc); end
                    else
                        % plot a motion ghost
                        if this.Group.Model.showBodyGhosts && this.MovingStatus ==
enumMove.Moving
                            [y1,y2,miny,maxy] = this.limits(enumOrient.Horizontal);
                            gminy = max(y1);
                            gmaxy = max(y2);
                            OffsetRot = this.Group.Position.Rot;
                            R = RotMatrix(OffsetRot);
                            RootPosition = [this.Group.Position.x; this.Group.Position.y];
                            p = [R*[gminy;maxx]+RootPosition ...
                                R*[gmaxy;maxx]+RootPosition ...
                                R*[gmaxy;-maxx]+RootPosition ...
                                R*[gminy;-maxx]+RootPosition];

                            this.Group.Model.GhostGUIObjects(end+1) = fill(p(1,:),p(2,:),...
                                fillcolor,...
                                'EdgeColor',edgecolor,...
                                'LineWidth',1,...
                                'HitTest','off',...
                                'FaceAlpha',0.25,...
                                'EdgeAlpha',0.75);
                        else
```

```
                [~,~,miny,maxy] = this.limits(enumOrient.Horizontal);
            end
        end

        OffsetRot = this.Group.Position.Rot;
        R = RotMatrix(OffsetRot);
        RootPosition = [this.Group.Position.x; this.Group.Position.y];
        p = [R*[miny;maxx]+RootPosition ...
            R*[maxy;maxx]+RootPosition ...
            R*[maxy;-maxx]+RootPosition ...
            R*[miny;-maxx]+RootPosition];

        this.removeFromFigure(AxisReference)
        this.GUIObjects = fill(p(1,:),p(2,:),...
            fillcolor,...'FaceColor',fillcolor,...
            'EdgeColor',edgecolor,...
            'LineWidth',1,...
            'HitTest','off');
        return;
    end
end

%% Case 3: It is an annulus
% Get extents of body
[~,~,minx, maxx] = this.limits(enumOrient.Vertical);
if nargin > 2 % Inc exists
    [miny, maxy,~,~] = this.limits(enumOrient.Horizontal);
    if length(miny) > 1; miny = miny(Inc); end
    if length(maxy) > 1; maxy = maxy(Inc); end
else
    % plot a motion ghost
    if this.Group.Model.showBodyGhosts && this.MovingStatus == enumMove.Moving
        [y1,y2,miny,maxy] = this.limits(enumOrient.Horizontal);
        gminy = max(y1);
        gmaxy = max(y2);
        OffsetRot = this.Group.Position.Rot;
        R = RotMatrix(OffsetRot);
        RootPosition = [this.Group.Position.x; this.Group.Position.y];
        p = [R*[gminy;maxx]+RootPosition ...
            R*[gmaxy;maxx]+RootPosition ...
            R*[gmaxy;minx]+RootPosition ...
            R*[gminy;minx]+RootPosition];

        this.Group.Model.GhostGUIObjects(end+1) = fill(p(1,:),p(2,:),...
            fillcolor,...
            'EdgeColor',edgecolor,...
            'LineWidth',1,...
            'HitTest','off',...
            'FaceAlpha',0.25,...
            'EdgeAlpha',0.75);

        p = [R*[gminy;-minx]+RootPosition ...
            R*[gminy;-maxx]+RootPosition ...
            R*[gmaxy;-maxx]+RootPosition ...
            R*[gmaxy;-minx]+RootPosition];

        this.Group.Model.GhostGUIObjects(end+1) = fill(p(1,:),p(2,:),...
            fillcolor,...'FaceColor',fillcolor,...
            'EdgeColor',edgecolor,...
            'LineWidth',1,...
            'HitTest','off',...
            'FaceAlpha',0.25,...
            'EdgeAlpha',0.75);
    else
        [~,~,miny,maxy] = this.limits(enumOrient.Horizontal);
    end
end
OffsetRot = this.Group.Position.Rot;
R = RotMatrix(OffsetRot);
RootPosition = [this.Group.Position.x; this.Group.Position.y];
```

```
            p1 = [R*[miny;maxx]+RootPosition ...
                R*[maxy;maxx]+RootPosition ...
                R*[maxy;minx]+RootPosition ...
                R*[miny;minx]+RootPosition];
            p2 = [R*[miny;-minx]+RootPosition ...
                R*[miny;-maxx]+RootPosition ...
                R*[maxy;-maxx]+RootPosition ...
                R*[maxy;-minx]+RootPosition];

            if length(this.GUIObjects) == 2 && ...
                    isgraphics(this.GUIObjects(1)) && ...
                    isgraphics(this.GUIObjects(2))
                set(this.GUIObjects(1),'XData',p1(1,:));
                set(this.GUIObjects(1),'YData',p1(2,:));
                set(this.GUIObjects(1),'FaceColor',fillcolor);
                set(this.GUIObjects(1),'EdgeColor',edgecolor);
                set(this.GUIObjects(2),'XData',p2(1,:));
                set(this.GUIObjects(2),'YData',p2(2,:));
                set(this.GUIObjects(2),'FaceColor',fillcolor);
                set(this.GUIObjects(2),'EdgeColor',edgecolor);
            else
                this.removeFromFigure(AxisReference)
                this.GUIObjects(2) = fill(p2(1,:),p2(2,:),...
                    fillcolor,...
                    'EdgeColor',edgecolor,...
                    'LineWidth',1,...
                    'HitTest','off');
                this.GUIObjects(1) = fill(p1(1,:),p1(2,:),...
                    fillcolor,...
                    'EdgeColor',edgecolor,...
                    'LineWidth',1,...
                    'HitTest','off');
            end

        end

    end
end
```

Bridge

The bridge is a class that includes:

A creation function.

A function that is called when the bridge is deleted, to clean up the references.

A get/set interface used by the property editor on the main GUI.

A set of functions for updating, the name, validity and discretization status.

The discretization function which may return faces depending on the mode.

A set of functions for displaying or not displaying the bridge on the GUI.

```
classdef Bridge < handle
  %UNTITLED Summary of this class goes here
  %   Detailed explanation goes here

  properties
    Body1 Body;
    Body2 Body;
    Connection1 Connection;
    Connection2 Connection;
    x double;

    GUIObjects;
    isActive logical = false;

    isChanged logical = true;
    isDiscretized logical = false;

    Faces Face;
  end

  properties (Dependent)
    isValid;
    name;
  end

  methods
    %% Constructor
    function this = Bridge(Body1,Body2,C1,C2,x)
      if nargin > 3
          this.Body1 = Body1;
          this.Body2 = Body2;
          this.Connection1 = C1;
          this.Connection2 = C2;
          if nargin > 4
            this.x = x;
          else
            this.x = 0;
          end
          fprintf('Bridge Created Successfully.\n');
      end
    end
    function deReference(this)
      if isvalid(this.Body1)
        iModel = this.Body1.Group.Model;
```

```
  elseif isvalid(this.Body2)
    iModel = this.Body2.Group.Model;
  end
  for i = length(iModel.Bridges):-1:1
    if iModel.Bridges(i) == this
      iModel.Bridges(i) = [];
      break;
    end
  end
  for iBody = [this.Body1 this.Body2]
    if isvalid(iBody); iBody.change(); end
  end
  for iCon = [this.Connection1 this.Connection2]
    if isvalid(iCon); iCon.change(); end
  end
  this.Faces(:) = [];
  if isvalid(gca)
    this.removeFromFigure(gca);
  end
  this.delete();
end

%% Get/Set Interface
function Item = get(this,PropertyName)
  switch PropertyName
    case 'Connection 1'
      Item = this.Connection1;
    case 'Connection 2'
      Item = this.Connection2;
    case 'Body 1'
      Item = this.Body1;
    case 'Body 2'
      Item = this.Body2;
    otherwise
      fprintf(['XXX Bridge GET Inteface for ' PropertyName ' is not found XXX\n']);
  end
end
function set(~,PropertyName,~)
  switch PropertyName
    otherwise
      fprintf(['XXX Bridge SET Inteface for ' PropertyName ' is not found XXX\n']);
      return;
  end
  this.change();
end

%% (Update on Demand)
function change(this)
  this.isChanged = true;
  this.isDiscretized = false;
  if this.isDiscretized
    this.Connection1.change();
    this.Connection2.change();
  end
end
function name = get.name(this)
  if this.Connection1.Orient == enumOrient.Vertical
    [~,~,x1,~] = this.Body1(1).limits(enumOrient.Vertical);
    if this.Connection1.x == x1; descriptor1 = 'Inside';
    else; descriptor1 = 'Outside'; end
  else
    [~,~,y1,~] = this.Body1(1).limits(enumOrient.Horizontal);
    if this.Connection1.x == y1; descriptor1 = 'Bottom';
    else; descriptor1 = 'Top'; end
  end
  if this.Connection2.Orient == enumOrient.Vertical
    [~,~,x1,~] = this.Body2(1).limits(enumOrient.Vertical);
    if this.Connection2.x == x1; descriptor2 = 'Inside';
    else; descriptor2 = 'Outside'; end
  else
    [~,~,y1,~] = this.Body2(1).limits(enumOrient.Horizontal);
```

```
    if this.Connection2.x == y1; descriptor2 = 'Bottom';
    else; descriptor2 = 'Top'; end
  end
  name1 = [];
  for iBody = this.Body1
    for i = 1:length(iBody.Group.Bodies)
      if iBody.Group.Bodies(i) == iBody
        break;
      end
    end
    name1 = [name1 num2str(i) ' '];
  end
  name1 = ['Bodies ' name1 ' of Group' this.Body1(1).Group.name];
  name2 = [];
  for iBody = this.Body2
    for i = 1:length(iBody.Group.Bodies)
      if iBody.Group.Bodies(i) == iBody
        break;
      end
    end
    name2 = [name2 num2str(i) ' '];
  end
  name1 = ['Bodies ' name1 ' of Group' this.Body1(1).Group.name];
  name = ['Bridge btwn. ' descriptor1 ' of ' name1 ' and ' ...
    descriptor2 ' of ' name2];
end
function Valid = get.isValid(this)
  Valid = true;
  if isempty(this.Body1) ...
      || isempty(this.Body2) ...
      || isempty(this.Connection1) ...
      || isempty(this.Connection2)
    Valid = false;
    fprintf('XXX Bridge is created but not fully defined XXX');
    return;
  end
  for iBody = this.Body1
    if ~any(iBody.Connections == this.Connection1)
      Valid = false;
      fprintf(['XXX Bridge ' this.name ...
        'has invalid, body and connection pairs']);
      return;
    end
  end
  for iBody = this.Body2
    if ~any(iBody.Connections == this.Connection2)
      Valid = false;
      fprintf(['XXX Bridge ' this.name ...
        'has invalid, body and connection pairs']);
      return;
    end
  end
end

%% Face Generation
function resetDiscretization(this)
  this.Faces(:) = [];
  this.isDiscretized = false;
  this.isChanged = true;
end
function discretize(this)
  this.isDiscretized = false;
  Con1 = this.Connection1;
  Con2 = this.Connection2;
  for iBody = [Con1.Bodies Con2.Bodies]
    if ~iBody.isDiscretized
      iBody.discretize();
      if ~iBody.isDiscretized
        fprintf(['XXX Exited Discretization at Body: ' iBody.name '.XXX\n']);
        return;
      end
```

```
  end
end

if Con1.Orient == Con2.Orient && this.x == 0
  %% Standard, same Orientation
  % Validity Check
  if Con1.Orient == enumOrient.Vertical
    if Con1.x ~= Con2.x
      fprintf(['XXX Bridge: ' this.name ...
        ' Failed to discretize due to incompatible radii']);
      this.isDiscretized = false;
      return;
    end
  end

  % Occlude non-B1 Con1 with B2 Con2
  i = 1;
  keep = true(size(Con1.NodeContacts));
  for Others = Con1.NodeContacts
    if Others.Node.Body ~= this.Body1
      for B2 = Con2.NodeContacts
        if B2.Node.Body == this.Body2
          keep(i) = B2.AlignedMask(Others,-inf,inf);
        end
        if ~keep(i); break; end
      end
    end
    i = i + 1;
  end
  Con1.NodeContacts = Con1.NodeContacts(keep);

  % Add B2 Con2 copies to Con1
  % ... Copy B2 Con2
  B2C2 = NodeContact.empty;
  for NC = Con2.NodeContacts
    if NC.Node.Body == this.Body2
      B2C2(end+1) = CopyClass(NC);
    end
  end

  % Occlude B2 Con2 with B1 Con1
  i = 1;
  keep = true(size(Con2.NodeContacts));
  for B2 = Con2.NodeContacts
    if B2.Node.Body == this.Body2
      for B1 = Con1.NodeContacts
        if B1.Node.Body == this.Body1
          keep(i) = B1.AlignedMask(B2,-inf,inf);
        end
        if ~keep(i); break; end
      end
    end
    i = i + 1;
  end
  Con2.NodeContacts = Con2.NodeContacts(keep);

  % ... Add to Con1
  Con1.addNodeContacts(B2C2);

elseif Con1.Orient == enumOrient.Vertical && Con1.Orient == Con2.Orient
  %% Both Vertical, Offset

  % Validity Check
  if Con1.x ~= Con2.x
    fprintf(['XXX Bridge: ' this.name ...
      ' Failed to discretize due to incompatible radii']);
    this.isDiscretized = true;
    return;
  end

  %% Both Vertical
```

```
  % Get node contacts from Con2 and shift them
  for NC = Con2.NodeContacts
    NC.Start = NC.Start + this.x;
    NC.End = NC.End + this.x;
  end

  % Con1 mask other of Con2 within bounds of B2
  keep = true(size(Con2.NodeContacts));
  switch Con1.Orient
    case enumOrient.Vertical
      [b1,b2,~,~] = this.Body2.limits(enumOrient.Horizontal);
    case enumOrient.Horizontal
      [b1,b2,~,~] = this.Body2.limits(enumOrient.Vertical);
  end
  for mask = Con1.NodeContacts
    if mask.Node.Body == this.Body1
      for i = 1:length(Con2.NodeContacts)
        if keep(i)
          target = Con2.NodeContacts(i);
          if target.Node.Body ~= this.Body2
            keep(i) = mask.AlignedMask(target,b1,b2);
          end
        end
      end
    end
  end
  Con2.NodeContacts = Con2.NodeContacts(keep);

  % Con2 mask other of Con1 within bounds of B1
  keep = true(size(Con1.NodeContacts));
  switch Con1.Orient
    case enumOrient.Vertical
      [b1,b2,~,~] = this.Body1.limits(enumOrient.Horizontal);
    case enumOrient.Horizontal
      [b1,b2,~,~] = this.Body1.limits(enumOrient.Vertical);
  end
  for mask = Con2.NodeContacts
    if mask.Node.Body == this.Body2
      for i = 1:length(Con1.NodeContacts)
        if keep(i)
          target = Con1.NodeContacts(i);
          if target.Node.Body ~= this.Body1
            keep(i) = mask.AlignedMask(target,b1,b2);
          end
        end
      end
    end
  end
  Con1.NodeContacts = Con1.NodeContacts(keep);

  % Copy NContacts of B1 from C1 onto C2
  MoveContacts = NodeContact.empty;
  for NC = Con1.NodeContacts
    if NC.Node.Body == this.Body1
      MoveContacts(end+1) = NodeContact(...
        NC.Node,NC.Start,NC.End,NC.Type,NC.Connection);
    end
  end
  Con2.addNodeContacts(MoveContacts);

  % Unshift Node Contacts in Con2
  for NC = Con2.NodeContacts
    NC.Start = NC.Start - this.x;
    NC.End = NC.End - this.x;
  end

elseif Con1.Orient == enumOrient.Horizontal && ...
    Con2.Orient == enumOrient.Horizontal
  %% Both Horizontal, Offset
  % Determine which one to take from, it would be the smaller of the
```

```
% two
r1 = 0;
r2 = 0;
for NContact = this.Connection1.NodeContacts
  if any(NContact.Node.Body == this.Body1)
    if r1 < NContact.End
      r1 = NContact.End;
    end
  end
end
for NContact = this.Connection2.NodeContacts
  if any(NContact.Node.Body == this.Body2)
    if r2 < NContact.End; r2 = NContact.End; end
  end
end
if r1 > r2
  Source = this.Connection2;
  Destination = this.Connection1;
  DestinationBody = this.Body1;
  SourceBody = this.Body2;
  max_r = r2;
else
  Source = this.Connection1;
  Destination = this.Connection2;
  DestinationBody = this.Body2;
  SourceBody = this.Body1;
  max_r = r1;
end
min_r = 10000;
for NContact = Source.NodeContacts
  if NContact.Node.Body == SourceBody
    if min_r > NContact.Start
      min_r = NContact.Start;
      if min_r == 0; break; end
    end
  end
end


% Gather Node Contacts from Source for comparison with Destination
SContacts(length(Source.NodeContacts)) = NodeContact; n = 1;
keep = true(size(Source.NodeContacts));
for i = 1:length(Source.NodeContacts)
  NContact = Source.NodeContacts(i);
  if NContact.Node.Body == SourceBody
    SContacts(n) = NContact; n = n + 1;
    keep(i) = false;
  end
end
Source.NodeContacts = Source.NodeContacts(keep);
SContacts = SContacts(1:n-1);
Ss = zeros(size(SContacts));
Es = zeros(size(SContacts));
i = 1;
for NContact = SContacts
  Es(i) = NContact.End;
  Ss(i) = NContact.Start;
  i = i + 1;
end

keep = true(size(Destination.NodeContacts));
keep2 = true(size(SContacts));
for i = 1:length(Destination.NodeContacts)
  if Destination.NodeContacts(i).Node.Body == DestinationBody
    DCont = Destination.NodeContacts(i);
    s = DCont.Start;
    e = DCont.End;
    for j = 1:length(SContacts)
      if keep2(j)
        % Calculate Percentange that the segment covers
        P = ...
```

```
            GetAreaPercentHorizontal(this.x,s,e,2*Es(j)) - ...
            GetAreaPercentHorizontal(this.x,s,e,2*Ss(j));
          if P == 0; continue; end
          if isempty(DCont.data)
            DCont.data = struct('Perc',1);
          end
          if isfield(DCont.data,'Perc')
            DCont.data.Perc = DCont.data.Perc - P;
          else; DCont.data.Perc = 1 - P;
          end

          % Calculate the Percentage of the source that the segment
          % ... covers
          P2 = ...
            GetAreaPercentHorizontal(this.x,Ss(j),Es(j),2*e) - ...
            GetAreaPercentHorizontal(this.x,Ss(j),Es(j),2*s);
          if isempty(SContacts(j).data)
            SContacts(j).data = struct('Perc',1);
          end
          if isfield(SContacts(j).data,'Perc')
            SContacts(j).data.Perc = SContacts(j).data.Perc - P2;
          else; SContacts(j).data.Perc = 1 - P2;
          end

          % Make Faces
          P1 = DCont.data.Perc;
          DCont.data.Perc = 1;
          NewFace = Face(...
            NodeContact(SContacts(j).Node,...
            SContacts(j).Start + this.x,SContacts(j).End + this.x,...
            SContacts(j).Type,SContacts(j).Connection),DCont,true);
          DCont.data.Perc = P1;

          % Modify Properties
          if isfield(NewFace.data,'Area')
            NewFace.data.Area = NewFace.data.Area*P;
            if isfield(NewFace.data,'R')
              NewFace.data.R = NewFace.data.R/P;
            elseif isfield(NewFace.data,'Dh')
              NewFace.data.Dh = 2*(max_r - min_r);
            end
          elseif isfield(NewFace.data,'U')
            NewFace.data.U = NewFace.data.U*P;
          end
          this.Faces = [this.Faces NewFace];

          if ~keep(i); break; end
        end
      end
    end
  end
  for i = 1:length(Destination.NodeContacts)
    if isfield(Destination.NodeContacts(i).data,'Perc')
      if Destination.NodeContacts(i).data.Perc <= 1e-6
        keep(i) = false;
      end
    end
  end
  Destination.NodeContacts = Destination.NodeContacts(keep);
  for i = 1:length(SContacts)
    if isfield(SContacts(i).data,'Perc')
      if SContacts(i).data.Perc <= 1e-6
        keep2(i) = false;
      end
    end
  end
  Source.addNodeContacts(SContacts(keep2));

else
  fprintf(['XXX The Bridge Discretization method has not been ' ...
    'updated to improved standards. It may not work as expected XXX\n']);
```

```
%% Mix, Offset
% Move Node Contacts from Connection2 that are associated with
% Body 2 and add them to Connection1 in range of Body1
if this.Connection1.Orient == enumOrient.Horizontal
  Source = this.Connection1;
  SourceBody = this.Body1;
  Destination = this.Connection2;
  DestinationBody = this.Body2;
else
  Source = this.Connection2;
  SourceBody = this.Body2;
  Destination = this.Connection1;
  DestinationBody = this.Body1;
end
max_r = 0;
min_r = 10000;
for NContact = Source.NodeContacts
  if max_r < NContact.End
    max_r = NContact.End;
  end
  if min_r > NContact.Start
    min_r = NContact.Start;
  end
end
Dh = 2*max_r - 2*min_r;
DontKeep = false(size(Source.NodeContacts));
for i = 1:length(Source.NodeContacts)
  if Source.NodeContacts(i).Node.Body == SourceBody
    SContacts = Source.NodeContacts(i);
    DontKeep(i) = true;
  end
end
Source.NodeContacts(DontKeep) = [];
for i = 1:length(Destination.NodeContacts)
  if Destination.NodeContacts(i).Node.Body == DestinationBody
    r = Destination.x;
    DCont = Destination.NodeContacts(i);
    s = DCont.Start;
    e = DCont.End;
    for j = 1:length(SContacts)
      SCont = SContacts(j);
      % Calculate Percentange that the segment covers
      if isscalar(s)
        if isscalar(e)
          % Both scalars
          P = GetAreaPercentMix(r,this.x,s,e,SCont.End) - ...
            GetAreaPercentMix(r,this.x,s,e,SCont.Start);
        else
          % just "s" is a scalar
          for k = 1:length(e)
            P(k) = GetAreaPercentMix(r,this.x,s,e(k),SCont.End) - ...
              GetAreaPercentMix(r,this.x,s,e(k),SCont.Start);
          end
        end
      else
        if isscalar(e)
          % just "e" is a scalar
          for k = 1:length(s)
            P(k) = GetAreaPercentMix(r,this.x,s(k),e,SCont.End) - ...
              GetAreaPercentMix(r,this.x,s(k),e,SCont.Start);
          end
        else
          % Both vectors
          for k = 1:length(s)
            P(k) = GetAreaPercentMix(r,this.x,s(k),e(k),SCont.End) - ...
              GetAreaPercentMix(r,this.x,s(k),e(k),SCont.Start);
          end
        end
      end
      if ~isempty(DCont.data) && isfield(DCont.data,'Perc')
        DCont.data.Perc = DCont.data.Perc - P;
```

```
          else
            DCont.data.Perc = 1 - P;
          end
          if any(P > 0)
            % Make Faces
            % Precondition
            SCont.Start = this.x - max_r;
            SCont.End = this.x + max_r;
            P1 = DCont.data.Perc;
            DCont.data.Perc = 1;
            NewFace = Face(SCont,DCont);
            % Recondition
            DCont.data.Perc = P1;
            if isfield(NewFace.data,'Area')
              NewFace.data.Area = NewFace.data.Area.*P;
              if isfield(NewFace.data,'Dh')
                NewFace.data.Dh = Dh;
              elseif isfield(NewFace.data,'R')
                NewFace.data.R = NewFace.data.R./P;
              end
            elseif isfield(NewFace.data,'U')
              NewFace.data.U = NewFace.data.U.*P;
            end
            this.Faces = [this.Faces NewFace];
          end
          if DontKeep(i)
            break;
          end
        end
      end
    end
    Destination.NodeContacts(DontKeep) = [];

  end
  this.isDiscretized = true;
end

%% Graphics
function removeFromFigure(this,AxisReference)
  if ~isempty(this.GUIObjects)
    children = get(AxisReference,'Children');
    for obj = this.GUIObjects
      if isgraphics(obj)
        for i = length(children):-1:1
          if isgraphics(children(i)) && children(i) == obj
            children(i).delete;
            break;
          end
        end
      end
    end
    this.GUIObjects = [];
  end
end
function show(this,AxisReference)
  this.removeFromFigure(AxisReference);
  % Plot a dotted line between the middle of the Connection1's Overlap
  % with Body1 to the middle of Connection2's Overlap with Body2

  % Find P1;
  Ax = this.Connection1.Group;
  R = RotMatrix(Ax.Position.Rot - pi/2);
  d = this.Connection1.x;
  switch this.Connection1.Orient
    case enumOrient.Vertical
      [~,~,y1,y2] = this.Body1.limits(enumOrient.Horizontal);
      A = [Ax.Position.x; Ax.Position.y] + R*[d; (y1+y2)/2];
      B = [Ax.Position.x; Ax.Position.y] + R*[-d; (y1+y2)/2];
    case enumOrient.Horizontal
      [~,~,x1,x2] = this.Body1.limits(enumOrient.Vertical);
      A = [Ax.Position.x; Ax.Position.y] + R*[(x1+x2)/2; d];
```

```
          B = [Ax.Position.x; Ax.Position.y] + R*[-(x1+x2)/2; d];
      end

      % Find P2;
      Ax = this.Connection2.Group;
      R = RotMatrix(Ax.Position.Rot - pi/2);
      d = this.Connection2.x;
      switch this.Connection1.Orient
        case enumOrient.Vertical
          [~,~,y1,y2] = this.Body2.limits(enumOrient.Horizontal);
          C = [Ax.Position.x; Ax.Position.y] + R*[d; (y1+y2)/2];
          D = [Ax.Position.x; Ax.Position.y] + R*[-d; (y1+y2)/2];
        case enumOrient.Horizontal
          [~,~,x1,x2] = this.Body2.limits(enumOrient.Vertical);
          C = [Ax.Position.x; Ax.Position.y] + R*[(x1+x2)/2; d];
          D = [Ax.Position.x; Ax.Position.y] + R*[-(x1+x2)/2; d];
      end

      % Find minimum pair
    % pair = zeros(2,2);
      dAC = Dist4Compare(A,C);
      dAD = Dist4Compare(A,D);
      dmin = Dist4Compare(B,D);
      if dAC < dmin; pair = [A C]; dmin = dAC;
      else; pair = [B D];
      end
      if dAD < dmin; pair = [A D]; dmin = dAD; end
      if Dist4Compare(B,C) < dmin; pair = [B C]; end

      % Find the closest blank space in the model and drag the label there
      %[d, y, h] = this.Body1.Group.Model.findInterSpace(pair);
      %newpair = [pair(:,1) [d; y+h/2] [d; y-h/2] pair(:,2)];

      % Two points in pair are minimum distance
      this.GUIObjects = line(...
        pair(1,:),pair(2,:),...
        'Color',[0.5 0.5 0.5]);
    end
  end
end
```

Connection

The connection is a class that includes the following functions:

A constructor / creation function.

A function that is called before it is deleted to clean up the external references.

A get/set interface used by the property dropdown editor on the main GUI.

A set of functions to append the internal lists of other classes.

A series of functions to update the name, list of node contacts

The discretization function.

A series of functions used to display or not display the connection on the main GUI.

```
classdef Connection < handle
  %UNTITLED Summary of this class goes here
  %   Detailed explanation goes here
  properties (Constant)
    Extension = 1.1;
    MinimumDisplayLength = 0.4;
    ActiveColor = [0 1 0];
    NormalColor = [0.2 0.2 0.2];
  end

  properties (Access = public)
      ID;
    Group Group;
    Bodies Body;
    isActive = false;
    x double = 0;
    Orient enumOrient = enumOrient.Horizontal;

    RefFrame Frame;
    GUIObjects;
    NodeContacts NodeContact;
    Faces Face;

    isDiscretized logical = false;
    isChanged logical = true;

    BodiesToNotJoin Body;
  end

  properties (Dependent)
    name;
    index;
    id;
  end

  methods
    %% Constructor
    function this = Connection(x,Orient,Group)
      switch nargin
        % case 0
        % obj.x = 0;
```

```
    % obj.Orient = enumOrient.Horizontal;
    case 1
      this.x = x;
      % this.Orient = enumOrient.Horizontal;
    case 2
      this.x = x;
      this.Orient = Orient;
    case 3
      this.x = x;
      this.Orient = Orient;
      this.Group = Group;
      this.ID = Group.Model.getConID();
  end
end

function deReference(this)
  % Remove Reference from Group
  iGroup = this.Group;
  for i = length(iGroup.Connections):-1:1
    if iGroup.Connections(i) == this
      iGroup.Connections(i) = [];
      iGroup.isChanged = true;
    end
  end

  % Remove relations from the relationship managers
  for RMan = iGroup.RelationManagers
      if RMan.Orient == this.Orient
          RMan.isChanged = true;
          for i = length(RMan.Relations):-1:1
              if RMan.Relations(i).con1 == this || ...
                      RMan.Relations(i).con2 == this
                  RMan.Relations(i).deReference();
              end
          end
          RMan.update();
      end
  end

  if ~isempty(this.Bodies) % i.e. Body/deReference has not been called already
    % Remove Reference from any Bodies
    for iBody = this.Bodies
      iBody.deReference();
      iBody.delete();
    end
    % Remove Reference from any Bridges
    iModel = iGroup.Model;
    for i = length(iModel.Bridges):-1:1
      if iModel.Bridges(i).Connection1 == this || iModel.Bridges(i).Connection2 == this
        iModel.Bridges(i).deReference();
        iModel.Bridge(i).delete();
        iModel.Bridges(i) = [];
      end
    end
    % Remove Reference from any Leaks
    for i = length(iModel.LeakConnections):-1:1
      if iModel.LeakConnections(i).Connection1 == this ...
          || iModel.LeakConnections(i).Connection2 == this
        iModel.LeakConnections(i).deReference();
        iModel.LeakConnections(i).delete();
        iModel.LeakConnections(i) = [];
      end
    end
    % Remove any visual remenant
    this.removeFromFigure(gca);
  end
  this.delete();
end
function change(this)
  this.isChanged = true;
  this.Faces(:) = [];
```

```
  this.NodeContacts(:) = [];
  for iBody = this.Bodies; iBody.change(); end
  this.isDiscretized = false;
end
function CleanUpBodies(this)
  for i = length(this.Bodies):-1:1
    if ~isvalid(this.Bodies(i))
      this.Bodies(i) = [];
    end
  end
end
function update(this)
    if isempty(this.ID)
        this.ID = this.Group.Model.getConID();
    end
  if any(~isvalid(this.Bodies))
    this.Bodies = this.Bodies(isvalid(this.Bodies));
  end
  if ~isvalid(this.RefFrame)
    this.RefFrame = [];
  end
  this.isChanged = false;
end
function [yesno] = IsFixedTo(this, other)
    yesno = false;
    for iRM = this.Group.RelationManagers
        if iRM.Orient == this.Orient && iRM.Orient == other.Orient
            iRM.update();
            for row = 1:size(iRM.Grid,1)
                if iRM.Grid(row,this.index) && ...
                        iRM.Grid_modes{row} == enumRelation.Constant
                    if iRM.Grid(row,other.index)
                        yesno = true;
                        return;
                    end
                end
            end
        end
    end
end

%% Get/Set Interface
function Item = get(this,PropertyName)
  if this.isChanged; this.update(); end
  switch PropertyName
    case 'x'
      Item = this.x;
    case 'RefFrame'
      Item = this.RefFrame;
    case 'Bodies'
      Item = this.Bodies;
    case 'Isolated Bodies'
      Item = this.BodiesToNotJoin;
    case 'isStationary'
      if isempty(this.RefFrame)
        Item = true;
      else
        Item = false;
      end
    otherwise
      fprintf(['XXX Connection GET Inteface for ' PropertyName ' is not found XXX\n']);
  end
end

%% (Update on Demand) Triggers
function name = get.name(this)
  switch this.Orient
    case enumOrient.Vertical
      name = ['Vertical Connection at x = ' num2str(this.x,3)];
    case enumOrient.Horizontal
      name = ['Horizontal Connection at y = ' num2str(this.x,3)];
```

```
  end
end
function index = get.index(this)
    i = 1;
    for iCon = this.Group.Connections
        if iCon == this
            index = i;
            return;
        end
        i = i + 1;
    end
    index = 0;
end


function set(this,PropertyName,Item)
  switch PropertyName
    case 'x'
        % Check all Relationships
        for iCon = this.Group.Connections
          if iCon.x == Item && ...
              iCon.Orient == this.Orient
            % This kind of shift can't result in a merge.
            return;
          end
        end
        for RMan = this.Group.RelationManagers
            if RMan.Orient == this.Orient
                RMan.Edit(this,Item-this.x);
                break;
            end
        end
    case 'RefFrame'
      if isempty(Item); this.RefFrame = Frame.empty;
      else; this.RefFrame = Item;
      end
    otherwise
      fprintf(['XXX Connection SET Inteface for ' ...
          PropertyName ' is not found XXX\n']);
      return;
  end
  this.change();
end

function set.isActive(this,value)
  if islogical(value)
    if isvalid(this)
      this.isActive = value;
    end
  else
    fprintf('Input to isActive must be a boolean value.\n');
  end
end

function functions(this,FunctionName)
  switch FunctionName
    case 'Add Bodies To Not Join'
      [cx,cy] = ginput(1);
      TheBody = findConnectedBody(this,[cx cy]);
      this.addBodyToNotJoin(TheBody);
    case 'Remove Bodies To Not Join'
      if ~isempty(this.BodiesToNotJoin)
        objects = cell(1,length(this.BodiesToNotJoin));
        names = objects;
        i = 1;
        for iBody = this.BodiesToNotJoin
          objects{i} = iBody;
          names{i} = iBody.name;
          i = i + 1;
        end
        [indx,tf] = listdlg(...
```

```
          'PromptString','Which one are you going to remove?',...
          'SelectionMode','single',...
          'ListString',names);
        if tf; this.BodiesToNotJoin(indx) = []; end
      end
    otherwise

  end
end

%% Operators
function isequal = isFunctionallyEqualTo(this,otherConnection)
  if this.x == otherConnection.x && ...
      this.Orient == otherConnection.Orient && ...
      ((isempty(this.RefFrame) && isempty(otherConnection.RefFrame)) || ...
      (isempty(this.RefFrame) == isempty(otherConnection.RefFrame) && ...
      this.RefFrame == otherConnection.RefFrame))
    isequal = true;
  else
    isequal = false;
  end
end

%% Interating
function addBody(this,BodiesToAdd)
  try
    count = length(this.Bodies);
    if isrow(BodiesToAdd)
      this.Bodies = [this.Bodies BodiesToAdd];
    else
      this.Bodies = [this.Bodies BodiesToAdd'];
    end
    this.Bodies = unique(this.Bodies);
    if count ~= length(this.Bodies)
      this.removeFaces();
    end
    return;
  catch
    fprintf('XXX Error in Connection/AddBody XXX\n');
  end
end
function addBodyToNotJoin(this,BodiesToNotJoin)
  len = length(this.BodiesToNotJoin);
  this.BodiesToNotJoin(len+length(BodiesToNotJoin)) = Body();
  this.BodiesToNotJoin(length(len+1:end)) = BodiesToNotJoin;
  this.BodiesToNotJoin = unique(this.BodiesToNotJoin);
end
function TheBody = findConnectedBody(this,Pnt)
  if this.isChanged; this.update(); end
  % Find a body in this Group that is selected and closest
  Pntmod = (RotMatrix(pi/2-this.Group.Position.Rot)*Pnt')...
    - [this.Group.Position.x; this.Group.Position.y];
  mindist = inf;
  for iBody = this.Bodies
    % Establish Rectangle of iBody
    [~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
    [~,~,y1,y2] = iBody.limits(enumOrient.Horizontal);

    R.Width = x2-x1;
    R.Height = y2-y1;
    R.Cx = (x1+x2)/2;
    R.Cy = (y1+y2)/2;
    dist = Dist2Rect(Pntmod(1),Pntmod(2),R.Cx,R.Cy,R.Width,R.Height);
    if dist < mindist
      mindist = dist;
      TheBody = iBody;
    else
      R.Cx = -R.Cx;
      dist = Dist2Rect(Pntmod(1),Pntmod(2),R.Cx,R.Cy,R.Width,R.Height);
      if dist < mindist
        if dist == 0
```

```
          TheBody = iBody;
          return;
        end
        mindist = dist;
        TheBody = iBody;
      end
    end
  end
end

%% Working with nodes
function deleteNodeContactsFromObj(this,Obj)
  for iBridge = this.Group.Model.Bridges
    if iBridge.Connection1 == this
      iBridge.change();
    elseif iBridge.Connection2 == this
      iBridge.change();
    end
  end
  this.cleanUpNodeContacts();
  LEN = length(this.NodeContacts);
  if LEN == 0; return; end
  if this.isDiscretized; this.removeFaces(); end
  i = 1;
  while (i < LEN+1 && this.NodeContacts(i).Node.Body ~= Obj); i = i + 1; end
  START = i - 1;
  while (i < LEN+1 && this.NodeContacts(i).Node.Body == Obj); i = i + 1; end
  END = i;
  if START ~= 0
    if END ~= LEN+1
      this.NodeContacts = [this.NodeContacts(1:START) this.NodeContacts(END:LEN)];
    else
      this.NodeContacts = this.NodeContacts(1:START);
    end
  else
    if END ~= LEN+1
      this.NodeContacts = this.NodeContacts(END:LEN);
    else
      this.NodeContacts = NodeContact.empty;
    end
  end
end
function addNodeContacts(this,newContacts)
  this.NodeContacts = [this.NodeContacts newContacts];
  if this.isDiscretized
    this.removeFaces();
  end
end
function removeFaces(this)
  this.Faces = Face.empty;
  this.isDiscretized = false;
end
function cleanUpNodeContacts(this)
  dontkeep = true(size(this.NodeContacts));
  for i = 1:length(this.NodeContacts)
    if isvalid(this.NodeContacts(i)) && ...
        isvalid(this.NodeContacts(i).Node) && ...
        isvalid(this.NodeContacts(i).Node.Body)
      dontkeep(i) = false;
    end
  end
  if any(dontkeep)
    this.NodeContacts = this.NodeContacts(~dontkeep);
  end
end
function resetDiscretization(this)
  if isvalid(this)
    this.NodeContacts(:) = [];
    this.Faces(:) = [];
    this.isDiscretized = false;
    this.isChanged = true;
```

```
  end
end
function discretize(this)
  if this.isChanged; this.update(); end
  this.Faces = Face.empty;
  if isempty(this.Bodies) || ...
      (this.Orient == enumOrient.Vertical && this.x == 0)
    this.isDiscretized = true;
    this.Faces = Face.empty;
    return;
  end

  % Remove Bodies that should not conduct
  keep = true(1,length(this.NodeContacts));
  for iBody = this.BodiesToNotJoin
    for i = 1:length(this.NodeContacts)
      if this.NodeContacts(i).Node.Body == iBody
        keep(i) = false;
      end
    end
  end
  this.NodeContacts = this.NodeContacts(keep);

  if ~this.isDiscretized
    for iBody = this.Bodies
      if ~iBody.isDiscretized
        iBody.discretize();
        if ~iBody.isDiscretized
          return;
        end
      end
    end
    if this.Group.isChanged
      this.Group.isEnvironmentCasted = true;
      this.Group.update();
    elseif ~this.Group.isEnvironmentCasted
      this.Group.isEnvironmentCasted = true;
      this.Group.updateBorder(true);
    end
    %% INITIALIZE
    this.Faces(2*length(this.NodeContacts)) = Face();
    n = 1;
    % Clean Up
    keep = true(size(this.NodeContacts));
    for i = 1:length(this.NodeContacts)
      if ~isvalid(this.NodeContacts(i)) || ...
          ~isvalid(this.NodeContacts(i).Node) || ...
          ~isvalid(this.NodeContacts(i).Node.Body)
        keep(i) = false;
      end
    end
    if any(~keep); this.NodeContacts = this.NodeContacts(keep); end

    % Sort the environmental connections to the end
    members = false(size(this.NodeContacts)); i = 1;
    for nc = this.NodeContacts
      members(i) = this.NodeContacts(i).Node.Type == enumNType.EN;
      i = i + 1;
    end
    envNC = this.NodeContacts(members);
    this.NodeContacts(members) = [];
    this.addNodeContacts(envNC);

    %% GO THROUGH EACH NODE COMBINATION
    keep = true(length(this.NodeContacts),1);
%     len = length(keep);
    for i = 1:length(this.NodeContacts)
      if length(keep) >= i && keep(i)
        for j = i+1:length(this.NodeContacts)
          if length(keep) >= j && keep(j)
            if this.NodeContacts(i).Node.Body ~= this.NodeContacts(j).Node.Body
```

```
            activeTimes = this.NodeContacts(i).activeTimes(this.NodeContacts(j));
            if ~isempty(activeTimes)
              this.Faces(n) = Face(this.NodeContacts(i),this.NodeContacts(j),activeTimes);
              if ~isempty(this.Faces(n).ActiveTimes)
                fc = this.Faces(n);
                switch fc.Type
                  case enumFType.Solid
                    if isempty(this.RefFrame) || ...
                        fc.Nodes(1).Type == enumNType.SN && ...
                        fc.Nodes(2).Type == enumNType.SN
                      if ~any(fc.data.U > 0)
                        n = n - 1;
                      end
                    end
                  case enumFType.Mix
                    if ~any(fc.data.Area > 0)
                      n = n - 1;
                    end
                  case enumFType.Environment
                    if isempty(this.RefFrame) && ~any(fc.data.U > 0)
                      n = n - 1;
                    end
                  case enumFType.Gas
                    if ~any(fc.data.Area > 0)
                      n = n - 1;
                    end
                end
                n = n + 1;
              end
            end
          end
        end
      end
    end
    this.Faces = this.Faces(1:n-1);
    this.isDiscretized = true;
  end
end

%% Display this Connection on the screen
function removeFromFigure(this,AxisReference)
  if ~isempty(this.GUIObjects)
    children = get(AxisReference,'Children');
    for obj = this.GUIObjects
      if isgraphics(obj)
        for i = length(children):-1:1
          if isgraphics(children(i)) && children(i) == obj
            children(i).delete;
            break;
          end
        end
      end
    end
  end
  this.GUIObjects = [];
end
function color = getColor(this)
  color = [0.5 0.5 0.5];
  if isempty(this.Group)
    if isempty(this.Bodies)
      fprinf(['XXX Connection '
        this.name ' does not know what its group is XXX\n']);
      return;
    else
      found = false;
      for i = 1:length(this.Bodies)
        if ~isempty(this.Bodies(i).Group)
          this.Group = this.Bodies(i).Group;
          found = true;
          break;
```

```
        end
      end
      if ~found
        fprinf(['XXX Connection '
          this.name ' does not know what its group is XXX\n']);
        return;
      end
    end
  end
  if this.Group.Model.showRelations
      for RMan = this.Group.RelationManagers
          if RMan.Orient == this.Orient
              ind = this.index;
              if isempty(RMan.Grid) || ind > size(RMan.Grid,2)
                  RMan.update();
              end
              rows = find(RMan.Grid(:,ind) == true);
              if ~isempty(rows)
                  max_count = 0;
                  max_index = 0;
                  for i = rows
                      count = sum(RMan.Grid(i,:));
                      if count > max_count
                          max_index = i;
                          max_count = count;
                      end
                  end
                  color = RMan.getColor(max_index);
                  break;
              end
              if this.isActive
                color = Connection.ActiveColor;
              else
                color = Connection.NormalColor;
              end
              break;
          end
      end
  else
      if this.isActive
        color = Connection.ActiveColor;
      else
        color = Connection.NormalColor;
      end
  end
end
function updateColor(this)
  if ~isempty(this.GUIObjects)
    for iGraphicsObject = this.GUIObjects
      set(iGraphicsObject,'Color',this.getColor());
    end
  end
end
function show(this, AxisReference)
  if this.isChanged; this.update(); end
  color = this.getColor();
  switch this.Orient
    case enumOrient.Vertical
      % Plot two lines on equal sides of the Group
      % Find vertical extent of the Group
      VectorLength = Connection.Extension*max(this.Group.Height,0.1);
      OffsetRot = this.Group.Position.Rot;
      Offset = (VectorLength-this.Group.Height)/2;
      % Make a template vector
      R = RotMatrix(OffsetRot);
      templateVector = R * [VectorLength; 0];
      Trans = [this.Group.Position.x; this.Group.Position.y];
      LeftStart = R * [-Offset; this.x] + Trans;
      RightStart = R * [-Offset; -this.x] + Trans;

      % Plot line
```

```
          if this.x == 0
%             if length(this.GUIObjects) == 1 && isgraphics(this.GUIObjects(1))
%               % Plot line
%               try
%                 set(this.GUIObjects,'Color',color);
%                 set(this.GUIObjects,'XData',...
%                   [LeftStart(1) LeftStart(1)+templateVector(1)]);
%                 set(this.GUIObjects,'YData',...
%                   [LeftStart(2) LeftStart(2)+templateVector(2)]);
%               catch
%                 this.removeFromFigure(AxisReference);
%                 this.GUIObjects(1) = line(...
%                   [LeftStart(1) LeftStart(1)+templateVector(1)],...
%                   [LeftStart(2) LeftStart(2)+templateVector(2)],...
%                   'Userdata',this,'Color',color,'LineStyle','--',...
%                   'HitTest','off');
%               end
%             else
              this.removeFromFigure(AxisReference);
              this.GUIObjects(1) = line(...
                [LeftStart(1) LeftStart(1)+templateVector(1)],...
                [LeftStart(2) LeftStart(2)+templateVector(2)],...
                'Userdata',this,'Color',color,'LineStyle','--',...
                'HitTest','off');
%             end
          else
%             if length(this.GUIObjects) == 2 && ...
%                 isgraphics(this.GUIObjects(1)) && isgraphics(this.GUIObjects(2))
%               set(this.GUIObjects(1),'Color',color);
%               set(this.GUIObjects(1),'XData',...
%                 [LeftStart(1) LeftStart(1)+templateVector(1)]);
%               set(this.GUIObjects(1),'YData',...
%                 [LeftStart(2) LeftStart(2)+templateVector(2)]);
%               set(this.GUIObjects(2),'Color',color);
%               set(this.GUIObjects(2),'XData',...
%                 [RightStart(1) RightStart(1)+templateVector(1)]);
%               set(this.GUIObjects(2),'YData',...
%                 [RightStart(2) RightStart(2)+templateVector(2)]);
%             else
              this.removeFromFigure(AxisReference);
              this.GUIObjects(2) = line(...
                [RightStart(1) RightStart(1)+templateVector(1)],...
                [RightStart(2) RightStart(2)+templateVector(2)],...
                'Userdata',this,'Color',color,'LineStyle','--',...
                'HitTest','off');
              this.GUIObjects(1) = line(...
                [LeftStart(1) LeftStart(1)+templateVector(1)],...
                [LeftStart(2) LeftStart(2)+templateVector(2)],...
                'Userdata',this,'Color',color,'LineStyle','--',...
                'HitTest','off');
%             end
          end
        case enumOrient.Horizontal
          % Plot a single line
          % Find horizontal extent of the Group
          VectorLength = Connection.Extension*this.Group.Width/2;
          OffsetRot = this.Group.Position.Rot;
          % Make a template vector
          R = RotMatrix(OffsetRot);
          Trans = [this.Group.Position.x ;
            this.Group.Position.y ];
          LeftPoint = R * [this.x; 0.5*VectorLength] + Trans;
          RightPoint = R * [this.x; -0.5*VectorLength] + Trans;

          % Plot line
          if length(this.GUIObjects) == 1 && isgraphics(this.GUIObjects)
            set(this.GUIObjects,'Color',color);
            set(this.GUIObjects,'XData',[LeftPoint(1) RightPoint(1)]);
            set(this.GUIObjects,'YData',[LeftPoint(2) RightPoint(2)]);
          else
            this.GUIObjects = line(...
```

```
            [LeftPoint(1) RightPoint(1)],[LeftPoint(2) RightPoint(2)],...
            'Userdata',this,'Color',color,'LineStyle','--',...
            'HitTest','off');
        end
      end
      % fprintf(['Plotted Connection ' this.name '.\n']);
    end
  end
end

% Helper functions - UNUSED
function face = appendDynamicFaceVert(face,k,T1,s,e,Area)
% Face.
%     .isDynamic - DONE
%     .Node1 - DONE
%     .Node2 - DONE
%     .A                  - Mix/Gas Append
%     .dh - Static
%     .Type - DONE
%     .value              - Solid/Mix/Gas Append
%     .K                  - Gas Append
%     .ActiveTimes        - Always Append
if s < e
  switch face.Type
    case enumFType.Solid
      % Combine resistances and store as a conductance
      face.value = [face.value Area(n,s,e)/(n1.value+n2.value)];
    case enumFType.Mix
      % Store only the resistance as a conductance
      if T1 == enumFType.Solid
        face.A = [face.A Area(n,s,e)];
        face.value = [face.value (face.A(end)/(n1.value))];
      else
        face.A = [face.A Area(n,s,e)];
        face.value = [face.value (face.A(end)/(n2.value))];
      end
    case enumFType.Gas
      % Record the combined distance stored in Ri
      face.A = [face.A Area(n,s,e)];
      face.value = [face.value n1.value + n2.value];
  end
  face.ActiveTimes = [face.ActiveTimes k];
end
end
function face = genStaticFace(n1,n2,Area)
face.Node1 = n1.node;
face.Node2 = n2.node;
face.isDynamic = false;
face.K = 0;
face.ActiveTimes = [];
face.Type = getFaceType(n1.Type,n2.Type);
switch face.Type
  case enumFType.Solid
    % Combine resistances and store as a conductance
    face.value = ...
      (Area(n,max([n1.Start n2.Start]),min([n1.End n2.End]))...
      /(n1.value + n2.value));
  case enumFType.Mix
    % Store only the resistance as a conductance
    if n1.Type == enumFType.Solid
      face.dh = n2.dh;
      face.A = Area(n,max([n1.Start n2.Start]),min([n1.End n2.End]));
      face.value = (face.A/(n1.value));
    else
      face.dh = n1.dh;
      face.A = Area(n,max([n1.Start n2.Start]),min([n1.End n2.End]));
      face.value = (face.A/(n2.value));
    end
  case enumFType.Gas
    % Record the combined distance stored in value
    face.value = n1.value + n2.value;
```

```
end
end
```

Environment

The environment is a class that contains the following functions:

A constructor / creation function.

A get / set interface used by the property drop-down editor on the main GUI.

A short discretize function.

A function to remove its graphical representation from the figure, show functionality is within group.

```
classdef Environment < handle
    %ENVIRONMENT Summary of this class goes here
    %   Detailed explanation goes here

    properties (Constant)
      StdPressure = 101325; % Pa
      StdTemperature = 298; % K
      Stdh = 20; % W/m*K
      StdGas = 'AIR';
    end

    properties
      Pressure double;
      Temperature double;
      h double;
      matl Material;
      nodeIndex double;
      name char;

      GUIObjects = [];

      isDiscretized logical = false;
      Node Node;
    end

    properties (Dependent)
        Group
    end

    methods
      %% Constructor
      function this = Environment(Pressure,Temperature,h,MaterialRef)
          switch nargin
            case 0
              this.Pressure = Environment.StdPressure;
              this.Temperature = Environment.StdTemperature;
              this.h = Environment.Stdh;
              this.matl = Material(Environment.StdGas);
              this.name = 'Standard AIR Environment';
            case 1
              this.Pressure = Pressure;
              this.Temperature = Environment.StdTemperature;
              this.h = Environment.Stdh;
              this.matl = Material(Environment.StdGas);
              this.name = 'Untitled Environment';
            case 2
              this.Pressure = Pressure;
              this.Temperature = Temperature;
```

```
            this.h = Environment.Stdh;
            this.matl = Material(Environment.StdGas);
            this.name = 'Untitled Environment';
          case 3
            this.Pressure = Pressure;
            this.Temperature = Temperature;
            this.h = h;
            this.matl = Material(Environment.StdGas);
            this.name = 'Untitled Environment';
          case 4
            this.Pressure = Pressure;
            this.Temperature = Temperature;
            this.h = h;
            this.matl = MaterialRef;
            this.name = 'Untitled Environment';
        end
      end

      %% Get/Set Interface
      function Item = get(this,PropertyName)
        switch PropertyName
          case 'Pressure'
            Item = this.Pressure;
          case 'Temperature'
            Item = this.Temperature;
          case 'h'
            Item = this.h;
          case 'Gas'
            Item = this.matl;
          case 'Name'
            Item = this.name;
          otherwise
            fprintf(['XXX Environment GET Inteface for ' PropertyName ' is not found XXX\n']);
        end
      end
      function set(this,PropertyName,Item)
        switch PropertyName
          case 'Pressure'
            this.Pressure = Item;
            if this.isDiscretized
              this.Node.data.Pressure = Item;
            end
          case 'Temperature'
             this.Temperature = Item;
             if this.isDiscretized
               this.Node.data.Temperature = Item;
             end
          case 'h'
            this.h = Item;
            if this.isDiscretized
                 this.Node.data.h = Item;
               end
          case 'Name'
            this.customname = Item;
          otherwise
            fprintf(['XXX Environment SET Inteface for ' PropertyName ' is not found XXX\n']);
        end
      end

      %% Node Management
      function resetDiscretization(this)
        this.Node(:) = [];
        this.isDiscretized = false;
      end
      function discretize(this)
        this.Node = Node.empty;
        this.Node = Node(enumNType.EN,0,0,0,0,Face.empty,Node.empty,this,0);
        this.isDiscretized = true;
        this.Node.data.Dh = 1e8;
%       if ~this.isDiscretized
%         delete(this.Node);
```

```
%           this.Node = Node(enumNType.EN,0,0,0,0,Face.empty,Node.empty,this,0); %#ok<PROP>
%           this.isDiscretized = true;
%         end
      end

      %% Graphics
      function removeFromFigure(this,AxisReference)
      if ~isempty(this.GUIObjects)
        children = get(AxisReference,'Children');
        for obj = this.GUIObjects
          if isgraphics(obj)
            for i = length(children):-1:1
              if isgraphics(children(i)) && children(i) == obj
                children(i).delete;
                break;
              end
            end
          end
        end
        this.GUIObjects = [];
      end
      end

      function igroup = get.Group(this)
          igroup = Group([],Position(0,0,pi/2),Body.empty);
      end
    end
end
```

Frame

The frame is a class that contains an array of positions, a reference to a mechanism and a method used to create a name.

```
classdef Frame < handle
   %FRAME Summary of this class goes here
   %   Detailed explanation goes here
   properties (Constant)
      NTheta = 200;
      DecimateFactor = 10;
   end

   properties
      % Kinematic frames can be precalculated
      isKinematic = true;
      %           = false; is for free piston designs
      % In these cases the position array simply defines a
      % uniformly spaced position array between the motion
      % extents

      Positions double = []; % no negative positions, pistons should be sketched at minimum, not
center.
      Mechanism LinRotMechanism; % as MechanicalSystem; % Defines a reference to the mechanism
output that defines the motion of this frame
      MechanismIndex int8 = 1; % By Default
      CustomName char = [];
   end

   properties (Dependent)
      CurrentPosition;
      name;
   end

   methods
     function name = get.name(this)
       if isvalid(this)
          if isempty(this.CustomName)
            ii = this.MechanismIndex;
            name = [this.Mechanism.Type ...
              ' L= ' num2str(this.Mechanism.Stroke(ii)) ...
              ' m , P= ' num2str(this.Mechanism.Phase(ii)) ' rad.\n'];
          end
       else
         name = '...';
       end
     end
   end

end
```

Group

The group is a class that contains the following functions:

A constructor.

A function called prior to its deletion, to clean up other objects.

A get / set interface used by the property drop-down editor on the main GUI.

A series of functions for managing the internal lists of other classes.

A series of functions of managing the derived properties of this class.

A function used to calculate the exposed surface of the child bodies.

A function for finding the nearest connection to a point.

A function for rotating the local coordinate to the world coordinates.

A series of functions for displaying the group on the GUI.

```
classdef Group < handle
    %Group Summary of this class goes here
    %   Detailed explanation goes here

    properties (Constant)
        ConnectionTolerance = 1e-6; % 0.001 mm plenty small enough for films
        Extension = 1.33;
        MinimumDisplayLength = 0.1;
        MinimumDisplayWidth = 0.1;
        HighlightedColor = [0 1 0];
        NormalColor = [0 0 0];
    end

    properties (Dependent)
        isValid;
        Width;
        Height;
        ValidBorder;
        InvalidBorder;
        isDiscretized;
    end

    properties (Hidden)
        isStateValid logical = false;
        WidthState double;
        HeightState double;
        ValidBorderState Line2DChain;
        InvalidBorderState Line2DChain;
        isStateDiscretized logical = false;
        isEnvironmentCasted logical = false;
    end

    properties
        isChanged logical = true;
        Bodies Body;
```

```
    Connections Connection;
    RelationManagers RelationManager;

    GUIObjects;
    isActive = true;
    name = 'Default Group';
    Model Model;
    Position Position;

    Nodes Node;
    Faces Face;
end

methods

    %% Constructor Function
    function this = Group(inputModel,inputPosition,inputBodies)
        if nargin == 0; return; end
        this.RelationManagers(2) = ...
            RelationManager(this, enumOrient.Horizontal);
        this.RelationManagers(1) = ...
            RelationManager(this, enumOrient.Vertical);
        switch nargin
            case 1
                % Only Model Provided
                this.Model = inputModel;
            case 2
                % A Model and positon is provided
                this.Model = inputModel;
                this.Position = inputPosition;
            case 3
                % A Model, position and a bunch of bodies are provided
                this.Model = inputModel;
                this.Position = inputPosition;
                this.addBody(inputBodies);
                for iBody = inputBodies
                    this.addConnection(iBody.Connections);
                end
        end
        this.Connections = [Connection(0,enumOrient.Vertical,this) ...
            Connection(0,enumOrient.Horizontal,this)];
        if ~isempty(this.Model)
            this.isActive = true;
            this.Model.switchHighLighting(this);
        end
        this.isChanged = true;
        fprintf('Created Group.\n');
    end
    function deReference(this)
        iModel = this.Model;
        iModel.isStateDiscretized = false;
        for i = length(iModel.Groups):-1:1
            if iModel.Groups(i) == this
                iModel.Groups(i) = [];
            end
        end
        for iBody = this.Bodies
            iBody.deReference();
        end
        this.Bodies = [];
        for iCon = this.Connections
            iCon.deReference();
        end
        this.Connections = [];
        % Remove any visual remenant
        this.removeFromFigure(gca);
    end

    %% Get/Set Interface
    function Item = get(this,PropertyName)
        switch PropertyName
```

```
        case 'Name'
            Item = this.name;
        case 'Position'
            Item = this.Position;
        case 'Bodies'
            Item = this.Bodies;
        case 'Connections'
            Item = this.Connections;
        case 'Leak Connections'
            Item = this.LeakConnections;
        case 'Relation Managers'
            Item = this.RelationManagers;
        otherwise
            fprintf(['XXX Group GET Inteface for ' PropertyName ...
                ' is not found XXX\n']);
    end
end
function set(this,PropertyName,Item)
    switch PropertyName
        case 'Name'
            this.name = Item;
        otherwise
            fprintf(['XXX Group SET Inteface for ' PropertyName ...
                ' is not found XXX\n']);
    end
end

%% Add Objects
function addBody(this,inputBodies)
    if isrow(inputBodies)
        this.Bodies = [this.Bodies inputBodies];
    else
        this.Bodies = [this.Bodies inputBodies'];
    end
    for iBody = inputBodies
        if isempty(iBody.ID)
            iBody.ID = this.Model.getBodyID();
        end
        this.addConnection(iBody.Connections);
        fprintf(['Added ' iBody.name ' to ' this.name '.\n']);
    end
    this.Bodies = unique(this.Bodies,'rows');
    this.isChanged = true;
    this.fixDatum();
end
function addConnection(this,inputobj)
    for RMan = this.RelationManagers
        RMan.isChanged = true;
    end
    if isrow(inputobj)
        this.Connections = [this.Connections inputobj];
    else
        this.Connections = [this.Connections inputobj'];
    end
    for iCon = inputobj
        if isempty(iCon.ID)
            iCon.ID = this.Model.getConID();
        end
    end
    this.Connections = unique(this.Connections,'rows');
end

%% Clean up and Organization
function cleanUpConnections(this)
    % Ensure Group.Connections Reflects the bodies within it
    keep = false(size(this.Connections));
    keep(1:2) = true;
    for iBody = this.Bodies
        for iCon = iBody.Connections
            found = false;
            for i = 1:length(this.Connections)
```

```
            if iCon == this.Connections(i)
                found = true;
                keep(i) = true;
                break;
            end
        end
        if ~found
            this.addConnection(iCon);
            keep(length(this.Connections)) = true;
        end
    end
end
if any(~keep); this.Connections = this.Connections(keep);
end

keep = true(size(this.Connections));
for i = 1:length(this.Connections)
    if ~keep(i)
        iCon = this.Connections(i);
        if isempty(iCon.Bodies); keep(i) = false; end
        for j = i+1:length(this.Connections)
            if ~keep(j)
                jCon = this.Connections(j);
                if iCOn.isFunctionallyEqualTo(jCon)
                    for jBody = jCon.Bodies
                        % Replace all references of j with i
                        for k = 1:length(jBody.Connections)
                            if jBody.Connections(k) == jCon
                                jBody.Connections(k) = iCon;
                            end
                        end
                        iCon.addBody(jBody);
                    end

                    for iBridge = this.Model.Bridges
                        if iBridge.Connection1 == jCon
                            iBridge.Connection1 = iCon;
                        elseif iBridge.Connection2 == jCon
                            iBridge.Connection2 = iCon;
                        end
                    end

                    for iLeak = this.Model.LeakConnections
                        if iLeak.Connection1 == jCon
                            iLeak.Connection1 = iCon;
                        elseif iLeak.Connection2 == jCon
                            iLeak.Connection2 = iCon;
                        end
                    end

                    jCon.removeFromFigure(gca);
                end
            end
        end
    end
end

if any(~keep)
    for i = 1:length(this.Connections)
        if ~keep(i)
            this.Connections(i).delete();
        end
    end
    this.Connections = this.Connections(keep);
end

for iCon = this.Connections
    keep = true(size(iCon.Bodies));
    for i = 1:length(iCon.Bodies)
        if ~any(this.Bodies == iCon.Bodies(i))
            keep(i) = false;
```

```
            end
        end
        if any(~keep)
            iCon.Bodies = iCon.Bodies(keep);
        end
    end

    count1 = false;
    count2 = false;
    for iCon = this.Connections
        if iCon.x == 0
            if iCon.Orient == enumOrient.Vertical; count1 = true;
            elseif iCon.Orient == enumOrient.Horizontal; count2 = true;
            end
        end
    end
    if ~count1; this.addConnection(Connection(0,enumOrient.Vertical,this)); end
    if ~count2; this.addConnection(Connection(0,enumOrient.Horizontal,this)); end
    fprintf(['Cleaned up Connections in Group ' this.name '.\n']);
end
function fixDatum(this)
    offset = 0;
    for iCon = this.Connections
        if iCon.Orient == enumOrient.Horizontal && iCon.x < offset
            offset = iCon.x;
        end
    end
    for iCon = this.Connections
        if iCon.Orient == enumOrient.Horizontal
            iCon.x = iCon.x - offset;
        end
    end
end
function isit = isOverlaping(this,TheBody)
    % Determine if TheBody is interfering with any other body
    % Determine if its in the same column
    isit = false;
    for iBody = this.Bodies
        if TheBody.overlaps(iBody)
            isit = true;
            return;
        end
    end
end

%% Update on Demand
function change(this)
    this.isChanged = true;
    this.Model.change();
end
function update(this)
    if isempty(this.RelationManagers)
        this.RelationManagers(2) = ...
            RelationManager(this, enumOrient.Horizontal);
        this.RelationManagers(1) = ...
            RelationManager(this, enumOrient.Vertical);
    end
    if length(this.Connections) > 2
        this.cleanUpConnections();
    end
    %% Update isValid
    varb = true;
    % Test to see if any bodies overlap
    for iBody = this.Bodies
        for jBody = this.Bodies
            if iBody ~= jBody
                [Ax1,Ax2,~,~] = iBody.limits(enumOrient.Vertical);
                [Bx1,Bx2,~,~] = jBody.limits(enumOrient.Vertical);
                if (Ax1 < Bx2 || Ax2 > Bx1) % overlap x's
                    [Ay1,Ay2,~,~] = iBody.limits(enumOrient.Horizontal);
                    [By1,By2,~,~] = jBody.limits(enumOrient.Horizontal);
```

```
                    if  (any(Ay1 < By2) || any(Ay2 > By1)) % overlap y's
                        varb = false;
                        fprintf(['XXX Overlap detected in Group ' ...
                            this.name ' between Bodies ' ...
                            iBody.name ' and ' jBody.name '. Please make sure ' ...
                            'that connections are properly defined XXX \n']);
                        break;
                    end
                end
            end
        end
    end
    % Test to see if there are any islands within the border
    this.updateBorder(this.isEnvironmentCasted);
    if ~isempty(this.InvalidBorderState)
        varb = false;
        fprintf(['XXX Unfilled hollow space found in Group ' ...
            this.name '. Please make sure to fill such spaces with a ' ...
            'Gas or other material, or review how bodies are connected ' ...
            'XXX \n']);
    end
    this.isStateValid = varb;

    %% Update Width
    % From each body get the maximum radius of the cylindrical connections
    vard = this.MinimumDisplayLength;
    for iConnection = this.Connections
        if iConnection.Orient == enumOrient.Vertical ...
                && iConnection.x > vard
            vard = iConnection.x;
        end
    end
    this.WidthState = vard*2;

    %% Update Height
    % From each body get the maximum radius of the cylindrical connections
    vard = this.MinimumDisplayWidth;
    for iConnection = this.Connections
        if iConnection.Orient == enumOrient.Horizontal ...
                && iConnection.x > vard
            vard = iConnection.x;
        end
    end
    this.HeightState = vard;

    %% Update isDiscretized
    varb = true;
    for iBody = this.Bodies
        if ~iBody.isDiscretized
            varb = false;
            break;
        end
    end
    if varb
        for iConnection = this.Connections
            if ~iConnection.isDiscretized
                varb = false;
                break;
            end
        end
    end
    this.isStateDiscretized = varb;

    this.isChanged = false;
end
function updateBorder(this,castToConnections)
    delete(this.ValidBorderState);
    delete(this.InvalidBorderState);
    if ~isempty(this.Bodies)
        %% Each connection must have a minimum of 2 bodies over all of its length
        if this.isChanged || (nargin > 1 && castToConnections)
```

```
Lines = Line2DChain.empty;
for iBody = this.Bodies
    [~, ~, x1, x2] = iBody.limits(enumOrient.Vertical);
    [~, ~, y1, y2] = iBody.limits(enumOrient.Horizontal);
    if x1 > 0
        Lines(end+4) = Line2DChain(x1, y1, x1, y2);
        Lines(end-1) = Line2DChain(x1, y2, x2, y2);
        Lines(end-2) = Line2DChain(x2, y1, x2, y2);
        Lines(end-3) = Line2DChain(x1, y1, x2, y1);
    else
        Lines(end+3) = Line2DChain(x1, y2, x2, y2);
        Lines(end-1) = Line2DChain(x2, y1, x2, y2);
        Lines(end-2) = Line2DChain(x1, y1, x2, y1);
    end
end
j = 0;
i = 0;
while (i < length(Lines))
    i = i + 1;
    while (j < length(Lines))
        j = j + 1;
        if i ~= j
            [Lines,i,j] = intersects(i,j, Lines);
        end
    end
    j = i + 1;
end

%% Decimate duplicate points and merge
Finished = Line2DChain.empty;
old_n = inf;
while ~isempty(Lines)
    % Combine Step
    n = length(Lines);

    Eliminated = zeros(1,n);
    for i = length(Lines):-1:2
        for j = i-1:-1:1
            if ~Eliminated(j)
                Eliminated(j) = Lines(i).attemptToMerge(Lines(j));
            end
        end
    end
    % Decimate Lines that have been added to others
    for i = length(Lines):-1:1
        if Eliminated(i)
            Lines(i) = [];
        end
    end
    % Pick out finished Lines
    isDone = false(1,length(Lines));
    for i = 1:length(Lines)
        isDone(i) = Lines(i).isFinished;
    end
    Finished = [Finished Lines(isDone)];
    Lines(isDone) = [];

    if old_n == n
        fprintf('XXX Infinite Loop detected, exiting XXX\n');
        Finished = [Finished Lines];
        Lines = [];
    end
    old_n = n;
end

if length(Finished) > 1
    % There can only be one valid border
    % Pick the one with the largest value of x
    maxx = 0;
    for i = 1:length(Finished)
        ix = max(Finished(i).XData);
```

```
                            if ix > maxx
                                index = i;
                                maxx = ix;
                            end
                        end
                        this.ValidBorderState = Finished(index);
                        this.InvalidBorderState = Finished(Finished~=Finished(index));
                        if castToConnections
                            this.isEnvironmentCasted = false;
                            fprintf(['XXX Environmental Shell generation failed, ' ...
                                'there are internal volumes XXX\n']);
                        end
                    else
                        this.ValidBorderState = Finished;
                        this.InvalidBorderState = Line2DChain.empty;
                        if castToConnections
                            this.castEnvironmentToConnections();
                        end
                    end
                    %% fprintf(['Group ' this.name ' has been scanned for contact with
surroundings.\n']);
                end
            end
        end
        function Valid = get.isValid(this)
            if ischanged
                this.update();
            end
            Valid = this.isStateValid;
        end
        function Width = get.Width(this)
            if this.isChanged; this.update(); end
            Width = this.WidthState;
        end
        function Height = get.Height(this)
            if this.isChanged
                this.update();
            end
            Height = this.HeightState;
        end
        function ValidBorder = get.ValidBorder(this)
            if this.isChanged
                this.update();
            end
            ValidBorder = this.ValidBorderState;
        end
        function InvalidBorder = get.InvalidBorder(this)
            if this.isChanged
                this.update();
            end
            InvalidBorder = this.InvalidBorderState;
        end
        function castEnvironmentToConnections(this)
            if ~this.Model.surroundings.isDiscretized
                this.Model.surroundings.discretize();
            end

            for iCon = this.Connections
                % Remove exising environment connections
                k = 1; keep = true(size(iCon.NodeContacts));
                for iNC = iCon.NodeContacts
                    if ~isvalid(iNC.Node) || ...
                            ~isvalid(iNC.Node.Body) || ...
                            isa(iNC.Node.Body,'Environment')
                        keep(k) = false;
                    end
                    k = k + 1;
                end
                iCon.NodeContacts = iCon.NodeContacts(keep);
            end
```

```
    % For each segment of pnts
    for i = 1:length(this.ValidBorderState.Pnts)-1
        Start = this.ValidBorderState.Pnts(i);
        End = this.ValidBorderState.Pnts(i+1);
        if Start.x ~= End.x % Horizontal
            for iCon = this.Connections
                if iCon.Orient == enumOrient.Horizontal && iCon.x == Start.y
                    iCon.addNodeContacts(NodeContact( ...
                        this.Model.surroundings.Node, ...
                        min([Start.x End.x]), ...
                        max([End.x Start.x]), ...
                        enumFType.Environment,iCon));
                end
            end
        else
            for iCon = this.Connections
                if iCon.Orient == enumOrient.Vertical && iCon.x == Start.x
                    iCon.addNodeContacts(NodeContact( ...
                        this.Model.surroundings.Node, ...
                        min([Start.y End.y]), ...
                        max([End.y Start.y]), ...
                        enumFType.Environment,iCon));
                end
            end
        end
    end
end
function Discretized = get.isDiscretized(this)
    if this.isChanged
        this.update();
    end
    Discretized = this.isStateDiscretized;
end

%% Discretizing
function resetDiscretization(this)
    for iBody = this.Bodies
        iBody.resetDiscretization();
    end
    for iCon = this.Connections
        iCon.resetDiscretization();
    end
    this.Nodes(:) = [];
    this.Faces(:) = [];
    this.isChanged = true;
    this.isStateDiscretized = false;
end
function discretize(this, derefinement_factor)
    this.isStateDiscretized = false;
    this.Nodes(:) = [];
    this.Faces(:) = [];
    nn = 0;
    nf = 0;
    if isempty(this.Bodies)
        this.isStateDiscretized = true;
        return;
    end
    for iBody = this.Bodies
        if ~iBody.isDiscretized
            if nargin == 2
                backup_divisions = iBody.divides;
                if iBody.matl.Phase == enumMaterial.Solid
                    iBody.divides = ceil(iBody.divides*derefinement_factor);
                else
                    if any(iBody.divides ~= 1)
                        if iBody.divides(1) == 1
                            iBody.divides(2) = ...
                                max(2,ceil(iBody.divides(2)*derefinement_factor));
                        elseif iBody.divides(2) == 1
                            iBody.divides(1) = ...
                                max(2,ceil(iBody.divides(2)*derefinement_factor));
```

```
                    end
                end
            end
        end
        iBody.discretize();
        if ~iBody.isDiscretized
            fprintf(['XXX Exited Discretization at Body: ' iBody.name '.XXX\n']);
            if nargin == 2; iBody.divides = backup_divisions; end
            return;
        end
        keep = true(size(iBody.Nodes));
        for i = length(iBody.Nodes):-1:1
            if ~isvalid(iBody.Nodes(i)) || ...
                    iBody.Nodes(i).xmin == iBody.Nodes(i).xmax
                keep(i) = false;
            end
        end
        if any(~keep); iBody.Nodes = iBody.Nodes(keep); end
        keep = true(size(iBody.Faces));
        for i = length(iBody.Faces):-1:1
            if ~isvalid(iBody.Faces(i)) || isempty(iBody.Faces(i).Nodes)
                keep(i) = false;
            end
        end
        if any(~keep); iBody.Faces = iBody.Faces(keep); end
        if nargin == 2; iBody.divides = backup_divisions; end
    end
    nn = nn + length(iBody.Nodes);
    nf = nf + length(iBody.Faces);
end
% Discretize the surroundings
this.updateBorder(true);

for iCon = this.Connections
    if ~iCon.isDiscretized
        iCon.discretize();
        if ~iCon.isDiscretized
            fprintf(['XXX Exited Discretization at Connection: ' ...
                iCon.name '.XXX\n']);
            return;
        end
    end
    keep = true(size(iCon.Faces));
    for i = length(iCon.Faces):-1:1
        if ~isvalid(iCon.Faces(i))
            keep(i) = false;
        else
            if isempty(iCon.Faces(i).Nodes)
                keep(i) = false;
            end
        end
    end
    if any(~keep)
        iCon.Faces = iCon.Faces(keep);
    end
    nf = nf + length(iCon.Faces);
end
if nn == 0
    return;
end
for i = nn:-1:1; this.Nodes(i) = Node(); end
for i = nf:-1:1; this.Faces(i) = Face(); end
if nf == 0
    nn = 1;
    for iBody = this.Bodies
        this.Nodes(nn:nn-1+length(iBody.Nodes)) = iBody.Nodes;
        nn = nn + length(iBody.Nodes);
    end
else
    nn = 1; nf = 1;
    for iBody = this.Bodies
```

```
            this.Nodes(nn:nn-1+length(iBody.Nodes)) = iBody.Nodes;
            this.Faces(nf:nf-1+length(iBody.Faces)) = iBody.Faces;
            nn = nn + length(iBody.Nodes);
            nf = nf + length(iBody.Faces);
        end
        for iCon = this.Connections
            this.Faces(nf:nf-1+length(iCon.Faces)) = iCon.Faces;
            nf = nf + length(iCon.Faces);
        end
    end
    this.isStateDiscretized = true;
end

%% Finding things
function Con = FindConnection(this,Pos,Orient,notCon)
    Pos = Pos(1,1:2);
    Pos(1) = Pos(1) - this.Position.x;
    Pos(2) = Pos(2) - this.Position.y;
    Con = [];
    distance = inf;
    if nargin == 4
        if Orient == enumOrient.Vertical
            C = RotMatrix(pi/2 - this.Position.Rot)*Pos';
            for iCon = this.Connections
                if iCon ~= notCon && iCon.Orient == Orient
                    if abs(C(1,1)-iCon.x) < distance
                        distance = abs(C(1,1)-iCon.x);
                        Con = iCon;
                    end
                    if abs(C(1,1)+iCon.x) < distance
                        distance = abs(C(1,1)+iCon.x);
                        Con = iCon;
                    end
                end
            end
        else % Horizontal
            C = RotMatrix(-this.Position.Rot)*Pos';
            for iCon = this.Connections
                if iCon ~= notCon && iCon.Orient == Orient
                    if abs(C(1,1)-iCon.x) < distance
                        distance = abs(C(1,1)-iCon.x);
                        Con = iCon;
                    end
                end
            end
        end
    end
    if nargin == 2
        CV = RotMatrix(pi/2 - this.Position.Rot)*Pos';
        CH = RotMatrix(-this.Position.Rot)*Pos';
        for iCon = this.Connections
            switch iCon.Orient
                case enumOrient.Vertical
                    if abs(CV(1,1)-iCon.x) < distance
                        distance = abs(CV(1,1)-iCon.x);
                        Con = iCon;
                    end
                    if abs(CV(1,1)+iCon.x) < distance
                        distance = abs(CV(1,1)+iCon.x);
                        Con = iCon;
                    end
                case enumOrient.Horizontal
                    if abs(CH(1,1)-iCon.x) < distance
                        distance = abs(CH(1,1)-iCon.x);
                        Con = iCon;
                    end
            end
        end
    end
end
function Pnt = TranslatePnt2D(this,center)
```

```
    Rot = RotMatrix(this.Position.Rot-pi/2);
    x = center.x*Rot(1,1) + center.y*Rot(1,2) + this.Position.x;
    y = center.x*Rot(2,1) + center.y*Rot(2,2) + this.Position.y;
    Pnt = Pnt2D(x,y);
end

%% Graphics
function color = getColor(this)
    if this.isActive; color = Group.HighlightedColor;
    else; color = Group.NormalColor;
    end
end
function removeFromFigure(this,AxisReference)
    if ~isempty(this.GUIObjects)
        children = get(AxisReference,'Children');
        for obj = this.GUIObjects
            if isgraphics(obj)
                for i = length(children):-1:1
                    if isgraphics(children(i)) && children(i) == obj
                        children(i).delete;
                        break;
                    end
                end
            end
        end
        this.GUIObjects = [];
    end
end
function show(this,CODE,AxisReference,Inc,showOptions)
    switch CODE
        case 'all'
            % Show everything in base state
            this.removeFromFigure(AxisReference); % Group and Environmental
            if showOptions(1) % Show Groups
                color = this.getColor();

                % Plot a single line
                % Find horizontal extent of the Group
                VectorLength = this.Width;
                TotalVectorLength = 1.2*max(VectorLength,0.1);
                OffsetRot = this.Position.Rot;
                % Make a template vector
                R = RotMatrix(OffsetRot);
                VStart = [this.Position.x ; this.Position.y ] - ...
                    R * [(TotalVectorLength-VectorLength)/2; 0];
                VEnd = R * [TotalVectorLength; 0] + VStart;

                % Plot line
                this.GUIObjects = line(...
                    [VStart(1) VEnd(1)],...
                    [VStart(2) VEnd(2)],...
                    'Userdata',this,...
                    'Color',color,...
                    'LineWidth',3,...
                    'LineStyle','--',...
                    'HitTest','off');
            end
            if showOptions(2) % Show Bodies
                for iBody = this.Bodies
                    iBody.show(AxisReference);
                end
            else
                for iBody = this.Bodies
                    iBody.removeFromFigure(AxisReference);
                end
            end
            if showOptions(3) % Show Connections
                for iCon = this.Connections
                    iCon.show(AxisReference);
                end
            else
```

```
        for iCon = this.Connections
            iCon.removeFromFigure(AxisReference);
        end
    end
    if showOptions(7) % Show Environment Connections
        shift = [this.Position.x; this.Position.y];
        rotate = RotMatrix(this.Position.Rot - pi/2);
        % Show the validBorder
        if ~isempty(this.ValidBorder)
          if ~isvalid(this.ValidBorder)
            this.update();
          end
          [XData, YData] = ...
                DistortPositionVectors(...
                this.ValidBorder.XData, this.ValidBorder.YData, ...
                shift, rotate);

            this.GUIObjects(end+1) = line(...
                'XData',XData,...
                'YData',YData,...
                'LineWidth',2,...
                'Color',[0 0 1]);
        end
        % Show the invalidBorder
        if ~isempty(this.InvalidBorder)
            for LineChain = this.InvalidBorder
                [XData, YData] = ...
                    DistortPositionVectors(...
                    LineChain.XData, LineChain.YData, ...
                    shift, rotate);
                this.GUIObjects(end+1) = line(...
                    'XData',XData,...
                    'YData',YData,...
                    'LineWidth',2,...
                    'LineStyle','--',...
                    'Color',[1 0 0]);
            end
        end
    end
case 'Dynamic'
    if showOptions(2) % Show Bodies
        for iBody = this.Bodies
            if iBody.MovingStatus ~= enumMove.Static
                iBody.show(AxisReference,Inc);
            end
        end
    end
case 'Static'
    if showOptions(1) % Show Groups
        color = this.getColor();

        % Plot a single line
        % Find horizontal extent of the Group
        VectorLength = max(...
            [Group.MinimumDisplayLength this.Width]);
        TotalVectorLength = VectorLength*Group.Extension;
        OffsetRot = this.Position.Rot;
        % Make a template vector
        R = RotMatrix(OffsetRot);
        VStart = [this.Position.x ;
            this.Position.y ] - ...
            R * [(TotalVectorLength-VectorLength)/2; 0];
        VEnd = R * [TotalVectorLength; 0] + VStart;

        % Plot line
        this.GUIObjects = line(...
            [VStart(1) VEnd(1)],...
            [VStart(2) VEnd(2)],...
            'Userdata',this,...
            'Color',color,...
            'LineWidth',3,...
```

```
                        'LineStyle','--',...
                        'HitTest','off');
                end
                if showOptions(2) % Show Bodies
                    for iBody = this.Bodies
                        if iBody.MovingStatus == enumMove.Static
                            iBody.show(AxisReference);
                        end
                    end
                end
            end
        end
    end
end

function [Lines,i,j] = intersects(i,j,Lines)
if i < 1 || j < 1 || i > length(Lines) || j > length(Lines)
    return;
end
kill_i = false;
kill_j = false;
istart = Lines(i).Pnts(1);
iend = Lines(i).Pnts(end);
jstart = Lines(j).Pnts(1);
jend = Lines(j).Pnts(end);
if all(Lines(i).XData == Lines(j).XData) && ~(istart.y == iend.y)
    % Both Vertical and may overlap
    if iend.y < jstart.y || istart.y > jend.y
        return;
    end
    x = istart.x;
    if istart.y <= jstart.y
        % i starts before j
        if iend.y <= jend.y
            % i is staggered with j
            temp = iend.y;
            if (istart == jstart)
                kill_i = true;
            else
                Lines(i).Pnts(end).y = jstart.y;
            end
            if (jend.y == temp)
                kill_j = true;
            else
                Lines(j).Pnts(1).y = temp;
            end
        else
            % j is within i
            if (iend ~= jend)
                Lines(end+1) = Line2DChain(x,jend.y,x,iend.y);
            end
            if (istart == jstart)
                kill_i = true;
            else
                Lines(i).Pnts(end).y = jstart.y;
            end
            kill_j = true;
        end
    else
        % j starts before i
        if jend.y <= iend.y
            % j is staggered with i
            temp = jend.y;
            if (istart == jstart)
                kill_j = true;
            else
                Lines(j).Pnts(end).y = istart.y;
            end
            if (iend.y == temp)
                kill_i = true;
            else
```

```
                Lines(i).Pnts(1).y = temp;
            end
        else
            % i is within j
            if (iend ~= jend)
                Lines(end+1) = Line2DChain(x,iend.y,x,jend.y);
            end
            if (istart == jstart)
                kill_j = true;
            else
                Lines(j).Pnts(end).y = istart.y;
            end
            kill_i = true;
        end
    end
elseif all(Lines(i).YData == Lines(j).YData) && ~(istart.x == iend.x)
    % Both Horizontal and may overlap
    if iend.x < jstart.x || istart.x > jend.x
        return;
    end
    if istart.x == jstart.x && iend.x == jend.x
        kill_i = true;
        kill_j = true;
    else
        y = istart.y;
        if istart.x <= jstart.x
            % i starts before j
            if iend.x <= jend.x
                % i is staggered with j
                % i --|-|
                % j   |-|--
                temp = iend.x;
                if (istart.x == jstart.x)
                    kill_i = true;
                else
                    Lines(i).Pnts(end).x = jstart.x;
                end
                if (temp == jend.x)
                    kill_j = true;
                else
                    Lines(j).Pnts(1).x = temp;
                end
            else
                % j is within i
                % i -|--|-
                % j  |--|
                kill_j = true;
                if (iend.x ~= jend.x)
                    Lines(end+1) = Line2DChain(jend.x,y,iend.x,y);
                end
                if (istart.x == jstart.x)
                    kill_i = true;
                end
                Lines(i).Pnts(end).x = jstart.x;
            end
        else
            % j starts before i
            if jend.x <= iend.x
                % j is staggered with i
                % i   |-|--
                % j --|-|
                temp = jend.x;
                if (istart == jstart)
                    kill_j = true;
                else
                    Lines(j).Pnts(end).x = istart.x;
                end
                if (iend.x == temp)
                    kill_i = true;
                else
                    Lines(i).Pnts(1).x = temp;
```

```
                end
            else
                % i is within j
                % i  |--|
                % j -|--|-
                kill_i = true;
                if (iend ~= jend)
                    Lines(end+1) = Line2DChain(iend.x,y,jend.x,y);
                end
                if (istart == jstart)
                    kill_j = true;
                else
                    Lines(j).Pnts(end).x = istart.x;
                end
            end
        end
    end
end
if kill_i
    Lines(i) = [];
    if kill_j
        if (i > j)
            Lines(j) = [];
        else
            Lines(j-1) = [];
        end
    end
    j = i;
    i = i - 1;
else
    if kill_j
        Lines(j) = [];
        j = j - 1;
    end
end
end
```

LeakConnection

The leak connection includes the following functions:

A constructor.

A destructor.

A get / set interface used by the property editor in the main GUI.

A discretize function.

A unused show function derived from the bridge component.

```
classdef LeakConnection < handle
  %UNTITLED Summary of this class goes here
  %   Detailed explanation goes here

  properties
    isChanged logical = true;
    isDiscretized logical = false;

    LeakFunc function_handle;
    obj1 = []; % Body or Environment
    obj2 = []; % Body or Environment
    Connection1 Connection;
    Connection2 Connection;
    Model Model;
  end

  properties (Hidden)
    customname;
  end

  properties (Dependent)
    name;
    isValid;
  end

  methods
    %% Constructor
    function this = LeakConnection(LeakFunc,obj1,obj2,Connection1,Connection2)
      if ~isa(LeakFunc,'function_handle')
        fprintf('You must define LeakFunc as a function handle, 0 assigned');
        this.LeakFunc = @(P1,P2) 0;
      else
        this.LeakFunc = LeakFunc;
      end
      if isa(obj1,'Body')
        this.obj1 = obj1;
        this.Connection1 = Connection1;
        this.Model = this.obj1.Group.Model;
      else; this.obj1 = obj1;
      end
      if isa(obj2,'Body')
        this.obj2 = obj2;
        this.Connection2 = Connection2;
        this.Model = this.obj2.Group.Model;
      else; this.obj2 = obj2;
      end
    end
```

```
function deReference(this)
  iModel = Body.Group.Model;
  for i = length(iModel.LeakConnections):-1:1
    if iModel.LeakConnections(i) == this
      iModel.LeakConnections(i) = LeakConnection.empty;
      break;
    end
  end
  if isa(this.obj1,'Body')
    this.obj1.change();
  end
  if isa(this.obj2,'Body')
    this.obj2.change();
  end
  this.Connection1.deleteNodeContactsFromObj(this.obj1);
  this.Connection1.deleteNodeContactsFromObj(this.obj2);
  this.Connection2.deleteNodeContactsFromObj(this.obj1);
  this.Connection2.deleteNodeContactsFromObj(this.obj2);
  this.Connection1.change();
  this.Connection2.change();
  this.removeFromFigure(gca);
  this.delete();
end

%% Get/Set Interface
function Item = get(this,PropertyName)
  switch PropertyName
    case 'Name'
      Item = this.name;
    case 'Connection 1'
      Item = this.Connection1;
    case 'Connection 2'
      Item = this.Connection2;
    case 'Object 1'
      Item = this.obj1;
    case 'Object 2'
      Item = this.obj2;
    case 'LeakFunc'
      Item = this.LeakFunc;
    otherwise
      fprintf(['XXX LeakConnection GET Inteface for ' PropertyName ' is not found XXX\n']);
  end
end
function set(this,PropertyName,Item)
  switch PropertyName
    case 'Name'
      if Item ~= this.name
        this.customname = Item;
        this.change();
      end
    case 'LeakFunc'
      this.LeakFunc = Item;
      this.change();
    otherwise
      fprintf(['XXX LeakConnection SET Inteface for ' PropertyName ' is not found XXX\n']);
  end
end

function change(this)
  this.isChanged = true;
  this.isDiscretized = false;
  fprintf('XXX Update Function for LeakConnection is Not written. XXX\n');
end

%% Generate Nodes
function leakfaces = getleakface(this)
    if this.isValid
        switch class(this.obj1)
            case 'Body'
                if this.obj1.isDiscretized
                    if this.Connection1 == false
```

```
                        n1 = this.obj1.nodeIndex(end);
                    else
                        n1 = this.obj1.nodeIndex(1);
                    end
                else
                    leakfaces = [];
                    return;
                end
            case 'Environment'
                if this.obj1.isValid
                    n1 = this.obj1.nodeIndex;
                end
        end
        switch class(this.obj2)
            case 'Body'
                if this.obj2.isDiscretized
                    if this.Connection1 == false
                        n2 = this.obj2.nodeIndex(end);
                    else
                        n2 = this.obj2.nodeIndex(1);
                    end
                else
                    leakfaces = [];
                    return;
                end
            case 'Environment'
                if this.obj2.isValid
                    n2 = this.obj2.nodeIndex;
                end
        end
        leakfaces = struct(...
            'Node1',n1,...
            'Node2',n2,...
            'LeakFunc',this.LeakFunc);
        this.isDiscretized = true;
    end
end

function [Faces] = discretize(this)
  fprintf('XXX Discretize function for LeakConnection is Not written. XXX\n');
  this.isDiscretized = true;
end

%% Testing
function Valid = get.isValid(this)
    Valid = true;
    if isempty(this.obj1)
        Valid = false;
        fprintf(['Missing reference for Leak Connection: ' ...
            this.name '.\n']);
    end
    if isempty(this.obj2)
        Valid = false;
        fprintf(['Missing reference for Leak Connection: ' ...
            this.name '.\n']);
    end
    if (class(this.obj1) == 'Body' && isempty(this.Connection1))
        Valid = false;
        fprintf(['Missing end descriptor for connection 1 of Leak ' ...
            'Connection: ' this.name '.\n']);
    end
    if (class(this.obj2) == 'Body' && isempty(this.Connection2))
        Valid = false;
        fprintf(['Missing end descriptor for connection 2 of Leak ' ...
            'Connection: ' this.name '.\n']);
    end
end

%% Graphics
function removeFromFigure(this,AxisReference)
  if ~isempty(this.GUIObjects)
```

```
    children = get(AxisReference,'Children');
    for obj = this.GUIObjects
      if isgraphics(obj)
        for i = length(children):-1:1
          if isgraphics(children(i)) && children(i) == obj
            children(i).delete;
            break;
          end
        end
      end
    end
    this.GUIObjects = [];
  end
end
function show(this,AxisReference)
  this.removeFromFigure(AxisReference);
  % Plot a dotted line between the middle of the Connection1's Overlap
  % with Body1 to the middle of Connection2's Overlap with Body2

  % Find P1;
  if isa(this.obj1,'Body')
    Ax = this.Connection1.Group;
    R = RotMatrix(Ax.Position.Rot);
    x = this.Connection1.x;
    switch this.Connection1.Orient
      case enumOrient.Vertical
        [~,~,y1,y2] = this.obj1.limits(enumOrient.Horizontal);
        A = [Ax.Position.x; Ax.Position.y] + ...
          R*[(y1+y2)/2; x];
        B = [Ax.Position.x; Ax.Position.y] + ...
          R*[(y1+y2)/2; -x];
      case enumOrient.Horizontal
        [~,~,y1,y2] = this.obj1.limits(enumOrient.Horizontal);
        A = [Ax.Position.x; Ax.Position.y] + ...
          R*[x; (y1+y2)/2];
        B = [Ax.Position.x; Ax.Position.y] + ...
          R*[x; -(y1+y2)/2];
    end
  elseif isa(this.obj1,'Environment')
    [x,y] = this.Model.EnvironmentPosition(this.obj1);
    A = [x; y];
    B = [x; y];
  else
    return;
  end

  % Find P2;
  if isa(this.obj2,'Body')
    Ax = this.Connection2.Group;
    R = RotMatrix(Ax.Position.Rot);
    x = this.Connection2.x;
    switch this.Connection1.Orient
      case enumOrient.Vertical
        [~,~,y1,y2] = this.obj2.limits(enumOrient.Vertical);
        C = [Ax.Position.x; Ax.Position.y] + ...
          R*[(y1+y2)/2; x];
        D = [Ax.Position.x; Ax.Position.y] + ...
          R*[(y1+y2)/2; -x];
      case enumOrient.Horizontal
        [~,~,y1,y2] = this.obj2.limits(enumOrient.Horizontal);
        C = [Ax.Position.x; Ax.Position.y] + ...
          R*[x; (y1+y2)/2];
        D = [Ax.Position.x; Ax.Position.y] + ...
          R*[x; -(y1+y2)/2];
    end
  elseif isa(this.obj2,'Environment')
    [x,y] = this.Model.EnvironmentPosition(this.obj2);
    C = [x; y];
    D = [x, y];
  else
    return;
```

```
      end

      % Find minimum pair
      % pair = zeros(2,2);
      if Dist4Compare(A,C) < Dist4Compare(B,D)
        pair = [A C];
        dmin = Dist4Compare(A,C);
      else
        pair = [B D];
        dmin = Dist4Compare(B,D);
      end
      if Dist4Compare(A,D) < dmin
        pair = [A D];
        dmin = Dist4Compar(A,D);
      end
      if Dist4Compare(B,C) < dmin
        pair = [B C];
      end

      % Find the closest blank space in the model and drag the label there
      [x, y, h] = this.Model.findInterSpace(pair);
      newpair = [pair(:,1) [x; y+h/2] [x; y-h/2] pair(:,2)];

      % Two points in pair are minimum distance
      this.GUIObjects = line(...
        newpair(1,:),newpair(2,:),...
        'Color',[0.5 0.5 0.5]);
    end
  end

end
```

Matrix

The matrix component is a class that includes the following functionality:

A constructor, destructor.

A get / set interface.

A modify function that walks the user through a series of uniforms specific to a particular matrix type.

A discretize function.

```
classdef Matrix < handle
  %MATRIX Summary of this class goes here
  %   Detailed explanation goes here
  properties (Constant)
    GeometrySource = {...
      'Woven Screen';
      'Random Fibre';
      'Packed Sphere';
      'Stacked Foil';
      'Custom Regen';
      'Heat Exchanger'};
  end

  properties
    GeometryEnum enumMatrix;

    matl Material;
    Geometry enumMatrix;

    fFunc_t function_handle;
    fFunc_l function_handle;
    NuFunc_t function_handle;
    NuFunc_l function_handle;
    NkFunc_l function_handle;
    NkFunc_t function_handle;

    Volumetric_HeatCapacity;

    Dh;
    Volumetric_SurfaceArea;
    data struct;
    isFullyLaminar logical = false;
    HasSource logical = false;

    Body Body;
    Nodes Node;
    Faces Face;
  end

  properties (Dependent)
    name;
  end

  methods
    function this = Matrix(Body)
      if nargin == 0
        return;
      end
```

```
  if nargin == 1
    this.Body = Body;
  end
  if isempty(this.GeometryEnum); this.assignGeometryEnum(); end
end
function deReference(this)
  if ~isempty(this)
    if ~isempty(this.Body)
      this.Body.Matrix = Matrix.empty;
      this.Body.change();
    end
    delete(this.Nodes);
    delete(this.Faces);
    if isfield(this.data,'Connection')
      this.data.Connection.change();
    end
    this.delete();
  end
end
function assignGeometryEnum(this)
  this.GeometryEnum(1) = enumMatrix.WovenScreen;
  this.GeometryEnum(2) = enumMatrix.RandomFiber;
  this.GeometryEnum(3) = enumMatrix.PackedSphere;
  this.GeometryEnum(4) = enumMatrix.StackedFoil;
  this.GeometryEnum(5) = enumMatrix.CustomRegen;
  this.GeometryEnum(6) = enumMatrix.HeatExchanger;
end
function item = get(this,PropertyName)
  switch PropertyName
    case 'Material'
      if isempty(this.matl)
        item = Material();
      else
        item = this.matl;
      end
    case 'Laminar Friction Function'
      item = this.fFunc_l;
    case 'Turbulent Friction Function'
      item = this.fFunc_t;
    case 'Laminar Nusselt Function'
      item = this.NuFunc_l;
    case 'Turbulent Nusselt Function'
      item = this.NuFunc_t;
    case 'Laminar Streamwise Cond. Enhancement'
      item = this.NkFunc_l;
    case 'Turbulent Streamwise Cond. Enhancement'
      item = this.NkFunc_t;
    case 'Source Temperature'
      if isfield(this.data,'SourceTemperature')
        item = this.data.SourceTemperature;
      else
        item = 0;
      end
  end
end
function set(this,PropertyName,item)
  switch PropertyName
    case 'Material'
      this.matl = item;
    case 'Laminar Friction Function'
      this.fFunc_l = item;
    case 'Turbulent Friction Function'
      this.fFunc_t = item;
    case 'Laminar Nusselt Function'
      this.NuFunc_l = item;
    case 'Turbulent Nusselt Function'
      this.NuFunc_t = item;
    case 'Laminar Streamwise Mixing Enhancement'
      this.NkFunc_l = item;
    case 'Turbulent Streamwise Mixing Enhancement'
      this.NkFunc_t = item;
```

```
        case 'Source Temperature'
          if isfield(this.data,'SourceTemperature')
            this.data.SourceTemperature = item;
          end
      end
    end
    function Modify(this)
      % define Material
      if isempty(this.matl); this.matl = Material(); end
      this.matl.Modify();

      % define Geometry
      if ~isempty(this.Geometry)
        for index = 1:length(this.GeometryEnum)
          if this.GeometryEnum(index) == this.Geometry; break; end
        end
      else; index = 1;
      end
      index = listdlg('ListString',this.GeometrySource,...
        'SelectionMode','single',...
        'InitialValue',index);
      if isempty(this.GeometryEnum); this.assignGeometryEnum(); end
      this.Geometry = this.GeometryEnum(index);

      % calculate Properties
      %% Regenerators
      if isempty(this.data); this.data = struct('hasSource',false);
      else; this.data.hasSource = false; end

      switch this.Geometry
        case enumMatrix.WovenScreen
          this.isFullyLaminar = true;
          this.HasSource = false;

          % Assign Default User Inputs, from history or hardcoded values
          op = {'90','0.001'}; % Default Values
          if isfield(this.data,'Porosity'); op{1} = num2str(this.data.Porosity*100); end
          if isfield(this.data,'dw'); op{2} = num2str(this.data.dw); end

          % Get User Inputs
          firstround = true;
          while firstround || ~isStrNumeric(op{1}) || ~isStrNumeric(op{2})
            if firstround; firstround = false;
            else; msgbox('Numeric Values only'); end
            op = inputdlg(...
              {'Porosity (%)','Wire Diameter (m)'},...
              'Generate a Woven Screen Matrix',[1 35],op);
          end
          this.data.Porosity = str2double(op{1})/100;
          %this.Volumetric_HeatCapacity = (1 -
this.data.Porosity)*this.matl.HeatCapacity*this.matl.Density;
          this.data.dw = str2double(op{2});
          this.Dh = this.data.dw/(1-this.data.Porosity);

          % Friction Factor
          this.fFunc_l = @(Re) 129./Re+2.91*(Re.^(-0.103));
          this.fFunc_t = this.fFunc_l;

          % Nusselt Number
          this.NuFunc_l = @(Re,Pr) (1+0.99*(this.data.Porosity^1.79)*(Re.*Pr).^0.66);
          this.NuFunc_t = this.NuFunc_l;

          % Streamwise mixing enhancement
          this.NkFunc_l = @(Re,Pr) 1+0.5*(this.data.Porosity^(-2.91))*((Re.*Pr).^0.66);
          this.NkFunc_t = this.NkFunc_l;
        case enumMatrix.RandomFiber
          this.isFullyLaminar = true;
          this.HasSource = false;

          % Assign Default User Inputs, from history or hardcoded values
          op = {'90','0.001'}; % Default Values
```

```
          if isfield(this.data,'Porosity'); op{1} = num2str(this.data.Porosity*100); end
          if isfield(this.data,'dw'); op{2} = num2str(this.data.dw); end

          % Get User Inputs
          firstround = true;
          while firstround || ~isStrNumeric(op{1}) || ~isStrNumeric(op{2})
            if firstround; firstround = false;
            else; msgbox('Numeric Values only'); end
            op = inputdlg(...
              {'Porosity (%)','Wire Diameter (m)'},...
              'Generate a Random Fibre Matrix',[1 35],op);
          end
          this.data.Porosity = str2double(op{1})/100;
          %this.Volumetric_HeatCapacity = (1-
this.data.Porosity)*this.matl.HeatCapacity*this.matl.Density;
          this.data.dw = str2double(op{2});
          this.Dh = this.data.dw/(1-this.data.Porosity);
          alpha = this.data.Porosity/(1-this.data.Porosity);

          % Friction Factor
          this.fFunc_l = @(Re) (25.7*alpha+79.8)./Re+...
            (0.146*alpha+3.76)*(Re.^(-0.00283*alpha-0.0748));
          this.fFunc_t = this.fFunc_l;

          % Nusselt Number
          this.NuFunc_l = @(Re,Pr) 1+0.186*alpha*(Re.*Pr).^0.55;
          this.NuFunc_t = this.NuFunc_l;

          % Streamwise Mixing Enhancement
          this.NkFunc_l = @(Re,Pr) (1+(Re.*Pr).^0.55);
          this.NkFunc_t = this.NkFunc_l;
        case enumMatrix.PackedSphere
          this.isFullyLaminar = true;
          this.HasSource = false;

          % Assign Default User Inputs, from history or hardcoded values
          op = {'90','0.001'}; % Default Values
          if isfield(this.data,'Porosity'); op{1} = num2str(this.data.Porosity*100); end
          if isfield(this.data,'Dp'); op{2} = num2str(this.data.dw); end

          % Get User Inputs
          firstround = true;Run
          while firstround || ~isStrNumeric(op{1}) || ~isStrNumeric(op{2})
            if firstround; firstround = false;
            else; msgbox('Numeric Values only'); end
            op = inputdlg(...
              {'Porosity (%)','Particle Diameter (m)'},...
              'Generate a Stacked Particle Matrix',[1 35],op);
          end
          this.data.Porosity = str2double(op{1});
          %this.Volumetric_HeatCapacity = (1-
this.data.Porosity)*this.matl.HeatCapacity*this.matl.Density;
          this.data.Dp = str2double(op{2});
          this.Dh = this.data.Dp*this.data.Porosity/(6*(1-this.data.Porosity));

          % Friction Factor
          this.fFunc_l = @(Re) (157./Re+(5.15*(this.data.Porosity/0.39)^(3.48))*(Re.^-0.137));
          this.fFunc_t = @(Re,Pr) (157./Re+(5.15*(this.data.Porosity/0.39)^(3.48))*(Re.^-0.137));

          % Nusselt Number
          this.NuFunc_l = @(Re,Pr) (1+0.48*(Re.*Pr).^0.65);
          this.NuFunc_t = this.NuFunc_l;

          % Streamwise Mixing Enhancement
          this.NkFunc_l = @(Re,Pr) 1+3*(Re.*Pr).^0.65;
          this.NkFunc_t = this.NkFunc_l;
        case enumMatrix.StackedFoil
          this.isFullyLaminar = false;
          this.HasSource = true;

          % Assign Default User Inputs, from history or hardcoded values
```

```
            op = {'0.00025','0.0001','0.0001'}; % Default Values
            if isfield(this.data,'gap'); op{1} = num2str(this.data.gap); end
            if isfield(this.data,'dw'); op{2} = num2str(this.data.dw); end
            if isfield(this.data,'e'); op{3} = num2str(this.data.e); end

            % Get User Inputs
            firstround = true;
            while firstround || ~isStrNumeric(op{1}) || ...
                ~isStrNumeric(op{2}) || ~isStrNumeric(op{3})
              if firstround; firstround = false;
              else; msgbox('Numeric Values only'); end
              op = inputdlg(...
                {'Gap Width (m)','Sheet Thickness (m)','Sheet Roughness (m)'},...
                'Generate a Stacked Foil Matrix',[1 35],op);
            end
            this.data.gap = str2double(op{1});
            this.data.dw = str2double(op{2});
            this.data.e = str2double(op{3});
            this.Dh = 2*this.data.gap;
            this.data.Porosity = this.data.gap/(this.data.gap+this.data.dw);
            %this.Volumetric_HeatCapacity = (1-
this.data.Porosity)*this.matl.HeatCapacity*this.matl.Density;

            % Friction Factors
            % E. Fried, I.E. Idelchik, Flow Resistance: A Design Guide for Engineers,
            %    Hemisphere, (1989)
            this.fFunc_l = @(Re) 96./Re;
            this.fFunc_t = @(Re) 0.121*(this.data.e/this.Dh+68./Re).^0.25;

            % Nusselt Number
            this.NuFunc_l = @(Re) 8.23;
            this.NuFunc_t = @(Re,Pr) 0.025*(Re.^0.79).*(Pr.^0.33);

            % Streamwise Mixing Enhancement
            this.NkFunc_l = @(Re) 1;
            this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr);

        case enumMatrix.CustomRegen
            this.isFullyLaminar = false;
            this.HasSource = true;
            op = {'0.025','0.80','0.121','-0.25','1000','0.95'}; % Default Values
            if isfield(this.data,'C1'); op{1} = num2str(this.data.C1); end
            if isfield(this.data,'C2'); op{2} = num2str(this.data.C2); end
            if isfield(this.data,'C3'); op{3} = num2str(this.data.C3); end
            if isfield(this.data,'C4'); op{4} = num2str(this.data.C4); end
            if isfield(this.data,'SA_V'); op{5} = num2str(this.data.SA_V); end
            if isfield(this.data,'Porosity'); op{6} = num2str(this.data.Porosity); end

            % Get User Inputs
            firstround = true;
            while firstround || ~isStrNumeric(op{1}) || ...
                ~isStrNumeric(op{2}) || ~isStrNumeric(op{3}) || ...
                ~isStrNumeric(op{4}) || ~isStrNumeric(op{5}) || ...
                ~isStrNumeric(op{6})
              if firstround; firstround = false;
              else; msgbox('Numeric Values only'); end
              op = inputdlg(...
                {'C1','C2','C3','C4','Surface area to volume ratio [m^2/m^3]','Porosity'},...
                'Provide Parameters Nu = C1*Re^C2, F = C3*Re^C4 and other properties',[1 35],op);
            end
            this.data.C1 = str2double(op{1});
            this.data.C2 = str2double(op{2});
            this.data.C3 = str2double(op{3});
            this.data.C4 = str2double(op{4});
            this.data.SA_V = str2double(op{5});
            this.data.Porosity = str2double(op{6});
            this.Dh = 4/this.data.SA_V;

            % Friction Factors
            this.fFunc_l = @(Re) this.data.C3.*Re.^this.data.C4;
            this.fFunc_t = this.fFunc_l;
```

```
          % Nusselt Number
          this.NuFunc_l = @(Re,Pr) this.data.C1.*Re.^this.data.C2.*Pr.^0.33333;
          this.NuFunc_t = this.NuFunc_l;

          % Streamwise Mixing Enhancement
          this.NkFunc_l = @(Re) 1;
          this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr);
      end
      %% Heat Exchangers
      switch this.Geometry
        % Friction Factors
        % G.W. Swift, Thermoacoustics: A Unifying Perspective for some Engines
        %    and Refrigerators, Fourth draft, LA-UR-99-895, 1999
        % this.fFunc_l = @(Va)
        % this.fFunc_t = @(Re) 0.11*(this.data.e/this.Dh+68/Re)^0.25;
        % Nusselt Numbers
        % this.NuFunc_l = @(Re)
        % this.NuFunc_t = @(Re,Pr) 0.036*(Re^0.8)*(
        case enumMatrix.HeatExchanger
          %% Determine what Classification
          % Fined Surface Type
          % Channel Type
          % Normal to Tube Type
          ChoosingClassification = true;
          while (ChoosingClassification)
            % Select Heat Exchanger Type from List
            Source = {'Fin Enhanced Surface','Fin Connected Channels','Staggered Fin Connected
Tubes','Tube Bank Internal','Custom HX'};
            found = false;
            if isfield(this.data,'Classification')
              for index = 1:length(Source)
                if strcmp(this.data.Classification,Source{index})
                  found = true;
                  break;
                end
              end
            end
            if ~found; index = 1; end
            index = listdlg('ListString',Source,'SelectionMode','single','InitialValue',index);
            if isempty(this.data); this.data = struct('Classification',Source{index});
            else; this.data.Classification = Source{index}; end

            % If the User Made a selection
            if index > 0
              ChoosingClassification = false;
              switch index
                case 1 % 'Fin Enhanced Surface'
                  %% Assume straight Flat fins aligned with flow direction
                  % Assign Values
                  Source = {'Fin Separation','Fin Thickness','Surface Roughness'};
                  op = {'0.00318', '0.00318', '0.000001'};
                  if isfield(this.data,'FinSeparation'); op{1} =
num2str(this.data.FinSeparation); end
                  if isfield(this.data,'FinThickness'); op{2} = num2str(this.data.FinThickness);
end
                  if isfield(this.data,'Roughness'); op{3} = num2str(this.data.Roughness); end

                  DeterminingFinProperties = true;

                  while (DeterminingFinProperties)
                    op = inputdlg(Source,'Determine Fin Properties',[1 35],op);
                    if isempty(op); ChoosingClassification = true; break; end

                    % If the User inputed the appropriate data
                    if isStrNumeric(op{1}) && isStrNumeric(op{2}) && isStrNumeric(op{3})
                      DeterminingFinProperties = false;
                      this.data.FinSeparation = str2double(op{1});
                      this.data.FinThickness = str2double(op{2});
                      this.data.Roughness = str2double(op{3});
                      lg = this.data.FinSeparation;
```

```
                        lth = this.data.FinThickness;
                        e = this.data.Roughness;

                        % Get the user to select a surface that will be
                        % ... enhanced
                        Source = cell(1,4);
                        i = 1;
                        for iCon = this.Body.Connections
                          Source{i} = iCon.name; i = i + 1;
                        end
                        index =
listdlg('ListString',Source,'SelectionMode','single','InitialValue',1);

                        % If the User made a selection
                        if index > 0
                          this.data.Connection = this.Body.Connections(index);
                          this.data.Porosity = lg/(lg+lth);

                          %% Hydraulic Diameter
                          if this.data.Connection.Orient == enumOrient.Vertical
                            % Along the wall
                            [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
                            this.data.FinLength = xmax - xmin;
                          else
                            % Along the top or bottom surface
                            [ymin,ymax,~,~] = this.Body.limits(enumOrient.Horizontal);
                            this.data.FinLength = min(ymax-ymin);
                          end
                          this.Dh = (4*lg*lth)/(2*lg + 2*lth);

                          % Friction Factor
                          % ... E. Fried, I.E. Idelchik, Flow Resistance: A Design Guide for
Engineers,
                          % ...    Hemisphere, (1989)
                          x = min(lg/lf,lf/lg);
                          C1 = -59.33*x^3+145.6*x^2-125.37*x+96;
                          this.fFunc_l = @(Re) C1./Re;
                          this.fFunc_t = @(Re) 0.121*(e/this.Dh+68./Re).^0.25;

                          % Nusselt Number
                          this.NuFunc_l = @(Re) 8.23;
                          this.NuFunc_t = @(Re,Pr) 0.025*(Re.^0.79).*(Pr.^0.33);

                          % Stramwise Mixing Enhancement
                          this.NkFunc_l = @(Re) 1;
                          this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr);

                        else
                          DeterminingFinProperties = true;
                        end
                      end
                    end
                    this.data.hasSource = false;
                  case 2 % 'Fin Connected Channels'
                    % Assume the source runs in planes concident with flow
                    % ... direction with fins weaving their way between these
                    % ... channels
                    % Assign Values
                    Source = {'Gap Between Source Channels',...
                      'Source Channel Total Width',...
                      'Source Channel Wall Thickness',...
                      'Surface Roughness'};
                    op = {'0.01','0.002','0.0005','0.000001'};
                    if isfield(this.data,'gap'); op{1} = num2str(this.data.gap); end
                    if isfield(this.data,'ChannelThickness'); op{2} =
num2str(this.data.ChannelThickness); end
                    if isfield(this.data,'WallThickness'); op{3} =
num2str(this.data.WallThickness); end
                    if isfield(this.data,'Roughness'); op{4} = num2str(this.data.Roughness); end

                    DeterminingGeneralChannelGeometry = true;
```

```
                while (DeterminingGeneralChannelGeometry)
                  op = inputdlg(Source,'Define General Heat Exchanger Geometry',...
                    [1 35],op);
                  if isempty(op); ChoosingClassification = true; break; end
                  if isStrNumeric(op{1}) && isStrNumeric(op{2}) && ...
                      isStrNumeric(op{3}) && isStrNumeric(op{4})
                    DeterminingGeneralChannelGeometry = false;
                    this.data.gap = str2double(op{1});
                    this.data.ChannelThickness = str2double(op{2});
                    this.data.WallThickness = str2double(op{3});
                    this.data.Roughness = str2double(op{4});
                    lf = this.data.gap;
                    lcth = this.data.ChannelThickness;
                    e = this.data.Roughness;
                    DeterminingGeometry = true;

                    % Pick the fin pattern, straight across or zig-zag
                    Source = {'Rectangular','Triangular'};
                    index = 1;
                    while (DeterminingGeometry)
                      index =
listdlg('ListString',Source,'SelectionMode','single','InitialValue',index);

                      % If the User made a selection
                      if index > 0
                        DeterminingGeometry = false;
                        this.data.Geometry = Source{index};

                        DetermingGeometryProperties = true;
                        % Assign Defaults
                        Source = {'Base Width','Fin Thickness'};
                        op = {'0.002','0.0002'};
                        if isfield(this.data,'BaseWidth'); op{1} =
num2str(this.data.BaseWidth); end
                        if isfield(this.data,'FinThickness'); op{2} =
num2str(this.data.FinThickness); end

                        while (DetermingGeometryProperties)
                          op = inputdlg(Source,'Define In Channel Geometry',...
                            [1 35],op);
                          if isempty(op); DeterminingGeometry = true; break; end
                          this.data.BaseWidth = str2double(op{1});
                          this.data.FinThickness = str2double(op{2});
                          lb = this.data.BaseWidth;
                          lth = this.data.FinThickness;
                          switch index
                            case 1 % 'Rectangular'
                              this.data.FinLength = lf;
                              % Porosity
                              this.data.Porosity = ...
                                ((lf - lth)/(lf - lth + lcth))*...
                                (lb/(lb + lth));

                              % Hydraulic Diameter
                              this.Dh = 4*lf*lb/(2*lf + 2*lb);

                              % Friction Factor
                              % E. Fried, I.E. Idelchik, Flow Resistance: A Design Guide for
Engineers,
                              %    Hemisphere, (1989)
                              x = min(lf/lb,lb/lf);
                              C1 = -59.33*x^3+145.6*x^2-125.37*x+96;
                              if C1 > 96; C1 = 96; elseif C1 < 56.92; C1 = 56.92; end
                              this.fFunc_l = @(Re) C1./Re;
                              this.fFunc_t = @(Re) 0.25*(e/this.Dh+68./Re).^0.25;

                              % Nusselt Number
                              this.NuFunc_l = @(Re) 8.23;
                              this.NuFunc_t = @(Re,Pr) 0.025*(Re.^0.79).*(Pr.^0.33);
```

```
                                % Streamwise Mixing Enhancement
                                this.NkFunc_l = @(Re) 1;
                                this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr);
                              case 2 % 'Triangular'
                                A = atan(lb/(2*(this.data.gap-lth)));
                                this.data.FinLength = this.data.gap/cos(A);
                                lf = this.data.FinLength;
                                % Porosity
                                lth2 = lth/cos(A);
                                this.data.Porosity = ...
                                  (this.data.gap/(this.data.gap + lcth))*...
                                  (lb/(lb + lth2));

                                % Hydraulic Diameter
                                this.Dh = (lb/2)/(1+sqrt(1/(tan(A)^2) + 1));

                                % Friction Factor
                                Cl = 2.263*A^3 - 7.208*A^2 + 5.738*A + 12;
                                this.fFunc_l = @(Re) Cl./Re;
                                C2 = -0.0184*A^2 + 0.0414*A + 0.0847;
                                this.fFunc_t = @(Re) C2*(e/this.Dh+68./Re).^0.25;

                                % Nusselt Number
                                NuT = 2.66*A^5 - 12.19*A^4 + 21.63*A^3 - 19.9*A^2 + 8.92*A +
0.956;
                                this.NuFunc_l = @(Re) NuT;
                                TempFunc = @(f,Re,Pr) (f./8).*Re.*Pr./(1.07+12.7*(Pr.^(2/3)-
1).*(f./8).^0.5);
                                this.NuFunc_t = @(Re,Pr) TempFunc(this.fFunc_t(Re),Re,Pr);

                                % Mixing
                                this.NkFunc_l = @(Re) 1;
                                this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr); % its similiar
to rectangular flows
                            end
                            DetermingGeometryProperties = false;
                          end
                        else
                          DeterminingGeneralChannelGeometry = true;
                          break;
                        end
                      end
                    end
                  end
                  this.data.hasSource = true;
                case 3 % 'Staggered Fin Connected Tubes'
                  Source = {'Spacing Perpendicular to Flow',...
                    'Spacing Parallel to Flow',...
                    'Fin: Thickness',...
                    'Fin: Separation',...
                    'Fin: Fin Radial Length (C: Continuous Plate)',...
                    'Tube Outer Diameter',...
                    'Tube Inner Diameter',...
                    'Surface Area Factor',...
                    'Heat Transfer Factor'};
                  op = {'0.02',...
                    '0.02',...
                    '0.0002',...
                    '0.002',...
                    'C',...
                    '0.00635',...
                    '0.00508',...
                    '1',...
                    '1'};
                  if isfield(this.data,'PerpSpacing'); op{1} = num2str(this.data.PerpSpacing);
end
                  if isfield(this.data,'ParaSpacing'); op{2} = num2str(this.data.ParaSpacing);
end
                  if isfield(this.data,'FinThickness'); op{3} = num2str(this.data.FinThickness);
end
```

```
                if isfield(this.data,'FinSeparation'); op{4} =
num2str(this.data.FinSeparation); end
                if isfield(this.data,'FinLength'); op{5} = num2str(this.data.FinLength); end
                if isfield(this.data,'do'); op{6} = num2str(this.data.do); end
                if isfield(this.data,'di'); op{7} = num2str(this.data.di); end
                if isfield(this.data,'SurfaceAreaFactor'); op{8} =
num2str(this.data.SurfaceAreaFactor); end
                if isfield(this.data,'HeatTransferFactor'); op{9} =
num2str(this.data.HeatTransferFactor); end

                DeterminingNormalToTubeType = true;
                while (DeterminingNormalToTubeType)
                  op = inputdlg(Source,'Define Finned Tube HX Geometry',...
                    [1 35],op);
                  if isempty(op); ChoosingClassification = true; break;
                  end
                  if isStrNumeric(op{1}) && isStrNumeric(op{2}) && ...
                      isStrNumeric(op{3}) && isStrNumeric(op{4}) && ...
                      (strcmp(op{5},'C') || isStrNumeric(op{5})) && ...
                      isStrNumeric(op{6}) && isStrNumeric(op{7}) && ...
                      isStrNumeric(op{8})
                    % Assign Base Properties
                    DeterminingNormalToTubeType = false;
                    this.data.PerpSpacing = str2double(op{1});
                    this.data.ParaSpacing = str2double(op{2});
                    this.data.FinThickness = str2double(op{3});
                    this.data.FinSeparation = str2double(op{4});
                    if ~strcmp(op{5},'C')
                      this.data.FinLength = str2double(op{5});
                      lf = this.data.FinLength;
                    end
                    this.data.do = str2double(op{6});
                    this.data.di = str2double(op{7});
                    this.data.SurfaceAreaFactor = str2double(op{8});
                    this.data.HeatTransferFactor = str2double(op{9});

                    lperp = this.data.PerpSpacing;
                    lpara = this.data.ParaSpacing;
                    lth = this.data.FinThickness;
                    lg = this.data.FinSeparation;
                    do = this.data.do;

                    Ao = lperp*lpara;
                    Vo = Ao*(lth + lg);

                    % Porosity
                    this.data.PercentageTube = (pi/4*do^2)/Ao;
                    if isfield(this.data,'FinLength')
                      ro = do/2 + lf;
                      this.data.Porosity = ...
                        (lg + lth)*(Ao - pi*ro^2)/Vo + ... Empty space
                        lg*pi*(ro^2 - 0.25*do^2)/Vo; % Finned Areas
                    else
                      this.data.Porosity = ...
                        lg*(Ao - pi/4*do^2)/Vo; % Finned Areas
                    end
                    this.Dh = do;

                    % Nusselt Number
                    % Aligned with theta; may be axial, may be radial
                    [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
                    [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
                    if this.Body.divides(1) > 1
                      dist = abs(xmax-xmin);
                    elseif this.Body.divides(2) > 1
                      dist = abs(ymax-ymin);
                    else
                      if abs(xmax-xmin) > abs(ymax-ymin)
                        dist = abs(xmax-xmin);
                      else
                        dist = abs(ymax-ymin);
```

```
                        end
                      end
                      Nr = dist/this.data.ParaSpacing;

                      if isfield(this.data,'FinLength')
                        % Individual Finned Tubes - Staggered
                        lf_do = this.data.FinLength/this.data.do;
                        if lf_do < 0.09
                          % Low finned tubes
                          % if Re -> (895, 713,000)
                          C1 = 0.255*(2*ro/lg);
                          this.NuFunc_t = @(Re,Pr) ...
                              this.data.HeatTransferFactor*...
                              C1*(Re.^0.7).*Pr.^(0.333);
                          do_Xt = do/lperp;
                          if do_Xt < 0.25
                            fprintf('XXX LaterialSpacing/OuterDiameter is out friction
correlation range XXX\n');
                          end
                          if round(Nr) < 4
                            fprintf('XXX Calcualted # of tube rows is out friction correlation
range XXX\n');
                          end
                          C2 = 4*1.748*(lf/lg)^0.552*do_Xt^0.599*(do/lpara)^0.1738;
                          this.fFunc_t = @(Re) C2*Re.^(-0.233);

                          % Laminar Cases - assume always turbulent
                          this.NuFunc_l = this.NuFunc_t;
                          this.fFunc_l = this.fFunc_t;

                        else % High finned tubes
                          % if Re -> (1100, 18,000)
                          s_lf = lg/lf;
                          s_df = lg/lth;
                          lf_do = lf/do;
                          df_do = lth/do;
                          Xt_do = lperp/do;
                          if s_lf < 0.13 || s_lf > 0.63
                            fprintf('XXX FinSeparation/FinLength is out of Nusselt correlation
range XXX\n');
                          end
                          if s_df < 1.01 || s_df > 6.62
                            fprintf('XXX FinSeparation/FinThickness is out of Nusselt correlation
range XXX\n');
                          end
                          if lf_do > 0.69 || lf_do < 0.09
                            fprintf('XXX FinLength/OuterDiameter is out of Nusselt correlation
range XXX\n');
                          end
                          if df_do < 0.011 || df_do > 0.15
                            fprintf('XXX FinThickness/OuterDiameter is out Nusselt correlation
range XXX\n');
                          end
                          if Xt_do < 1.54 || Xt_do > 8.23
                            fprintf('XXX LaterialSpacing/OuterDiameter is out Nusselt correlation
range XXX\n');
                          end
                          if this.data.do < 0.0111 || this.data.do > 0.0409
                            fprintf('XXX OuterDiameter is out Nusselt correlation range XXX\n');
                          end
                          C1 = 0.134*(s_lf^0.2)*(s_df^0.11);
                          this.NuFunc_t = @(Re,Pr) ...
                              this.data.HeatTransferFactor*...
                              C1*(Re.^(0.681)).*(Pr.^(0.333));
                          C2 = (2*this.Dh/dist)*4*9.465*(Xt_do^-0.927)*(lperp/...
                            sqrt(lperp^2 + lpara^2))^0.515;
                          this.fFunc_t = @(Re) C2*Re.^(-0.316);

                          % Laminar Cases - assume always turbulent
                          this.NuFunc_l = this.NuFunc_t;
                          this.fFunc_l = this.fFunc_t;
```

```
                        end
                      else
                        fprintf('XXX Sorry, the Flat Plan Fins on Staggered Tube Bank is
currently under development\n');
                        fprintf('The Best Source is here:
http://thermopedia.com/content/750/\n');
                        %{
                        % Flat Plain Fins on a Staggered Tube Bank
                        C1 = 0.14*...
                          (lperp/lpara)^-0.502*...
                          (lg/do)^0.031;
                        if Nr >= 4
                          this.NuFunc_t = @(Re,Pr) C1*Re^0.672*Pr^0.333;
                        else
                          C2 = C1*0.991*(2.24*(Nr/4)^-0.031)^(-0.607*(4-Nr));
                          C3 = 1+(-0.092*0.607*(4-Nr))-0.328;
                          this.NuFunc_t = @(Re,Pr) C2*Re^C3*Pr^0.333;
                        end
                        % Re -> (500, 24,700)
                        Xt_do = lperp/do;
                        Xl_do = lpara/do;
                        s_do = lg/do;
                        C4 = SFin/(STube+SFin);
                        C5 = (1-C4)*FinVoid;
                        if Xt_do < 1.97 || Xt_do > 2.55
                          fprintf('XXX LaterialSpacing/OuterDiameter is out of Friction
correlation range XXX\n');
                        end
                        if Xl_do < 1.7 || Xl_do > 2.58
                          fprintf('XXX LongitudinalSpacing/OuterDimeter is out of Friction
correlation range XXX\n');
                        end
                        if s_do < 0.08 || s_do > 0.64
                          fprintf('XXX FinSeparation/OuterDimeter is out of Friction correlation
range XXX\n');
                        end
                        C4a = 4*C4*0.508*(Xt_do)^1.318;
                        % Staggered Tube Grid Friction Factor
                        % Re -> (300, 15,000)
                        C5a = 4*C5*TubeBankFriction(lperp,lpara,do);
                        this.fFunc_t = @(Re) C4a*Re^(-0.521) + C5a*((do/this.Dh)*Re)^(-0.18);

                        % Laminar Cases - assume always turbulent due to
                        %   being tripped
                        this.NuFunc_l = this.NuFunc_t;
                        this.fFunc_l = this.fFunc_t;
                        %}
                      end

                      %% Mixing
                      % Axial Conduction Enhancement
                      %      Taken From woven regenerators
                      this.NkFunc_l = @(Re,Pr) 1+0.5*(this.data.Porosity^(-
2.91))*((Re.*Pr).^0.66);
                      this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr);
                    end
                  end
                  this.data.hasSource = true;
                case 4 % Tube Bank Internal
                  Source = {'Number of Tubes',...
                    'Tube Outer Diameter',...
                    'Tube Inner Diameter'};
                  op = {'100',...
                    '0.01',...
                    '0.008'};
                  if isfield(this.data,'Number'); op{1} = num2str(this.data.Number); end
                  if isfield(this.data,'do'); op{2} = num2str(this.data.do); end
                  if isfield(this.data,'di'); op{3} = num2str(this.data.di); end

                  DeterminingNormalToTubeType = true;
```

```
                while (DeterminingNormalToTubeType)
                  op = inputdlg(Source,'Define Tube Bank Internal HX Geometry',...
                    [1 35],op);
                  if isempty(op); ChoosingClassification = true; break;
                  end
                  if isStrNumeric(op{1}) && isStrNumeric(op{2}) && ...
                      isStrNumeric(op{3})
                    DeterminingNormalToTubeType = false;
                    this.data.Number = str2double(op{1});
                    this.data.do = str2double(op{2});
                    this.data.di = str2double(op{3});
                    di = this.data.di;

                    % Nusselt Number
                    % Aligned with theta; may be axial, may be radial
                    [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
                    [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
                    if this.Body.divides(1) > 1
                      dist = abs(xmax-xmin);
                      A = 2*pi*abs(ymax-ymin)*xmin;
                    elseif this.Body.divides(2) > 1
                      dist = abs(ymax-ymin);
                      A = pi*(xmax^2-xmin^2);
                    else
                      if abs(xmax-xmin) > abs(ymax-ymin)
                        dist = abs(xmax-xmin);
                        A = 2*pi*(ymax-ymin)*xmin;
                      else
                        dist = abs(ymax-ymin);
                        A = pi*(xmax^2-xmin^2);
                      end
                    end
                    this.data.Ao = A/this.data.Number;
                    this.data.Spacing = sqrt(4*this.data.Ao/sqrt(3));
                    this.data.Porosity = ((pi/4)*di^2)/this.data.Ao;
                    this.Dh = di;

                    Cturb = 0.036*(dist/di)^(-0.055);
                    this.NuFunc_t = @(Re,Pr) Cturb*(Re.^0.8).*(Pr.^0.33);
                    this.fFunc_t = @(Re) 0.11*(this.Body.Group.Model.roughness/di
+68./Re).^0.25;

                    % Laminar Cases - assume always turbulent
                    this.NuFunc_l = @(Re) 6;
                    this.fFunc_l = @(Re) 64./Re;

                    %% Mixing
                    % Axial Conduction Enhancement
                    %      Taken From woven regenerators
                    this.NkFunc_l = @(Re) 1;
                    this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*Pr;
                  end
                end
                this.data.hasSource = true;
              case 5 % Custon HX
                Source = {'C1','C2','C3','C4','Surface are to gas volume ratio
[m^2/m^3]','Porosity'};
                op = {'0.020', '0.8', '0.11', '-0.25', '1.5', '0.5'};
                if isfield(this.data,'C1'); op{1} = num2str(this.data.C1); end
                if isfield(this.data,'C2'); op{2} = num2str(this.data.C2); end
                if isfield(this.data,'C3'); op{3} = num2str(this.data.C3); end
                if isfield(this.data,'C4'); op{4} = num2str(this.data.C4); end
                if isfield(this.data,'SA_V'); op{5} = num2str(this.data.SA_V); end
                if isfield(this.data,'Porosity'); op{6} = num2str(this.data.Porosity); end

                DeterminingParameterSet = true;
                while (DeterminingParameterSet)
                  op = inputdlg(Source,'Pick Nu = C1*Re^C2*Pr^0.33, F = C3*Re^C4, HX Surface to
Volume Ratio and porosity',...
                    [1 35],op);
                  if isempty(op); ChoosingClassification = true; break;
```

```
                end
                if isStrNumeric(op{1}) && isStrNumeric(op{2}) && ...
                    isStrNumeric(op{3}) && isStrNumeric(op{4}) && ...
                    isStrNumeric(op{5}) && isStrNumeric(op{6})
                  DeterminingParameterSet = false;
                  this.data.C1 = str2double(op{1});
                  this.data.C2 = str2double(op{2});
                  this.data.C3 = str2double(op{3});
                  this.data.C4 = str2double(op{4});
                  this.data.SA_V = str2double(op{5});
                  this.data.Porosity = str2double(op{6});

                  this.Dh = 4/this.data.SA_V;

                  % Nusselt Number
                  % Aligned with theta; may be axial, may be radial
                  this.NuFunc_t = @(Re,Pr) this.data.C1.*(Re.^this.data.C2).*(Pr.^0.33);
                  this.fFunc_t = @(Re) this.data.C3.*Re.^this.data.C4;

                  % Laminar Cases - assume always turbulent
                  this.NuFunc_l = @(Re) 3.66;
                  this.fFunc_l = @(Re) 64./Re;

                  %% Mixing
                  % Axial Conduction Enhancement
                  %      Taken From woven regenerators
                  this.NkFunc_l = @(Re) 1;
                  this.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*Pr;
                end
              end
              this.data.hasSource = true;
            end
          else
            fprintf('XXX Matrix not finished XXX\n');
            return;
          end
        end
    end
    if this.data.hasSource
      op = cell(1);
      if isfield(this.data,'SourceTemperature')
        op{1} = num2str(this.data.SourceTemperature);
      else
        op{1} = '';
      end
      op = inputdlg('What will be the source Temperature?','Define Source Temperature',1,op);
      if ~isnan(str2double(op{1}))
        this.data.SourceTemperature = str2double(op{1});
      else
        this.data.SourceTemperature = this.Body.Temperature();
      end
    end
  end
  function [nodes, faces] = discretize(this,pnd)
    Np = length(pnd);
    this.Nodes = Node.empty;
    this.Faces = Face.empty;
    k = this.matl.ThermalConductivity;
    % Create Nodes to depth based on biot number
    switch this.Geometry
      case {enumMatrix.WovenScreen, ...
          enumMatrix.RandomFiber, ...
          enumMatrix.PackedSphere, ...
          enumMatrix.StackedFoil, ...
          enumMatrix.CustomRegen}
        this.data.ignore_canister = true;
        ncount = Np + 1;
        fcount = Np + 1;
        switch this.Geometry
          case {enumMatrix.WovenScreen, enumMatrix.RandomFiber}
            % Coefficient = Length of wire per volume * pi * diameter
```

```
      % ... Total_Area/Volume = pi*dw*L / (0.25*pi*dw*dw*L)
      % ... Total_Area/Volume = 1 / (0.25*dw)
      A_V = 4*(1-this.data.Porosity)/this.data.dw;
      % ... Resistance * Total_Area = log(2)/(2*pi*L*k) * pi*dw*L
      % ... = log(2)/(2) * dw/k
      RxA = 0.3466*this.data.dw/k; % ds/(2*k/ln(2));
    case enumMatrix.PackedSphere
      % Coefficient = Number of spheres per volume*pi*dw^2
      % ... A/V = (pi*dw^2)/(4*pi*dw^3/(8*3)) = 6/dw
      A_V = 6*(1-this.data.Porosity)/this.data.dw;
      % Resistance * Total_Area = 0.5*dw/(4*pi*k*dw*dw*0.5) *
      % ... pi*dw^2
      % ... = pi*dw^2/(4*pi*k*dw) = dw/(4*k)
      RxA = this.data.dw/(4*k);
    case enumMatrix.StackedFoil
      % Coefficient = Area/Volume = 2/(gap + dw)
      A_V = 2/(this.data.gap + this.data.dw);
      % Resistance = L/(k*A) = (dw/2) / (k*2)
      % Total_Area = 2
      RxA = this.data.dw/(2*k);
    case enumMatrix.CustomRegen
      A_V = this.data.SA_V;
      dw = 4*(1-this.data.Porosity)/this.data.SA_V;
      RxA = 0.3466*dw/k;
  end
  this.Nodes(1,Np) = Node();
  % Define Nodes
  i = 1;
  for nd = pnd
    newnd = this.Nodes(i); %
    newnd.Type = enumNType.SN;
    newnd.data = struct('matl',this.matl,...
      'T',nd.data.T,'dT_dU',this.matl.dT_du);
    newnd.xmin = nd.xmin; %
    newnd.xmax = nd.xmax; %
    newnd.ymin = nd.ymin; %
    newnd.ymax = (nd.ymax-nd.ymin).*(1-this.data.Porosity) + nd.ymin; %
    i = i + 1;
  end

  % Define Faces
  this.Faces(1,Np) = Face();
  i = 1;
  for nd = pnd
    % Create a mixed Face
    newfc = this.Faces(i);
    newfc.Type = enumFType.Mix;
    newfc.Orient = enumOrient.Vertical;
    newfc.isEdge = false;
    newfc.ActiveTimes = true;
    newfc.Nodes = [nd this.Nodes(i)];
    newfc.data = struct('Area',nd.total_vol()*A_V,'R',RxA);
    i = i + 1;
  end

case enumMatrix.HeatExchanger
  % Treat the heat exchanger material as a lumped model.
  % Heat Comes from the source, using convection, heat leaves the
  % heat exchanger by convection
  switch this.data.Classification
    case 'Fin Enhanced Surface' % Channel Fins -
      this.data.ignore_canister = false;
      % Source is a connection
      % FinSeparation, FinThickness, Roughness, Porosity, Dh
      N = this.Body.Group.Model.Mesher.HeatExchangerFinDivisions;
      for i = Np*N:-1:1; this.Nodes(i) = Node(); end
      for i = (Np + 1)*N*Np:-1:1; this.Faces(i) = Face(); end
      ncount = 1; fcount = 1;
      Con = this.data.Connection;

      % Find xs and ys from parent nodes
```

```
if length(pnd)>1 || pnd(1).xmin ~= pnd(2).xmin
  % Discretized in X
  if Con.Orient == enumOrient.Vertical
    % Discretized Across the gas path
    xs = zeros(Np+1,1); i = 1;
    for nd = pnd; xs(i) = nd.xmin; i=i+1; end
    xs(end) = pnd(end).xmax;
    ys = linspace(pnd(1).ymin(1),pnd(1).ymax(1),N+1);
  else
    % Discretized with the gas path
    xs = zeros(Np*N+1,1); i = 1; k = 1;
    for nd = pnd
      xs(i:i+N-1) = linspace(pnd(k).xmin,pnd(k).xmax,N);
      i = i + N;
      k = k + 1;
    end
    xs(end) = pnd(end).xmax;
    ys = [pnd(1).ymin(1) pnd(2).ymax(1)];
  end
else
  % Discretized in Y
  if Con.Orient == enumOrient.Horizontal
    % Discretized Across the gas path
    ys = zeros(Np+1,1); i = 1;
    for nd = pnd; ys(i) = nd.ymin(1); i=i+1; end
    ys(end) = pnd(end).ymax(1);
    xs = linspace(pnd(1).xmin,pnd(1).xmax,N+1);
  else
    % Discretized with the gas path
    ys = zeros(Np*N+1,1); i = 1; k = 1;
    for nd = pnd
      ys(i:i+N-1) = linspace(pnd(k).ymin(1),pnd(k).ymax(1),N);
      i = i + N;
      k = k + 1;
    end
    ys(end) = pnd(end).ymax(1);
    xs = [pnd(1).xmin pnd(2).xmax];
  end
end

% Declare Nodes
ncount = Np*N;
for j = length(ys)-1:-1:1
  for i = length(xs)-1:-1:1
    this.Nodes(ncount).xmin = xs(i);
    this.Nodes(ncount).xmax = xs(i+1);
    this.Nodes(ncount).ymin = ys(i,:);
    this.Nodes(ncount).ymax = ys(i+1,:);
    this.Nodes(ncount).Type = enumNType.SN;
    index = findmatching(pnd, this.Nodes(ncount));
    this.Nodes(ncount).data = struct(...
      'T',this.Body.Temperature(),...
      'dT_dU',this.matl.dT_du,...
      'matl',this.matl,...
      'ParentNode',index);
    ncount = ncount - 1;
  end
end

% Declare Mixed Faces
% Area / Total Volume
A_V = 2/(this.data.FinThickness + this.data.FinSeparation);
RxA = this.data.FinThickness/(2*k);
for i = 1:length(this.Nodes)
  this.Faces(fcount).Type = enumFType.Mix;
  this.Faces(fcount).Nodes = ...
    [pnd(this.Nodes(i).data.ParentNode) this.Nodes(i)];
  this.Faces(fcount).data = struct(...
    'Area',A_V*this.Nodes(i).total_vol(),...
    'R',RxA,...
    'NuFunc_l',this.NuFunc_l,...
```

```
    'NuFunc_t',this.NuFunc_t);
  this.Faces(fcount).isDynamic = false;
  fcount = fcount + 1;
end

% Declare Internal Faces
NY = length(ys)-1;
for i = 1:length(this.Nodes)
  nd = this.Nodes(i);
  if i > 1 && this.Nodes(i-1).xmax == nd.xmin
    this.Faces(fcount) = Face([this.Nodes(i-1) nd], ...
      enumFType.Solid,enumOrient.Vertical);
    this.Faces(fcount).data.U = ...
      this.Faces(fcount).data.U*(1-this.data.Porosity);
    fcount = fcount + 1;
  end
  if i > NY
    this.Faces(fcount) = Face([this.Nodes(i-NY) nd], ...
      enumFType.Solid, enumOrient.Horizontal);
    this.Faces(fcount).data.U = ...
      this.Faces(fcount).data.U*(1-this.data.Porosity);
    fcount = fcount + 1;
  end
end

% Modify Gas Node Connections to Selected Connection
for NdCon = Con.NodeContacts
  if NdCon.Node.Body == this.Body
    if isfield(this.data,'Perc')
      this.data.Perc = this.data.Perc * this.data.Porosity;
    else
      this.data.Perc = this.data.Porosity;
    end
  end
end

% Declare Connections to Selected Connection
x = Con.x;
if Con.Orient == enumOrient.Vertical
  for i = 1:length(this.Nodes)
    if this.Nodes(i).xmin == x || this.Nodes(i).xmax == x
      Con.addNodeContacts(...
        NodeContact(this.Nodes(i),...
        this.Nodes(i).ymin,this.Nodes(i).ymax,...
        enumFType.Solid,Con));
      Con.NodeContacts(end).data.Perc = (1-this.data.Porosity);
    end
  end
else
  x = x(1);
  for i = 1:length(this.Nodes)
    if this.Nodes(i).ymin(1) == x || ...
        this.Nodes(i).ymax(1) == x
      Con.addNodeContacts(...
        NodeContact(this.Nodes(i),...
        this.Nodes(i).xmin,this.Nodes(i).xmax,...
        enumFType.Solid,Con));
      Con.NodeContacts(end).data.Perc = (1-this.data.Porosity);
    end
  end
end

% Modify Gas and Solid Node volume
for i = 1:4
  if Con == this.Body.Connections(i)
    break;
  end
end
switch i
  case {1, 2}
    for fc = this.Faces
```

```
        if fc.Type == enumFType.Mix
          % Get parent node
          if fc.Nodes(1).Type == enumNType.SN
            p = fc.Nodes(2); s = fc.Nodes(1);
          else
            p = fc.Nodes(1); s = fc.Nodes(2);
          end
          anchor = p.ymax;
          s.ymin = anchor + ...
            (s.ymin - anchor)*(1-this.data.Porosity);
          s.ymax = anchor + ...
            (s.ymax - anchor)*(1-this.data.Porosity);
          anchor = p.ymin;
          p.ymax = anchor + ...
            (p.ymax - anchor)*this.data.Porosity;
        end
      end
    case {3, 4}
      for fc = this.Faces
        if fc.Type == enumFType.Mix
          % Get parent node
          if fc.Nodes(1).Type == enumNType.SN
            p = fc.Nodes(2); s = fc.Nodes(1);
          else
            p = fc.Nodes(1); s = fc.Nodes(2);
          end
          anchor = p.xmax;
          s.xmin = anchor + ...
            (s.xmin - anchor)*(1-this.data.Porosity);
          s.xmax = anchor + ...
            (s.xmax - anchor)*(1-this.data.Porosity);
          anchor = p.xmin;
          p.xmax = anchor + ...
            (p.xmax - anchor)*this.data.Porosity;
        end
      end
  end
case 'Fin Connected Channels'
  this.data.ignore_canister = true;
  % Properties:
  % gap, ChannelThickness, WallThickness, Roughness, BaseWidth,
  % ... FinThickness, FinLength, sourceConvection
  % Make the source node
  N = double(this.Body.Group.Model.Mesher.HeatExchangerFinDivisions);
  for i = (Np + 1)*N + 1:-1:1; this.Nodes(i) = Node(); end
  for i = (Np + 1)*N*Np:-1:1; this.Faces(i) = Face(); end
  ncount = 1; fcount = 1;
  lcth = this.data.ChannelThickness;
  lwth = this.data.WallThickness;
  lg = this.data.gap;
  lth = this.data.FinThickness;
  lb = this.data.BaseWidth;


  % Volume of source / total volume
  SourceV_V = (lcth - lwth)/(lg + lcth);
  % Surface area of source / total volume
  SourceA_V = 2/(lg + lcth);
  % As a multiple of Remaining Volume
  switch this.data.Geometry
    case 'Rectangular'
      % Volume of fin / total volume
      FinV_V = lth*lg/((lg+lcth)*lb);
      FinA_FinV = 2/lth;
      % Linear Distance between fin nodes
      Li = lg/N;
    case 'Triangular'
      lf = this.data.FinLength;
      % Volume of fin / total volume
      FinV_V = lth*lf/((lg+lcth)*lb);
      FinA_FinV = 2/lth;
```

```
    % Linear Distance between fin nodes
    Li = lf/N;
end
% Exposed surface of source skin / total volume
SkinA_V = SourceA_V*(lb/(lth+lb));
% Proportion of channel wall / total volume
SkinV_V = lwth/(lg + lcth);

% Define Source Node
SourceNd = this.Nodes(ncount);
SourceNd.Type = enumNType.SN;
SourceNd.data = struct(...
  'matl',Material('Constant Temperature'),...
  'T',this.data.SourceTemperature,...
  'dT_dU',-1);
[~,~,x1,x2] = this.Body.limits(enumOrient.Vertical);
[~,~,y1,y2] = this.Body.limits(enumOrient.Horizontal);
isHorizontal = this.Body.divides(1) > this.Body.divides(2);
SourceNd.xmin = x1;
SourceNd.ymin = y1;
if isHorizontal
  % Discretized along the x direction
  SourceNd.xmax = x2;
  y1 = offsety(SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),y1);
  SourceNd.ymax = y1;
else
  % Discretized along the y direction
  x1 = offsetx(SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),x1);
  SourceNd.xmax = x1;
  SourceNd.ymax = y2;
end

ncount = ncount + 1;
j = 0;
backup = x1;
backup_y1 = y1;
for nd = pnd
  j = j + 1;
  Vp = nd.total_vol();
  % Define Skin Node
  this.Nodes(ncount) = Node();
  SkinNd = this.Nodes(ncount);
  SkinNd.Type = enumNType.SN;
  SkinNd.data = struct(...
    'matl',this.matl,...
    'T',this.data.SourceTemperature,...
    'dT_dU',this.matl.dT_du);
  if isHorizontal
    SkinNd.xmin = nd.xmin;
    SkinNd.xmax = nd.xmax;
    SkinNd.ymin = backup_y1;
    front = offsety(SkinV_V,nd,backup_y1);
    SkinNd.ymax = front;
  else
    SkinNd.xmin = backup;
    front = offsetx(SkinV_V,nd,backup);
    SkinNd.xmax = front;
    SkinNd.ymin = nd.ymin(1);
    SkinNd.ymax = nd.ymax(1);
  end
  ncount = ncount + 1;

  % Define Conduction between Skin Node and Source
  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Solid;
  newfc.Nodes = [SkinNd SourceNd];
  USkin2Source = SourceA_V*Vp*k*2/lwth;
  newfc.data = struct('U',USkin2Source);
  newfc.isDynamic = false;
  fcount = fcount + 1;
```

```
% Define Mixed Face to Skin Node
if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
newfc = this.Faces(fcount);
newfc.Type = enumFType.Mix;
newfc.Nodes = [SkinNd nd];
RxA = this.data.WallThickness/(k*2);
newfc.data = struct(...
  'R',RxA,...
  'Area',SkinA_V*Vp,...
  'NuFunc_l',this.NuFunc_l,...
  'NuFunc_t',this.NuFunc_t);
fcount = fcount + 1;

% Define Fin Nodes
Vi = FinV_V*Vp/N;
% Li - Defined Earlier
for i = 1:N
  this.Nodes(ncount) = Node();
  newnd = this.Nodes(ncount);
  newnd.Type = enumNType.SN;
  newnd.data = struct(...
    'matl',this.matl,...
    'T',this.data.SourceTemperature,...
    'dT_dU',this.matl.dT_du);
  if isHorizontal
    newnd.xmin = nd.xmin;
    newnd.xmax = nd.xmax;
    newnd.ymin = front;
    front = offsety(FinV_V/double(N),nd,front);
    newnd.ymax = front;
  else
    newnd.xmin = front;
    front = offsetx(FinV_V/double(N),nd,front);
    newnd.xmax = front;
    newnd.ymin = nd.ymin(1);
    newnd.ymax = nd.ymax(1);
  end
  ncount = ncount + 1;
end

% Define Conduction between 1st Fin Node and Skin
if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
newfc = this.Faces(fcount);
newfc.Type = enumFType.Solid;
newfc.Nodes = [this.Nodes(ncount-N) this.Nodes(ncount-N-1)];
newfc.data = struct(...
  'U',FinV_V*SourceA_V*Vp*k*2/(Li+lwth));
newfc.isDynamic = false;
fcount = fcount + 1;

for i = 1:N-1
  % Define Conduction between Fin Nodes (1-N)
  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Solid;
  newfc.Nodes = [this.Nodes(ncount-N-1+i) this.Nodes(ncount-N+i)];
  newfc.data = struct('U',FinV_V*SourceA_V*Vp*k/Li);
  newfc.isDynamic = false;
  fcount = fcount + 1;
end

for i = 1:N
  % Define Mixed Faces to Fin Nodes
  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Mix;
  newfc.Nodes = [this.Nodes(ncount-N-1+i) nd];
  newfc.data = struct(...
    'Area',Vi*FinA_FinV,...
    'R',lth/(4*k),...
```

```
        'NuFunc_l',this.NuFunc_l,...
        'NuFunc_t',this.NuFunc_t);
      newfc.isDynamic = false;
      fcount = fcount + 1;
    end

    if j > 1
      % Define Downstream Conduction
      for i = 1:N
        if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
        newfc = this.Faces(fcount);
        newfc.Type = enumFType.Solid;
        newfc.Nodes = [this.Nodes(ncount-(N+1)+i) this.Nodes(ncount-2*(N+1)+i)];
        if isHorizontal
          newfc.data = struct('U',FinV_V*2*k*...
            (2*pi*nd.xmin*(nd.ymax(1)-nd.ymin(1)))/...
            (nd.xmax-oldnd.xmin));
        else
          newfc.data = struct('U',FinV_V*2*k*...
            (pi*(nd.xmax^2-nd.xmin^2))/...
            (nd.ymax(1)-oldnd.ymin(1)));
        end
        newfc.isDynamic = false;
        fcount = fcount + 1;
      end
    end
    oldnd = nd;
  end
case 'Staggered Fin Connected Tubes'
  this.data.ignore_canister = true;
  % Source is a reservoir with h
  % TubeOrient, PerpSpacing, ParaSpacing, Alignment
  %   FinThickness, FinSeparation, FinLength, do, di
  %   PercentageTube, PercentageFin
  ncount = 1;
  fcount = 1;
  N = this.Body.Group.Model.Mesher.HeatExchangerFinDivisions;
  if isfield(this.data,'FinLength')
    this.Faces = Face.empty;
    for i = (2*N+2)*Np - 1:-1:1; this.Faces(i) = Face(); end
  else
    this.Faces = Face.empty;
    for i = (2*N+2)*Np - 1:-1:1; this.Faces(i) = Face(); end
    this.Faces((2*N+2)*Np - 1) = Face();
  end
  this.Nodes = Node.empty;
  for i = Np*(N+1) + 1:-1:1; this.Nodes(i) = Node(); end

  % Make the source node
  [~,~,x1,x2] = this.Body.limits(enumOrient.Vertical);
  [~,~,y1,y2] = this.Body.limits(enumOrient.Horizontal);
  lth = this.data.FinThickness;
  lg = this.data.FinSeparation;
  di = this.data.di;
  do = this.data.do;
  VTube_V = this.data.PercentageTube;
  VFin_VFinned = lth/(lth + lg);

  % Percentage of the volume that is the temperature source
  SourceV_V = VTube_V*(di/do)^2;
  SkinV_V = VTube_V - SourceV_V;

  % Surface Area of the tubular source elements
  SourceA_V = 4*SourceV_V/di;
  SkinA_V = (1-VFin_VFinned)*do/di*SourceA_V;
  isHorizontal = this.Body.divides(1) > this.Body.divides(2);

  % Create the Source Node
  SourceNd = this.Nodes(ncount);
  SourceNd.Type = enumNType.SN;
  SourceNd.xmin = x1;
```

```
              SourceNd.ymin = y1;
              if isHorizontal
                SourceNd.xmax = x2;
                front =
offsety(this.data.SurfaceAreaFactor*SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),y1);
                SourceNd.ymax = front;
              else
                front =
offsetx(this.data.SurfaceAreaFactor*SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),x1);
                SourceNd.xmax = front;
                SourceNd.ymax = y2;
              end
              SourceNd.data = struct(...
                'matl',Material('Constant Temperature'),...
                'T',this.data.SourceTemperature,...
                'dT_du',-1);
              ncount = ncount + 1;

              % Define Volume, Radii and Surface Area Values
              % FinRadii(i) - N + 1 length
              % FinVolume(i) - N length
              % FinArea(i) - N length
              Ao = this.data.PerpSpacing*this.data.ParaSpacing;
              if isfield(this.data,'FinLength')
                % FinRadii
                ri = linspace(do,do+this.data.FinLength,N+1);
                % FinVolume
                FinV_V = VFin_VFinned*pi*(ri(2:end).^2 - ri(1:end-1).^2)/Ao;
                % FinArea
                FinA_V = FinV_V*2/lth;
                FinA_V(N) = (FinA_V(N) + 2*pi*ri(N+1)*VFin_VFinned/Ao);
              else
                % FinRadii
                Rmax = sqrt(Ao/pi);
                ri = linspace(do,Rmax,N+1);
                % FinVolume
                FinV_V =  VFin_VFinned*pi*(ri(2:end)^2 - ri(1:end-1)^2)/Ao;
                % FinArea
                FinA_V = FinV_V*2/lth;
              end
              RxA_Fin = lth/(4*k);

              backup = front;
              for nd = pnd
                front = backup;

                Vp = nd.total_vol();
                Vp = Vp(1);
                Lpipe = SourceV_V*Vp/(pi/4*(di^2));

                % Generate Skin Node
                SkinNd = this.Nodes(ncount);
                SkinNd.Type = enumNType.SN;

                if isHorizontal
                  SkinNd.xmin = nd.xmin;
                  SkinNd.xmax = nd.xmax;
                  SkinNd.ymin = front;
                  front = offsety(this.data.SurfaceAreaFactor*SkinV_V,...
                    nd,front);
                  SkinNd.ymax = front;
                else
                  SkinNd.xmin = front;
                  front = offsetx(this.data.SurfaceAreaFactor*SkinV_V,...
                    nd,front);
                  SkinNd.xmax = front;
                  SkinNd.ymin = nd.ymin;
                  SkinNd.ymax = nd.ymax;
                end
                SkinNd.data = struct(...
                  'matl',this.matl,...
```

```
  'T',this.data.SourceTemperature,...
  'dT_du',this.matl.dT_du);
ncount = ncount + 1;

% Generate Conduction Face Between Source and Skin
if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
newfc = this.Faces(fcount);
newfc.Type = enumFType.Solid;
newfc.Nodes = [SkinNd SourceNd];
ro = sqrt(di*do/4);
newfc.data = struct('U',...
  this.data.SurfaceAreaFactor*...
  2*pi*Lpipe*k/log(ro/(di/2)));
newfc.isDynamic = false;
fcount = fcount + 1;

% Generate Mixed Face Between Skin and Gas
if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
newfc = this.Faces(fcount);
newfc.Type = enumFType.Mix;
newfc.Nodes = [SkinNd nd];
RxA = log(2*do/(di + do))*(do/2)/k;
newfc.data = struct(...
  'Area',this.data.SurfaceAreaFactor*Vp*SkinA_V,...
  'R',RxA,...
  'NuFunc_l',this.NuFunc_l,...
  'NuFunc_t',this.NuFunc_t);
newfc.isDynamic = false;
fcount = fcount + 1;


for i = 1:N
  % Define Node
  newnd = this.Nodes(ncount);
  newnd.Type = enumNType.SN;
  if isHorizontal
    newnd.xmin = nd.xmin;
    newnd.xmax = nd.xmax;
    newnd.ymin = front;
    front = offsety(this.data.SurfaceAreaFactor*FinV_V(i),nd,front);
    newnd.ymax = front;
  else
    newnd.xmin = front;
    front = offsetx(this.data.SurfaceAreaFactor*FinV_V(i),nd,front);
    newnd.xmax = front;
    newnd.ymin = nd.ymin;
    newnd.ymax = nd.ymax;
  end
  newnd.data = struct(...
    'matl',this.matl,...
    'T',this.Body.Temperature,...
    'dT_du',this.matl.dT_du);
  ncount = ncount + 1;

  % Define Mixed Face
  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Mix;
  newfc.Nodes = [this.Nodes(ncount-1) nd];
  newfc.data = struct(...
    'Area',this.data.SurfaceAreaFactor*Vp*FinA_V(i),...
    'R',RxA_Fin,...
    'NuFunc_l',this.NuFunc_l,'NuFunc_t',this.NuFunc_t);
  newfc.isDynamic = false;
  fcount = fcount + 1;

  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Solid;
  newfc.Nodes = [this.Nodes(ncount-1) this.Nodes(1)];
  outside = sqrt(ri(i)*ri(i+1));
```

```
            if i > 1
              % Define Internal Conduction
              inside = sqrt(ri(i)*ri(i-1));
              newfc.data = struct(...
                'U',this.data.SurfaceAreaFactor*VFin_VFinned*...
                2*pi*Lpipe*k/log(outside/inside));
            else
              % Define Skin-Fin Conduction
              inside = sqrt(sqrt(di*do/4)*ri(i));
              newfc.data = struct(...
                'U',this.data.SurfaceAreaFactor*VFin_VFinned*...
                2*pi*Lpipe*k/log(outside/inside));
            end
            newfc.isDynamic = false;
            fcount = fcount + 1;
          end
        end
        %% Testing Outputs
%         AreaSum = 0;
%         CondSum = 0;
%         for i = 1:length(this.Faces)
%           fc = this.Faces(i);
%           if ~isempty(fc.data)
%             if isfield(fc.data,'Area')
%               AreaSum = AreaSum + fc.data.Area;
%             end
%             if isfield(fc.data,'U')
%               CondSum = CondSum + fc.data.U;
%             end
%           end
%         end
%         VolumeSum = 0;
%         for i = 1:length(this.Nodes)
%           nd = this.Nodes(i);
%           VolumeSum = VolumeSum + nd.vol();
%         end
%         fprintf([...
%           'Area Sum: ' num2str(AreaSum) ...
%           ' - Cond Sum: ' num2str(CondSum) ...
%           ' - Vol Sum: ' num2str(VolumeSum) '.\n']);
      case 'Tube Bank Internal'
        this.data.ignore_canister = true;
        % Properties:
        % gap, ChannelThickness, WallThickness, Roughness, BaseWidth,
        % ... FinThickness, FinLength, sourceConvection
        % Make the source node
        for i = Np + 1:-1:1; this.Nodes(i) = Node(); end
        for i = 3*Np - 1:-1:1; this.Faces(i) = Face(); end
        ncount = 1; fcount = 1;
        % Volume of source / total volume
        SourceV_V = ...
          (this.data.Ao - pi/4*this.data.do^2)/this.data.Ao;
        % Surface area of source / total volume
        SourceA_V = pi*this.data.do/this.data.Ao;
        % Surface area of skin / total volume
        SkinA_V = pi*this.data.di/this.data.Ao;
        % Volume of skin / total volume
        SkinV_V = pi/4*...
          (this.data.do^2 - this.data.di^2)/this.data.Ao;


        % Define Source Node
        SourceNd = this.Nodes(ncount);
        SourceNd.Type = enumNType.SN;
        SourceNd.data = struct(...
          'matl',Material('Constant Temperature'),...
          'T',this.data.SourceTemperature,...
          'dT_dU',-1);
        [~,~,x1,x2] = this.Body.limits(enumOrient.Vertical);
        [~,~,y1,y2] = this.Body.limits(enumOrient.Horizontal);
        isHorizontal = this.Body.divides(1) > this.Body.divides(2);
```

```
SourceNd.xmin = x1;
SourceNd.ymin = y1;
if isHorizontal
  % Discretized along the x direction
  SourceNd.xmax = x2;
  front = offsety(SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),y1);
  SourceNd.ymax = front;
else
  % Discretized along the y direction
  front = offsetx(SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),x1);
  SourceNd.xmax = front;
  SourceNd.ymax = y2;
end

%{
% Remove Gas Contacts from overlaping solid neighbours
for iCon = this.Body.Connections
  i = 0;
  keep = true(size(iCon.NodeContacts));
  NodeContactsBackup = cell(length(iCon.NodeContacts),2);
  for iNC = iCon.NodeContacts
    i = i + 1;
    NodeContactsBackup{i,1} = iNC.Start;
    NodeContactsBackup{i,2} = iNC.End;
    if iNC.Node.Body == this.Body
      for iBody = iCon.Bodies
        if iBody ~= this.Body
          if iBody.matl.Phase == enumMaterial.Solid
            % Get the connections
            switch iCon.Orient
              case enumOrient.Vertical
                S = iBody.get('Bottom Connection');
                E = iBody.get('Top Connection');
                Sx = S.x;
                Ex = E.x;
              case enumOrient.Horizontal
                S = iBody.get('Inner Connection');
                E = iBody.get('Outer Connection');
                if ~isempty(S.RefFrame)
                  Sx = S.x + S.RefFrame.Positions;
                else
                  Sx = S.x;
                end
                if ~isempty(E.RefFrame)
                  Ex = E.x + E.RefFrame.Positions;
                else
                  Ex = E.x;
                end
            end
            Mask = NodeContact(Node.empty,Sx,Ex,...
              enumFType.Gas,this.Body.Connections);
            keep(i) = Mask.AlignedMask(iNC,-inf,inf);
            if ~keep(i); break; end
          end
        end
      end
    end
    if ~keep(i); break; end
  end
end
% Replace them with References to the Source
newNCs = NodeContact.empty;
for i = 1:length(iCon.NodeContacts)
  oNC_Start = NodeContactsBackup{i,1};
  oNC_End = NodeContactsBackup{i,2};
  nNC = iCon.NodeContacts(i);
  if ~keep(i)
    nNC.Start = oNC_Start;
    nNC.End = oNC_End;
    nNC.Node = SourceNd;
    nNC.Type = enumFType.Solid;
```

```
  else
    d1 = nNC.Start - oNC_Start;
    d2 = oNC_End - nNC.End;
    if any(d1 > 0)
      newNCs(end+1) = NodeContact(SourceNd, ...
        oNC_Start,oNC_Start + d1, enumFType.Solid, ...
        this.Body.Connections);
    end
    if any(d2 > 0)
      newNCs(end+1) = NodeContact(SourceNd, ...
        oNC_End - d2,oNC_End, enumFType.Solid, ...
        this.Body.Connections);
    end
  end
  iCon.addNodeContacts(newNCs);
end
%}

ncount = ncount + 1;
j = 0;
backup = front;
for nd = pnd
  front = backup;
  if isHorizontal
    % Discretized along the x direction
    Lcond = (nd.xmax - nd.xmin);
  else
    % Discretized along the y direction
    Lcond = (nd.ymax - nd.ymin);
  end
  j = j + 1;
  Vp = nd.total_vol();
  % Define Skin Node
  SkinNd = this.Nodes(ncount);
  SkinNd.Type = enumNType.SN;
  SkinNd.data = struct(...
    'matl',this.matl,...
    'T',this.data.SourceTemperature,...
    'dT_dU',this.matl.dT_du);
  if isHorizontal
    SkinNd.xmin = nd.xmin;
    SkinNd.xmax = nd.xmax;
    SkinNd.ymin = front;
    front = offsety(SkinV_V,nd,front);
    SkinNd.ymax = front;
  else
    SkinNd.xmin = front;
    front = offsetx(SkinV_V,nd,front);
    SkinNd.xmax = front;
    SkinNd.ymin = nd.ymin(1);
    SkinNd.ymax = nd.ymax(1);
  end
  ncount = ncount + 1;

  % Define Conduction between Skin Node and Source
  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Solid;
  newfc.Nodes = [SkinNd SourceNd];
  USkin2Source = ...
    (SourceA_V*Vp)*k*4/abs(this.data.do-this.data.di);
  newfc.data = struct('U',USkin2Source);
  newfc.isDynamic = false;
  fcount = fcount + 1;

  % Define Mixed Face to Skin Node
  th = (this.data.do - this.data.di)/2;
  if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
  newfc = this.Faces(fcount);
  newfc.Type = enumFType.Mix;
  newfc.Nodes = [SkinNd nd];
```

```
          RxA = th/(k*2);
          newfc.data = struct('R',RxA,'Area',SkinA_V*Vp);
          fcount = fcount + 1;

          if j > 1
            % Define Downstream Conduction
            if fcount > length(this.Faces); this.Faces(fcount) = Face(); end
            newfc = this.Faces(fcount);
            newfc.Type = enumFType.Solid;
            newfc.Nodes = [SkinNd oldnd];
            newfc.data = struct('U',k*this.data.Number*pi/4*...
              (this.data.do^2 - this.data.di^2)/Lcond);
            newfc.isDynamic = false;
            fcount = fcount + 1;
          end
          oldnd = SkinNd;
        end
      case 'Custom HX'
        this.data.ignore_canister = true;
        % Make the source node
        this.Nodes(1) = Node();
        for i = Np:-1:1; this.Faces(i) = Face(); end
        ncount = 1; fcount = 1;
        % Volume of source / total volume
        SourceV_V = 1-this.data.Porosity;
        % Surface area of source / total volume
        SourceA_V = this.data.SA_V/(1-this.data.Porosity);

        % Define Source Node
        SourceNd = this.Nodes(ncount);
        SourceNd.Type = enumNType.SN;
        SourceNd.data = struct(...
          'matl',Material('Constant Temperature'),...
          'T',this.data.SourceTemperature,...
          'dT_dU',-1);
        [~,~,x1,x2] = this.Body.limits(enumOrient.Vertical);
        [~,~,y1,y2] = this.Body.limits(enumOrient.Horizontal);
        isHorizontal = this.Body.divides(1) > this.Body.divides(2);
        SourceNd.xmin = x1;
        SourceNd.ymin = y1;
        if isHorizontal
          % Discretized along the x direction
          SourceNd.xmax = x2;
          front = offsety(SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),y1);
          SourceNd.ymax = front;
        else
          % Discretized along the y direction
          front = offsetx(SourceV_V,Node(enumNType.SN,x1,x2,y1,y2),x1);
          SourceNd.xmax = front;
          SourceNd.ymax = y2;
        end

        ncount = ncount + 1;
        for nd = pnd
          Vp = nd.total_vol();

          % Define Mixed Face to Source Node
          if fcount > length(this.Faces); this.Faces(end+1) = Face(); end
          newfc = this.Faces(fcount);
          newfc.Type = enumFType.Mix;
          newfc.Nodes = [SourceNd nd];
          RxA = 0;
          newfc.data = struct('R',RxA,'Area',SourceA_V*Vp);
          fcount = fcount + 1;
        end
    end
end
% Remove extra elements
if ncount <= length(this.Nodes); this.Nodes(ncount:end) = []; end
if fcount <= length(this.Faces); this.Faces(fcount:end) = []; end
for i = 1:length(this.Nodes)
```

```
        this.Nodes(i).Body = this.Body;
      end
      nodes = this.Nodes;
      faces = this.Faces;
      for nd = nodes
        nd.Body = this.Body;
        nd.data.Porosity = this.data.Porosity;
      end
      % WSNG = this.WSNG;
    end
    % get Properties
    function name = get.name(this)
    if ~isempty(this.Geometry)
      for index = 1:length(this.GeometryEnum)
        if this.GeometryEnum(index) == this.Geometry
          break;
        end
      end
    else
      name = 'Undefined Matrix';
      return;
    end
    name = [this.GeometrySource{index} 'Matrix with ' ...
      num2str(round(this.data.Porosity*100,1)) ...
      '% Porosity and Hydraulic Diameter: ' num2str(this.Dh)];
    end
  end
end

function newy = offsety(V_V, parent, y)
  newy = ...
    y + V_V*parent.total_vol()/(pi*(parent.xmax^2 - parent.xmin^2));
end

function newx = offsetx(V_V, parent, x)
  newx = ...
    sqrt(V_V*parent.total_vol()/(pi*(parent.ymax(1)-parent.ymin(1))) + x^2);
end

%{
function [xvals,j] = xvals_by_alpha_omega(alpha_omega,dw)
scale = 0.112167*Sqrt(alpha_omega);
% Element size = scale*e^(sqrt(omega/(2*alpha))*x)
% Elements are sized such that there are 10 elements within the
%   oscillation penetration depth. With a growth rate cap at
%   1.5 times
% e^sqrt(omega/2*alpha)
expAlphaOmega = exp(sqrt(1/(2*alpha_omega)));
x = 0;
j = 1;
xvals = zeros(1,10);
dx = scale;
while x < dw/2
  % Move Inward
  dx = min([dx*1.5 scale*(expAlphaOmega^x)]);
  x = x + dx;
  j = j + 1;
  xvals(j) = x;
end
xvals(j) = min([xvals(j) dw/2]);
if xvals(j) - xvals(j-1) < 0.1 * (xvals(j-1) - xvals(j-2))
  j = j - 1;
  xvals(j) = dw/2;
  xvals(j+1:end) = [];
elseif j < 10
  xvals(j+1:end) = [];
end
xvals = dw/2 - xvals;
end
%}
```

```
function [U,x1,x2,y1,y2] = InternalNodesVertical(xmin,xmax,ymin,ymax,N,Perc,k,Dir)
x = xmin:(xmax-xmin)/N:xmax;
L = ymax-ymin;
U = zeros(1,N-1);
x1 = zeros(1,N); x2 = x1;
for i = 1:N-1
  U(i) = Perc*k*2*pi*L/log((x(i+2)+x(i+1))/(x(i)+x(i+1)));
end
Vi = Perc*pi*(xmax^2-xmin^2)*L/N;
switch Dir
  case 'In'; xstart = xmin;
  case 'Out'; xstart = sqrt(Vi*N/(pi*L)-xmax^2);
end
for i = 1:N
  xend = sqrt(Vi/(pi*L)+xstart^2);
  x1(i) = xstart;
  x2(i) = xend;
  xstart = xend;
end
y1 = ymin(ones(1,N));
y2 = ymax(ones(1,N));
end

function [U,x1,x2,y1,y2] = InternalNodesHorizontal(xmin,xmax,ymin,ymax,N,Perc,k,Dir)
y = ymin:(ymax-ymin)/N:ymax;
U = zeros(1,N-1);
y1 = zeros(1,N); y2 = y1;
for i = 1:N-1
  U(i) = Perc*k*pi*(xmax^2-xmin^2)*N/(ymax-ymin);
end
d = Perc*(ymax-ymin)/N;
switch Dir
  case 'Down'; ystart = ymin;
  case 'Up'; ystart = ymax - N*d;
end
for i = 1:N
  yend = ymin + d;
  y1(i) = ystart;
  y2(i) = yend;
  ystart = yend;
end
x1 = xmin(ones(1,N));
x2 = xmax(ones(1,N));
y1 = y(1:end-1);
y2 = y(2:end);
end

function GenNodeContact(Connection,Perc,NodeToReference,NodeToFind)
  found = false;
  for ncontact = Connection.NodeContacts
    if ncontact.Node == NodeToReference
      if ~isempty(ncontact.data) && isfield(ncontact.data,'Perc')
        ncontact.data.Perc = ncontact.data.Perc.*(1-Perc);
      else
        ncontact.data.Perc = this.data.Porostiy;
      end
      found = true;
      break;
    end
  end
  if found
    NewNodeContact = NodeContact(NodeToFind,ncontact.Start,...
      ncontact.End,enumFType.Solid,Connection);
    NewNodeContact.data.Perc = Perc;
    Connection.addNodeContacts(NewNodeContact);
  end
end

function i = findmatching(pnd, nd)
  i = 1;
  for p = pnd
```

```
    if p.xmin <= nd.xmin && p.xmax >= nd.xmax
      if p.ymin(1) <= nd.ymin && p.ymax(1) >= nd.ymax
        return;
      end
    end
    i = i + 1;
  end
end
```

Mesher

The mesher is a class that contains the following functionality:

A get / set interface.

A function for determining if a body is exposed to an air body on a particular side.

```
classdef Mesher < handle
    %UNTITLED2 Summary of this class goes here
    %   Detailed explanation goes here

    properties
        % Solid Related
        oscillation_depth_N int16 = 6;
        maximum_thickness double = 0.02;
        maximum_growth double = 1.5;
        HeatExchangerFinDivisions int16 = 3;
        MinSolidTimeStep = 1e-4;

        % Gas Related
        Gas_Entrance_Exit_N int16 = 8;
        Gas_Maximum_Size double = 0.02;
        Gas_Minimum_Size double = 0.003;
        name = 'Universal Mesher';
    end

    methods
        function item = get(this,Property)
            switch Property
                case 'name'
                    item = this.name;
                case 'Nodes through Oscillation Depth'
                    item = this.oscillation_depth_N;
                case 'Maximum Node Thickness'
                    item = this.maximum_thickness;
                case 'Maximum Growth Rate'
                    item = this.maximum_growth;
                case 'Heat Exchanger Fin Divisions'
                    item = this.HeatExchangerFinDivisions;
                case 'Minimum Solid Time Step'
                    item = this.MinSolidTimeStep;
                case 'Gas Entrance Exit N'
                  item = this.Gas_Entrance_Exit_N;
                case 'Gas Maximum Size'
                  item = this.Gas_Maximum_Size;
                case 'Gas Minimum Size'
                  item = this.Gas_Minimum_Size;
                otherwise
                    fprintf(['XXX Mesher GET Inteface for ' Property ' is not found XXX\n']);
            end
        end
        function set(this,Property,item)
            switch Property
                case 'name'
                    this.name = item;
                case 'Nodes through Oscillation Depth'
                    this.oscillation_depth_N = item;
                case 'Maximum Node Thickness'
                    this.maximum_thickness = item;
                case 'Maximum Growth Rate'
                    this.maximum_growth = item;
                case 'Heat Exchanger Fin Divisions'
                    this.HeatExchangerFinDivisions = item;
                case 'Minimum Solid Time Step'
```

```
            this.MinSolidTimeStep = item;
        case 'Gas Entrance Exit N'
          this.Gas_Entrance_Exit_N = item;
        case 'Gas Maximum Size'
          this.Gas_Maximum_Size = item;
        case 'Gas Minimum Size'
          this.Gas_Minimum_Size = item;
        otherwise
            fprintf(['XXX Mesher SET Inteface for ' Property ' is not found XXX\n']);
    end
end
function doesit = isInsideRadiiExposed(~,Body)
    [~,~,xmin,~] = Body.limits(enumOrient.Vertical);
    [ymin,ymax,~,~] = Body.limits(enumOrient.Horizontal);
    xdepth = 3*sqrt(2*Body.matl.thermaldiffusivity/...
        Body.Group.Model.engineSpeed) * 1.5;
    for iBody = Body.Group.Bodies
        if iBody ~= Body && iBody.matl.Phase == enumMaterial.Gas
            % Get x limits and see if they could touch
            [~,~,~,xmaxi] = iBody.limits(enumOrient.Vertical);
            if abs(xmin - xmaxi) < xdepth
                % Get y limits and see if they infact overlap at any time
                [ymini,ymaxi,~,~] = iBody.limits(enumOrient.Horizontal);
                if any(~((ymin >= ymaxi) + (ymini >= ymax)))
                    doesit = true;
                    return;
                end
            end
        end
    end
    doesit = false;
end
function doesit = isOutsideRadiiExposed(~,Body)
    [~,~,~,xmax] = Body.limits(enumOrient.Vertical);
    [ymin,ymax,~,~] = Body.limits(enumOrient.Horizontal);
    xdepth = 3*sqrt(2*Body.matl.thermaldiffusivity/...
        Body.Group.Model.engineSpeed) * 1.5;
    for iBody = Body.Group.Bodies
        if iBody ~= Body && iBody.matl.Phase == enumMaterial.Gas
            % Get x limits and see if they could touch
            [~,~,xmini,~] = iBody.limits(enumOrient.Vertical);
            if abs(xmax - xmini) < xdepth
                % Get y limits and see if they infact overlap at any time
                [ymini,ymaxi,~,~] = iBody.limits(enumOrient.Horizontal);
                if any(~((ymin >= ymaxi) + (ymini >= ymax)))
                    doesit = true;
                    return;
                end
            end
        end
    end
    doesit = false;
end
function doesit = isBottomExposed(~,Body)
    [~,~,xmin,xmax] = Body.limits(enumOrient.Vertical);
    xdepth = 3*sqrt(2*Body.matl.thermaldiffusivity/...
        Body.Group.Model.engineSpeed) * 1.5;
    for iBody = Body.Group.Bodies
        if iBody ~= Body && iBody.matl.Phase == enumMaterial.Gas
            % Get x limits and see if they could touch
            [~,~,xmini,xmaxi] = iBody.limits(enumOrient.Vertical);
            if ~(xmax <= xmini) && ~(xmin >= xmaxi)
                % See if they get close to each other
                [ymin,~,~,~] = Body.limits(enumOrient.Horizontal);
                [~,ymaxi,~,~] = iBody.limits(enumOrient.Horizontal);
                if min(abs(ymin-ymaxi)) < xdepth
                    doesit = true;
                    return;
                end
            end
        end
```

```
            end
            doesit = false;
        end
        function doesit = isTopExposed(~,Body)
            [~,~,xmin,xmax] = Body.limits(enumOrient.Vertical);
            xdepth = 3*sqrt(2*Body.matl.thermaldiffusivity/...
                Body.Group.Model.engineSpeed) * 1.5;
            for iBody = Body.Group.Bodies
                if iBody ~= Body && iBody.matl.Phase == enumMaterial.Gas
                    % Get x limits and see if they could touch
                    [~,~,xmini,xmaxi] = iBody.limits(enumOrient.Vertical);
                    if ~(xmax <= xmini) && ~(xmin >= xmaxi)
                        % See if they get close to each other
                        [~,ymax,~,~] = Body.limits(enumOrient.Horizontal);
                        [ymini,~,~,~] = iBody.limits(enumOrient.Horizontal);
                        if min(abs(ymax-ymini)) < xdepth
                            doesit = true;
                            return;
                        end
                    end
                end
            end
            doesit = false;
        end
    end

end
```

Model

The model is a class that contains the following functionality:

A constructor and destructor.

A get / set interface.

A set of internal list managers.

A set of functions for triggering updates and checking things in the object.

A discretize function.

A run function with various modes.

A function for assigning snapshots to nodes.

A set of functions which support the interface: the nearest group, nearest body, set of nearest objects, find reference frames, determining if something is in the display window, formatting the display options, getting the active group, model extents in the GUI.

A set of functions managing selection.

A set of functions for showing the model and animating it.

```
classdef Model < handle
  %MODEL Summary of this class goes here
  %   Detailed explanation goes here
  properties (Constant)
    ProportionTolerance = 0.02; % 2% error is pretty reasonable
    dt = 0.01;          % Seconds              ???
    NTheta = 400;       % Number of divisions  400 intervals
    dOmega2 = pi^2/2;   % (Radians/second)^2   32 intervals between 0->2 Hz
    dAppliedForce = 1;  % Newtons              ???
    AnimationLength_s = 30;
    AnimationSpeed_rads = pi;
    MaxFourierNumber = 0.25;
  end

  properties (Dependent)
    ActiveGroup;
    isDefaultModel;
    isDiscretized;
  end

  properties
    isChanged logical = true;
    Selection = cell(0); % Various Objects
    name = '';
    Groups Group; % A container of Group
    Mesher Mesher; % A container for meshing options
    Bridges Bridge;
```

```
  LeakConnections LeakConnection;
  RefFrames Frame;
  Sensors Sensor;
  PVoutputs PVoutput;
  SnapShots cell;
  NonConnections NonConnection;
  CustomMinorLosses CustomMinorLoss;
  OptimizationSchemes OptimizationScheme;
  CurrentSim Simulation; % Simulations are stored in a named file folder
  Converters LinRotMechanism;
  AxisReference;
  setConditions Environment;
  MechanicalSystem MechanicalSystem;
  initConditions Environment;
  surroundings Environment;
  roughness double = 0.000045; % 0.045 mm - Commercial or welded steel

  Faces Face;
  Nodes Node;

  Simulations Simulation;

  PressureContacts PressureContact;
  ShearContacts ShearContact;

  Results Result;
  engineTemperature double = 298;
  enginePressure double = 101325;
  engineSpeed double = 1;

  RelationOn = true;
end

properties (Hidden)
  StaticGUIObjects = [];
  DynamicGUIObjects = [];
  GhostGUIObjects = [];
  BodyIDIndex = 1;
  ConIDIndex = 1;
  OptIDIndex = 1;
  LRMIDIndex = 1;
  % GUI Options
  showGroups = true;
  showBodies = true;
  showBodyGhosts = true;
  showConnections = true;
  showLeaks = true;
  showBridges = true;
  showSensors = true;
  showInterConnections = false;
  showEnvironmentConnections = false;
  showNodes = false;
  showRelations = false;

  % Simulation Options
  showLivePV = true;
  showPressureAnimation = true;
  recordPressure = true;
  showTemperatureAnimation = true;
  recordTemperature = true;
  showVelocityAnimation = true;
  recordVelocity = true;
  showTurbulenceAnimation = true;
  recordTurbulence = true;
  showConductionAnimation = true;
  recordConductionFlux = true;
  showPressureDropAnimation = true;
  recordPressureDrop = true;
  recordOnlyLastCycle = true;
  recordStatistics = true;
  outputPath = '';
```

```
    warmUpPhaseLength = 0;
    animationFrameTime = 0.05;
    deRefinementFactorInput = 1;

    MaxCourantFinal = 0.025;
    MaxFourierFinal = 0.025;
    MaxCourantConverging = 0.025;
    MaxFourierConverging = 0.025;

    % RunTime Options
    stopSimulation = false;

    isStateDiscretized logical;
    isAnimating logical;
  end

  methods
    %% Creating, Reseting, Debugging
    function this = Model(AxisReference)
      this.initConditions = Environment();
      this.surroundings = Environment();
      this.Mesher = Mesher();
      this.MechanicalSystem =
MechanicalSystem(this,LinRotMechanism.empty,[],1,function_handle.empty);
      switch nargin
        case 0
          this.Groups = Group(this,Position(0,0,pi/2)); % The first Group
        case 1
          this.Groups = Group(this,Position(0,0,pi/2)); % The first Group
          this.AxisReference = AxisReference;
      end
      this.isChanged = true;
    end
    function ID = getBodyID(this)
      % Creates a unique id when called
      this.BodyIDIndex = this.BodyIDIndex + 1;
      ID = this.BodyIDIndex;
    end
    function ID = getConID(this)
        % Creates a unique id when called
      this.ConIDIndex = this.ConIDIndex + 1;
      ID = this.ConIDIndex;
    end
    function ID = getOptimizationStudyID(this)
        % Creates a unique id when called
      this.OptIDIndex = this.OptIDIndex + 1;
      ID = this.OptIDIndex;
    end
    function ID = getLRMID(this)
        % Creates a unique id when called
      this.LRMIDIndex = this.LRMIDIndex + 1;
      ID = this.LRMIDIndex;
    end
    function Bodies = BodyList(this)
      % Makes a list of all bodies in the Model, spanning multiple groups
      n = 0;
      for iGroup = this.Groups
        n = n + length(iGroup.Bodies);
      end
      Bodies(n) = Body();
      n = 0;
      for iGroup = this.Groups
        Bodies(n+1:n+length(iGroup.Bodies)) = iGroup.Bodies;
        n = n + length(iGroup.Bodies);
      end
    end
    function resetDiscretization(this)
      % Reset the discretization of the entire model, removing all faces
      % ... and nodes
      for iLRM = this.Converters
          iLRM.Model = this;
```

```
      if isempty(iLRM.ID)
        iLRM.ID = this.getLRMID();
      end
  end
  for iGroup = this.Groups
    iGroup.resetDiscretization();
  end
  for iBridge = this.Bridges
    iBridge.resetDiscretization();
  end
  for iLeak = this.LeakConnections
    iLeak.resetDiscretization();
  end
  this.Nodes(:) = [];
  this.Faces(:) = [];
  this.PressureContacts(:) = [];
  this.ShearContacts(:) = [];
  this.CurrentSim(:) = [];
  this.surroundings.resetDiscretization();
  this.change();
end
function dispNodeIndexes(this)
  % Prints to screen the index associated with a node its display
  % ... position
  for iNd = this.Nodes
    pnt = iNd.minCenterCoords;
    text(pnt.x,pnt.y,num2str(iNd.index));
  end
end

%% GET/SET Interface
function Item = get(this,PropertyName)
  switch PropertyName
    case 'Name'
      Item = this.name;
    case 'Groups'
      Item = this.Groups;
    case 'Bridges'
      Item = this.Bridges;
    case 'Leaks'
      Item = this.LeakConnections;
    case 'Sensors'
      Item = this.Sensors;
    case 'PVoutputs'
      Item = this.PVoutputs;
    case 'Lin. to Rot. Mechanisms'
      Item = this.Converters;
    case 'Optimization Studies'
          Item = this.OptimizationSchemes;
    case 'Initial Internal Conditions'
      Item = this.initConditions;
    case 'External Conditions'
      Item = this.surroundings;
    case 'Engine Temperature'
      Item = this.engineTemperature;
    case 'Engine Pressure'
      Item = this.enginePressure;
    case 'Minimum Speed'
      Item = this.engineSpeed;
    case 'SnapShots'
      Item = cell(length(this.SnapShots),1);
      for i = 1:length(this.SnapShots)
        Item{i} = this.SnapShots{i}.Name;
      end
    case 'NonConnections'
      Item = cell(length(this.NonConnections),1);
      for i = 1:length(this.NonConnections)
        Item{i} = this.NonConnections(i).name;
      end
    case 'Custom Minor Losses'
      Item = cell(length(this.CustomMinorLosses),1);
```

```
      for i = 1:length(this.CustomMinorLosses)
        Item{i} = this.CustomMinorLosses(i).name;
      end
    case 'Mesher'
      Item = this.Mesher;
    case 'Mechanical System'
      if isempty(this.MechanicalSystem)
        this.MechanicalSystem = MechanicalSystem(this,...
          LinRotMechanism.empty,[],1,function_handle.empty);
      end
      Item = this.MechanicalSystem;
    case 'Max Courant Final'
      Item = this.MaxCourantFinal;
    case 'Max Fourier Final'
      Item = this.MaxFourierFinal;
    case 'Max Courant Converging'
      Item = this.MaxCourantConverging;
    case 'Max Fourier Converging'
      Item = this.MaxFourierConverging;
    otherwise
      fprintf(['XXX Model GET Inteface for ' PropertyName ' is not found XXX\n']);
      return;
  end
  this.change();
end
function set(this,PropertyName,Item)
  switch PropertyName
    case 'Name'
      this.name = Item;
    case 'Engine Temperature'
      this.engineTemperature = Item;
    case 'Engine Pressure'
      this.enginePressure = Item;
    case 'Minimum Speed'
      this.engineSpeed = Item;
    case 'SnapShots'
      for i = length(Item):-1:1
        if Item(i); this.SnapShots(i) = []; end
      end
    case 'NonConnections'
      for i = length(Item):-1:1
        if Item(i); this.NonConnections(i) = []; end
      end
    case 'Custom Minor Losses'
      for i = length(Item):-1:1
        if Item(i); this.CustomMinorLosses(i) = []; end
      end
    case 'Max Courant Final'
      this.MaxCourantFinal = Item;
    case 'Max Fourier Final'
      this.MaxFourierFinal = Item;
    case 'Max Courant Converging'
      this.MaxCourantConverging = Item;
    case 'Max Fourier Converging'
      this.MaxFourierConverging = Item;
    otherwise
      fprintf(['XXX Model SET Inteface for ' PropertyName ' is not found XXX\n']);
  end
end

%% Adding Elements
function addGroup(this,GroupToAdd)
  if isrow(GroupToAdd)
    this.Groups = [this.Groups GroupToAdd];
  else
    this.Groups = [this.Groups GroupToAdd'];
  end
end
function addBridge(this,BridgeToAdd)
  if isrow(BridgeToAdd)
    this.Bridges = [this.Bridges BridgeToAdd];
```

```
  else
    this.Bridges = [this.Bridges BridgeToAdd'];
  end
end
function addLeakConnection(this,LeakToAdd)
  if isrow(LeakToAdd)
    this.LeakConnections = [this.LeakConnections LeakToAdd];
  else
    this.LeakConnections = [this.LeakConnections LeakToAdd'];
  end
end
function addConverter(this,ConverterToAdd)
  LEN = length(this.Converters);
  for i = length(ConverterToAdd):-1:1
    this.Converters(LEN+i) = ConverterToAdd(i);
    this.addFrame(ConverterToAdd(i).Frames);
  end
end
function addFrame(this,FrameToAdd)
  LEN = length(this.RefFrames);
  for i = length(FrameToAdd):-1:1
    this.RefFrames(LEN+i) = FrameToAdd(i);
  end
end
function addSensor(this,SensorToAdd)
  LEN = length(this.Sensors);
  for i = length(SensorToAdd):-1:1
    this.Sensors(LEN+i) = SensorToAdd(i);
    if this.isDiscretized
      this.Sensors(LEN+1).update();
    end
  end
  this.Sensors = unique(this.Sensors);
end
function addPVoutput(this,PVoutputToAdd)
  LEN = length(this.PVoutputs);
  for i = length(PVoutputToAdd):-1:1
    this.PVoutputs(LEN+i) = PVoutputToAdd(i);
  end
  this.PVoutputs = unique(this.PVoutputs);
end
function addSnapShot(this,SnapShotToAdd)
  this.SnapShots{end+1} = SnapShotToAdd;
end
function addNonConnection(this,NonConnectionToAdd)
  LEN = length(this.NonConnections);
  for i = length(NonConnectionToAdd):-1:1
    this.NonConnections(LEN+i) = NonConnectionToAdd(i);
    this.resetDiscretization();
  end
  this.NonConnections = unique(this.NonConnections);
end
function addCustomMinorLoss(this,CustomMinorLossToAdd)
  LEN = length(this.CustomMinorLosses);
  for i = length(CustomMinorLossToAdd):-1:1
    this.CustomMinorLosses(LEN+i) = CustomMinorLossToAdd(i);
    this.resetDiscretization();
  end
  this.CustomMinorLosses = unique(this.CustomMinorLosses);
end

%% Update on Demand
function update(this)
  this.isStateDiscretized = true;
  if any(~isvalid(this.Bridges))
    this.Bridges = this.Bridges(isvalid(this.Bridges));
  end
  keep = true(size(this.Bridges));
  for i = 1:length(this.Bridges)
      for j = i+1:length(this.Bridges)
          if (this.Bridges(i).Body1 == this.Bridges(j).Body1 && ...
```

```
              this.Bridges(i).Body2 == this.Bridges(j).Body2) ...
              || (this.Bridges(i).Body2 == this.Bridges(j).Body1 && ...
              this.Bridges(i).Body1 == this.Bridges(j).Body2)
            keep(j) = false;
          end
      end
  end
  for i = length(keep):-1:1
      if ~keep(i)
          this.Bridges(i).deReference();
      end
  end
  if any(~isvalid(this.Groups))
    this.Groups = this.Groups(isvalid(this.Groups));
  end
  if any(~isvalid(this.LeakConnections))
    this.LeakConnections = this.LeakConnections(isvalid(this.LeakConnections));
  end
  if any(~isvalid(this.Converters))
    this.Converters = this.Converters(isvalid(this.Converters));
  end
  for iConverter = this.Converters
    if isempty(iConverter.Model); iConverter.Model = this; end
  end
  if any(~isvalid(this.RefFrames))
    this.RefFrames = this.RefFrames(isvalid(this.RefFrames));
  end
  if any(~isvalid(this.Sensors))
    this.Sensors = this.Sensors(isvalid(this.Sensors));
  end
  if any(~isvalid(this.PVoutputs))
    this.PVoutputs = this.PVoutputs(isvalid(this.PVoutputs));
  end
  for i = length(this.Selection):-1:1
    if ~isvalid(this.Selection{i})
      this.Selection(i) = [];
    end
  end
  for iGroup = this.Groups
    if ~iGroup.isDiscretized
      this.isStateDiscretized = false;
      break;
    end
  end
  this.isChanged = false;
end
function change(this)
  % Records that the model is changed and should be updated when
  % ... required
  this.isChanged = true;
  this.Faces(:) = [];
  this.Nodes(:) = [];
  this.CurrentSim(:) = [];
  this.isStateDiscretized = false;
end

%% Process nodes and faces
function isit = get.isDiscretized(this)
  if this.isChanged; this.update(); end
  isit = this.isStateDiscretized;
end
function discretize(this, run)
  this.resetDiscretization();
  for iLinRot = this.Converters
      iLinRot.Populate(iLinRot.Type,iLinRot.originalInput);
  end
  if this.isChanged; this.update(); end

  %% Initializing Meshing
  progressbar('Calculating Surroundings');
```

```
% Test if everything is discretized
this.surroundings.discretize();
if nargin > 1 && isfield('rpm',run)
  this.engineSpeed = run.rpm;
end

if nargin > 1 && isfield('NodeFactor',run) && run.NodeFactor ~= 1
  backup_ODN = this.Mesher.oscillation_depth_N;
  backup_MXT = this.Mesher.maximum_thickness;
  backup_HEFD = this.Mesher.HeatExchangerFinDivisions;
  backup_gas_entrance = this.Mesher.Gas_Entrance_Exit_N;
  backup_gas_maximum_size = this.Mesher.Gas_Maximum_Size;
  backup_gas_minimum_size = this.Mesher.Gas_Minimum_Size;
%   this.Mesher.oscillation_depth_N = ...
%       ceil(sqrt(double(derefinement_factor))*double(backup_ODN));
%   this.Mesher.maximum_thickness = ...
%       backup_MXT/sqrt(double(derefinement_factor));
  this.Mesher.Gas_Entrance_Exit_N = ...
      double(run.NodeFactor)*double(backup_gas_entrance);
  this.Mesher.Gas_Maximum_Size = ...
      double(backup_gas_maximum_size)/double(run.NodeFactor);
  this.Mesher.Gas_Minimum_Size = ...
      double(backup_gas_minimum_size)/double(run.NodeFactor);
end

progressbar('Discretizing Bridges');
% Test and Discretize Bridges
for iBridge = this.Bridges
  if ~iBridge.isDiscretized
    iBridge.discretize();
    if ~iBridge.isDiscretized
      fprintf(['XXX Exited Discretization at Bridge Connection: ' ...
        iBridge.name '. XXX\n']);
      if nargin > 1 && isfield('NodeFactor',run) && run.NodeFactor ~= 1
        this.Mesher.oscillation_depth_N = backup_ODN;
        this.Mesher.maximum_thickness = backup_MXT;
        this.Mesher.HeatExchangerFinDivisions = backup_HEFD;
        this.Mesher.maximum_growth = backup_growth;
        this.Mesher.Gas_Entrance_Exit_N = backup_gas_entrance;
        this.Mesher.Gas_Maximum_Size = backup_gas_maximum_size;
        this.Mesher.Gas_Minimum_Size = backup_gas_minimum_size;
        clear backup_ODN;
        clear backup_MXT;
        clear backup_HEFD;
        clear backup_growth;
      end
      return;
    end
  end
end
progressbar('Discretizing Groups');
% Test and Discretize Groups
for iGroup = this.Groups
  if ~iGroup.isDiscretized
    if nargin > 1
      iGroup.discretize(run.NodeFactor);
    end
    if ~iGroup.isDiscretized
      fprintf(['XXX Exited Discretization at Group: ' iGroup.name '. XXX\n']);
      if nargin > 1 && isfield('NodeFactor',run) && run.NodeFactor ~= 1
        this.Mesher.oscillation_depth_N = backup_ODN;
        this.Mesher.maximum_thickness = backup_MXT;
        this.Mesher.HeatExchangerFinDivisions = backup_HEFD;
        this.Mesher.Gas_Entrance_Exit_N = backup_gas_entrance;
        this.Mesher.Gas_Maximum_Size = backup_gas_maximum_size;
        this.Mesher.Gas_Minimum_Size = backup_gas_minimum_size;
        clear backup_ODN;
        clear backup_MXT;
        clear backup_HEFD;
        clear backup_growth;
      end
```

```
      return;
    end
  end
end
progressbar('Discretizing Leaks');
% Test and Discretize LeakConnections
for iLeak = this.LeakConnections
  if ~iLeak.isDiscretized
    iLeak.getFaces();
    if ~iLeak.isDiscretized
      fprintf(['XXX Exited Discretization at Leak Connection: ' ...
        iLeak.name '. XXX\n']);
      if nargin > 1 && isfield('NodeFactor',run) && run.NodeFactor ~= 1
        this.Mesher.oscillation_depth_N = backup_ODN;
        this.Mesher.maximum_thickness = backup_MXT;
        this.Mesher.HeatExchangerFinDivisions = backup_HEFD;
        this.Mesher.Gas_Entrance_Exit_N = backup_gas_entrance;
        this.Mesher.Gas_Maximum_Size = backup_gas_maximum_size;
        this.Mesher.Gas_Minimum_Size = backup_gas_minimum_size;
        clear backup_ODN;
        clear backup_MXT;
        clear backup_HEFD;
        clear backup_growth;
      end
      return;
    end
  end
end

if nargin > 1 && isfield('NodeFactor',run) && run.NodeFactor ~= 1
  this.Mesher.oscillation_depth_N = backup_ODN;
  this.Mesher.maximum_thickness = backup_MXT;
  this.Mesher.HeatExchangerFinDivisions = backup_HEFD;
  this.Mesher.Gas_Entrance_Exit_N = backup_gas_entrance;
  this.Mesher.Gas_Maximum_Size = backup_gas_maximum_size;
  this.Mesher.Gas_Minimum_Size = backup_gas_minimum_size;
  clear backup_ODN;
  clear backup_MXT;
  clear backup_HEFD;
  clear backup_growth;
end
progressbar('Counting Elements');
% Count the Nodes and Faces
ndequ = 1; % <-- Environment Node
fcequ = 0;
for iLeak = this.LeakConnections
  fcequ = fcequ + length(iLeak.Faces);
end
for iBridge = this.Bridges
  fcequ = fcequ + length(iBridge.Faces);
end
for iGroup = this.Groups
  fcequ = fcequ + length(iGroup.Faces);
  ndequ = ndequ + length(iGroup.Nodes);
end

% Start Simulation Definition
this.CurrentSim = Simulation();
Sim = this.CurrentSim;
Sim.Model = this;

%% Acquiring Nodes and Faces
progressbar('Acquiring Nodes and Faces');

% Collect Nodes and Faces
% Environment
this.Nodes(ndequ) = this.surroundings.Node;
ndequ = ndequ - 1;
% LeakConnections
for iLeak = this.LeakConnections
  len = length(iLeak.Faces);
```

```
  this.Faces(fcequ - len + 1:fcequ) = iLeak.Faces;
  fcequ = fcequ - len;
end
% Bridges
for iBridge = this.Bridges
  len = length(iBridge.Faces);
  this.Faces(fcequ - len + 1:fcequ) = iBridge.Faces;
  fcequ = fcequ - len;
end
% Groups
for iGroup = this.Groups
  this.Faces(fcequ - length(iGroup.Faces) + 1:fcequ) = iGroup.Faces;
  fcequ = fcequ - length(iGroup.Faces);
  this.Nodes(ndequ - length(iGroup.Nodes) + 1:ndequ) = iGroup.Nodes;
  ndequ = ndequ - length(iGroup.Nodes);
end

% Exclude invalid nodes
keep = true(size(this.Nodes));
for i = 1:length(this.Nodes)
  if ~isvalid(this.Nodes(i))
    keep(i) = false;
  end
end
this.Nodes = this.Nodes(keep);

% Exclude Faces with invalid nodes
keep = true(size(this.Faces));
for i = 1:length(this.Faces)
  Fc = this.Faces(i);
  if ~isvalid(Fc) || ...
      ~isvalid(Fc.Nodes(1)) || ...
      ~isvalid(Fc.Nodes(2))
    keep(i) = false;
  end
end
this.Faces = this.Faces(keep);

% Assign Faces/Node Connections to Nodes
for Nd = this.Nodes
  Nd.Faces = Face.empty;
  Nd.Nodes = Node.empty;
end
for Fc = this.Faces
  % Add to each Node
  Fc.Nodes(1).addFace(Fc);
  Fc.Nodes(2).addFace(Fc);
end

% Remove faces that are not allowed
keep2 = true(size(this.NonConnections));
i = 1;
for nonCon = this.NonConnections
  iBody = nonCon.Body1;
  if ~isvalid(iBody)
    keep2(i) = false;
  else
    if isa(nonCon.Body2,'Environment')
      for nd = iBody.Nodes
        keep = true(size(nd.Faces));
        i = 1;
        for fc = nd.Faces
          if (fc.Nodes(1).Body == iBody && ...
              (isa(fc.Nodes(2).Body,'Environment') && ...
              fc.Nodes(2).Body == nonCon.Body2)) || ...
              ((isa(fc.Nodes(1).Body,'Environment') && ...
              fc.Nodes(1).Body == nonCon.Body2) && ...
              fc.Nodes(2).Body == iBody)
            keep(i) = false;
          end
          i = i + 1;
```

```
        end

        if any(~keep)
          for i = 1:length(keep)
            if ~keep(i)
              this.Faces(this.Faces==nd.Faces(i)) = [];
            end
          end
          nd.Faces = nd.Faces(keep);
        end
      end
    else
      for nd = iBody.Nodes
        keep = true(size(nd.Faces));
        i = 1;
        for fc = nd.Faces
          if (fc.Nodes(1).Body == iBody && ...
              fc.Nodes(2).Body == nonCon.Body2) || ...
              (fc.Nodes(1).Body == nonCon.Body2 && ...
              fc.Nodes(2).Body == iBody)
            keep(i) = false;
          end
          i = i + 1;
        end

        if any(~keep)
          for i = 1:length(keep)
            if ~keep(i)
              this.Faces(this.Faces==nd.Faces(i)) = [];
            end
          end
          nd.Faces = nd.Faces(keep);
        end
      end
    end
  end
  i = i + 1;
end
if any(~keep2)
  this.NonConnections = this.NonConnections(keep2);
end

%% Cleaning up solid connections that are too small
progressbar('Cleaning up solid connections that are too small');

% Clean up small nodes near bigger nodes
keep = true(size(this.Faces));
nds2del = Node.empty;
count = 0;
if nargin > 1 && isfield('NodeFactor',run) && run.NodeFactor ~= 1
  for i = 1:length(this.Faces)
    fc = this.Faces(i);
    [should_remove, nd2del, ~] = fc.Nodes(1).combineSolid(fc.Nodes(2),run.NodeFactor);
    if should_remove
      count = count + 1;
      keep(i) = false;
      nds2del(end+1) = nd2del;
    end
  end
else
  for i = 1:length(this.Faces)
    fc = this.Faces(i);
    [should_remove, nd2del, ~] = fc.Nodes(1).combineSolid(fc.Nodes(2),1);
    if should_remove
      count = count + 1;
      keep(i) = false;
      nds2del(end+1) = nd2del;
    end
  end
end
fprintf([num2str(count) ' Node pairs collapsed\n']);
```

```
this.Faces = this.Faces(keep);

% Remove these nodes from were they came
for nd = nds2del
  if ~isempty(nd.Body) && isa(nd.Body,'Body')
    keep2 = true(size(nd.Body.Nodes));
    for i = 1:length(nd.Body.Nodes)
      if nd.Body.Nodes(i) == nd
        keep2(i) = false;
      end
    end
    nd.Body.Nodes = nd.Body.Nodes(keep2);
  end
end

% Remove the nodes from the bulk list
keep = true(size(this.Nodes));
for nd = nds2del
  keep(this.Nodes==nd) = false;
end
this.Nodes = this.Nodes(keep);
clear nds2del;

%% Assigning Node and Face Indexes
progressbar('Assigning Node and Face Indexes');

% Assign Face/Node indexs to Faces and Nodes
% Determine the amount of Solid, Wall, Environment and Gas Nodes
S_count = 0;
E_count = 0;
for Nd = this.Nodes
  if Nd.Type == enumNType.SN
    S_count = S_count + 1;
  elseif Nd.Type == enumNType.EN
    E_count = E_count + 1;
  end
end
% Arrange, GN, EN, SN
G_count = length(this.Nodes) - E_count - S_count;
fprintf(['Found: ' num2str(G_count) ' Gas Nodes, ' ...
  num2str(E_count) ' Environment Nodes, ' ...
  num2str(S_count) ' Solid Nodes\n']);
E_count = G_count + E_count;
S_count = length(this.Nodes);

S_count_backup = S_count;
E_count_backup = E_count;
G_count_backup = G_count;

for Nd = this.Nodes
  if Nd.Type == enumNType.SN
    Nd.index = S_count;
    S_count = S_count - 1;
  elseif Nd.Type == enumNType.EN
    Nd.index = E_count;
    E_count = E_count - 1;
  else
    Nd.index = G_count;
    G_count = G_count - 1;
  end
end

% Exclude faces with nodes with no index
keep = true(size(this.Faces));
for i = 1:length(this.Faces)
  Fc = this.Faces(i);
  if isempty(Fc.Nodes(1).index) || isempty(Fc.Nodes(2).index) || ...
      Fc.Nodes(1).index < 1 || Fc.Nodes(2).index < 1
    keep(i) = false;
  end
end
```

```
this.Faces = this.Faces(keep);


%% Assessing Connections
progressbar('Assessing Connections');

% Orient them such that the node closer to 0,0 is
% ... listed first
for Fc = this.Faces
  if Fc.Type == enumFType.Gas || Fc.Type == enumFType.MatrixTransition
    if isempty(Fc.Connection)
      O = Fc.Orient;
    else
      O = Fc.Connection.Orient;
    end
    switch O
      case enumOrient.Vertical
        if Fc.Nodes(1).xmin(1) > Fc.Nodes(2).xmin(1)
          % Swap Nodes
          TempNode = Fc.Nodes(1);
          Fc.Nodes(1) = Fc.Nodes(2);
          Fc.Nodes(2) = TempNode;
        end
      case enumOrient.Horizontal
        if Fc.Nodes(1).ymin(1) > Fc.Nodes(2).ymin(1)
          % Swap Nodes
          TempNode = Fc.Nodes(1);
          Fc.Nodes(1) = Fc.Nodes(2);
          Fc.Nodes(2) = TempNode;
        end
    end
  end
end

% For Gas-Gas Faces that have a connection (from node contacts), determine K
% Determine if applicable
isSubject = false(length(this.Faces),1);
for fcequ = 1:length(this.Faces)
  % Gather all Gas-Gas faces that are on possible discontinuities
  isSubject(fcequ) = ...
    ((this.Faces(fcequ).Type == enumFType.Gas || ...
    this.Faces(fcequ).Type == enumFType.MatrixTransition) && ...
    ~isempty(this.Faces(fcequ).Connection)) && ...
    ~isfield(this.Faces(fcequ).data,'K12');
end

% Group based on common connection & body
subSet = this.Faces(isSubject);
isExcluded = false(length(subSet),1);
n = 1;
for i = 1:length(subSet)
  if ~isExcluded(i)
    isSubject = false(length(subSet),1);
    isSubject(i) = true;
    for j = 1:length(subSet)
      if ~isExcluded(j) && ...
          subSet(i).Connection == subSet(j).Connection
        % The two Faces are very likely somehow adjacent
        isSubject(j) = true;
      end
    end
    % should have acquired a subSet with a common connection
    % Mark off Exclusion
    isExcluded(isSubject) = true;
    subsubSet = subSet(isSubject);

    % So we have grabbed a subset of the select nodes that share a
    % ... connection with element i
    index = zeros(length(subsubSet),1);

    % Determine if they are part of some adjacent chain by going
```

```
% ... through each combination and passing a index between
% ... connected elements.
for k = 1:length(subsubSet)
  for x = k+1:length(subsubSet)
    % Test if they link to the same nodes or the linked nodes are
    % touching, for both sides of the face.
    if ((subsubSet(k).Nodes(1) == subsubSet(x).Nodes(1) || ...
        subsubSet(k).Nodes(1).isTouching(subsubSet(x).Nodes(1))) && ...
        (subsubSet(k).Nodes(2) == subsubSet(x).Nodes(2) || ...
        subsubSet(k).Nodes(2).isTouching(subsubSet(x).Nodes(2))))
      if index(k) == 0
        if index(x) == 0
          index(k) = n;
          index(x) = n;
        else
          index(k) = index(x);
        end
      else
        if index(x) == 0
          index(x) = index(k);
        else
          index(index==index(x)) = index(k);
        end
      end
    else
      if index(k) == 0
        index(k) = n;
        n = n + 1;
      end
    end
  end
end

% Pick out groups that have the same index (i.e. part of the same
% ... chain)
issubExcluded = false(length(subsubSet),1);
for k = 1:length(subsubSet)
  if ~issubExcluded(k)
    issubExcluded(index==index(k)) = true;
    neighbourhood = subsubSet(index==index(k));
    isDynamic = false;
    for Fc = neighbourhood
      if Fc.isDynamic
        isDynamic = true;
        break;
      end
    end
    if isDynamic
      % For each moment in time, get the total area as a vector
      Area1 = zeros(1,Frame.NTheta);
      Area2 = zeros(1,Frame.NTheta);
      for x = 1:length(neighbourhood)
        for ind = 0:Frame.NTheta-1
          Area1(ind+1) = Area1(ind+1) + ...
            neighbourhood(x).Nodes(1).getArea(ind,neighbourhood(x).Connection);
          Area2(ind+1) = Area2(ind+1) + ...
            neighbourhood(x).Nodes(2).getArea(ind,neighbourhood(x).Connection);
        end
      end
      Area1 = CollapseVector(Area1);
      Area2 = CollapseVector(Area2);
      ratio = Area1./Area2;
      if ~all(ratio == 1)
          ratio(ratio>1)=1./ratio(ratio>1);
          firstformula = ratio>0.76;
          K12 = zeros(size(firstformula));
          K12(firstformula) = (1-ratio(firstformula).^2).^2;
          K12(~firstformula) = 0.42*(1-ratio(~firstformula).^2);
          K12 = CollapseVector(K12);
          K21 = K12;
          Entrance = Area1 > Area2;
```

```
                    if length(Entrance) > 1
                      for b = 1:length(Entrance)
                        x12 = min(b,length(K12));
                        x21 = min(b,length(K21));
                        if Entrance(b)
                          if K12(x12) > 0.5; K12(x12) = 0.5; end
                        else
                          if K21(x21) > 0.5; K21(x21) = 0.5; end
                        end
                      end
                    elseif Entrance
                      K12(K12>0.5) = 0.5;
                    elseif ~Entrance
                        K21(K21>0.5) = 0.5;
                    end
                  else
                      K12 = 0;
                      K21 = 0;
                  end
                else
                  % Get the area as a static scalar
                  Area1 = 0; Area2 = 0;
                  for x = 1:length(neighbourhood)
                    Area1 = Area1 +
neighbourhood(x).Nodes(1).getArea(0,neighbourhood(x).Connection);
                    Area2 = Area2 +
neighbourhood(x).Nodes(2).getArea(0,neighbourhood(x).Connection);
                  end
                  ratio = Area1/Area2;
                  if ratio ~= 1
                      if ratio > 1; ratio = 1/ratio; end
                      if ratio > 0.76; K12 = (1-ratio.^2).^2;
                      else; K12 =  0.42*(1-ratio.^2);
                      end
                      K21 = K12;
                      if Area1 > Area2
                        if K12 > 0.5
                          K12 = 0.5;
                        end
                      else
                        if K21 > 0.5
                          K21 = 0.5;
                        end
                      end
                  else
                      K12 = 0;
                      K21 = 0;
                  end
                end
                if all(K12 == 0)
                  % It is straight, this is simply a pipe
                  for Fc = neighbourhood
                    if Fc.Orient == enumOrient.Vertical
                      if Fc.Nodes(1).xmin == 0
                        % Cylindrical
                        C = 64;
                      else
                        % Annuluar
                        C = 96;
                      end
                    else % Horizontal
                      C = 96;
                    end
                    Fc.data.fFunc_l = @(Re) C./Re;
                    Fc.data.fFunc_t = @(Re) 0.11*(this.roughness/Fc.data.Dh+68./Re).^0.25;

                    % Streamwise conduction enhancement
                    Fc.data.NkFunc_l = @(Re) 1;
                    Fc.data.NkFunc_t = @(Re,Pr) 0.022*(Re.^0.75).*(Pr);
                  end
                else
```

```
          for Fc = neighbourhood
            Fc.data.K12 = K12;
            Fc.data.K21 = K21;
          end
        end
      end
    end
  end
end

% Overwrite K of Custom Minor Losses
for CustomK = this.CustomMinorLosses
  if this.CustomMinorLosses.isValid()
    for Fc = this.Faces
      if isa(Fc.Nodes(1).Body,'Body') && ...
          isa(Fc.Nodes(2).Body,'Body')
        if (Fc.Nodes(1).Body == CustomK.Body1 && ...
            Fc.Nodes(2).Body == Custom.Body2)
          Fc.data.K12 = CustomK.K12;
          Fc.data.K21 = CustomK.K21;
        elseif (Fc.Nodes(2).Body == CustomK.Body1 && ...
            Fc.Nodes(1).Body == Custom.Body2)
          Fc.data.K12 = CustomK.K21;
          Fc.data.K21 = CustomK.K12;
        end
      end
    end
  end
end

%% Decimating Loops
progressbar('Decimating Extra Loops');
% debug_loopPlot(this,false);
% Decimate extra loops
Triads = cell(0,0);
for Nd = this.Nodes
  if Nd.Type ~= enumNType.SN && Nd.Type ~= enumNType.EN
    visited = GetTriad(Nd);
    for set = visited
      fcs = set{1};
      % Prevent duplicate loops from showing up
      found = false;
      for i = 1:length(Triads)
        if any(Triads{i}(1) == fcs) && any(Triads{i}(2) == fcs) && ...
            any(Triads{i}(3) == fcs)
          found = true; break;
        end
      end
      if ~found; Triads{end+1} = fcs; end
    end
  end
end

% Look at Triads
Scores = cell(size(Triads));
Tri_Nodes = Scores;
for i = 1:length(Scores)
  Scores{i} = zeros(1,3);
  Tri_Nodes{i} = Node.empty;
end
% Score All the Triads
for k = 1:length(Triads)
  Tri = Triads{k};
  Tri_Node_i = 3;
  backup = [0 0];
  % Get nodes for the Tri
  for fc = Tri
    for nd = fc.Nodes
      if isempty(Tri_Nodes{k}) || ...
          all(Tri_Nodes{k} ~= nd)
        Tri_Nodes{k}(Tri_Node_i) = nd; Tri_Node_i = Tri_Node_i - 1;
```

```
      end
    end
  end
  % Assign a score based on the area that enters than node
  for fc = Tri
    score = mean(fc.data.Area);
    for nd = fc.Nodes
      index = find(Tri_Nodes{k}==nd);
      Scores{k}(index) = Scores{k}(index) + score;
    end
  end
  % Normalize the Scores According to the other Options
  backup(1) = Scores{k}(1); backup(2) = Scores{k}(2);
  Scores{k}(1) = backup(1) / (backup(2) + Scores{k}(3));
  Scores{k}(2) = backup(2) / (backup(1) + Scores{k}(3));
  Scores{k}(3) = Scores{k}(3) / (backup(1) + backup(2));
  Scores{k}(isnan(Scores{k})) = 0;
  % Ensure that faces that can't be closed will not be looked at
  % ... As the number of faces that can't will only increase
  Backup_Tri = Tri;
  for i = 1:3
    for j = 1:length(Backup_Tri)
      fc = Backup_Tri(j);
      if ~any(fc.Nodes == Tri_Nodes{k}(i))
        Tri(i) = fc;
        if ~canClose(fc)
          Scores{k}(i) = 0;
        end
        break;
      end
    end
  end
  % Rearrange the Tri so that the faces correspond to the correct
  % ... score

end

while ~isempty(Triads)
  Best_Tri = 0;
  Open_Triads = true(length(Triads),1);
  Best_Score = 0;
  Best_Index = 0;

  % Find Best Possible Face to close
  finding_best = true;
  while finding_best
    for k = 1:length(Triads)
      % Get the best
      finding_best = true;
      for i = 1:3
        if Scores{k}(i) > Best_Score
          Best_Score = Scores{k}(i);
          Best_Index = i;
          Best_Tri = k;
        end
      end
    end
    if Best_Score == 0; break; end
    closing_face = Triads{Best_Tri}(Best_Index);
    if canClose(closing_face)
      finding_best = false;
    else
      Scores{Best_Tri}(Best_Index) = 0;
      Best_Score = 0;
    end
  end

  % Collapse the face, closing the triad
  if Best_Score > 0

    % Adjust the area and minor loss coefficients of the other two faces
```

```
          for fc = Triads{Best_Tri}
            if fc ~= closing_face
              if isfield(fc.data,'K12')
                if isfield(closing_face.data,'K12')
                  fc.data.K12 = (fc.data.K12.*fc.data.Area + ...
                    closing_face.data.K12.*closing_face.data.Area)./ ...
                    (fc.data.Area + closing_face.data.Area);
                  fc.data.K21 = (fc.data.K21.*fc.data.Area + ...
                    closing_face.data.K21.*closing_face.data.Area)./ ...
                    (fc.data.Area + closing_face.data.Area);
                end
              end
              fc.data.Area = fc.data.Area + closing_face.data.Area;
            end
          end

          % Delete the face from the list
          closing_face.data.Area = 0;
          for nd = closing_face.Nodes
            nd.Faces(nd.Faces == closing_face) = [];
          end
          this.Faces(this.Faces == closing_face) = [];

          for k = 1:length(Triads)
            if any(Triads{k} == closing_face)
              Open_Triads(k) = false;
            end
          end
          Open_Triads(Best_Tri) = false;
          Triads = Triads(Open_Triads);
          Scores = Scores(Open_Triads);
          fprintf(['Decimated a Triad with ' num2str(length(Open_Triads) - sum(Open_Triads) - 1)
' others.\n']);
        else
          Triads = cell(0);
        end
      end
      %{
      for Tri = Triads
        Tri_Nodes = Node.empty;
        Scores = {0,0,0};
        for fc = Tri{1}
          for nd = fc.Nodes
            if isempty(Tri_Nodes) || all(Tri_Nodes ~= nd)
              Tri_Nodes = [Tri_Nodes nd];
              index = length(Tri_Nodes);
            else
              index = find(Tri_Nodes==nd);
            end
            Scores{index} = Scores{index} + fc.data.Area;
          end
        end
        %}

        % Starting at the node with maximum area, test if the opposite face
        % can be closed
        %{
        bestrecord = 0;
        bestindex = 0;
        for i = 1:3
          if mean(Scores{i}) > bestrecord
            for fc = Tri{1}
              if ~any(fc.Nodes == Tri_Nodes(i))
                if canClose(fc)
                  bestindex = i;
                  bestrecord = mean(Scores{i});
                end
                break;
              end
            end
          end
```

```
  end

  % Collapse the triad
  if bestindex > 0 && bestrecord > 0
    fprintf('Decimated a Triad\n');
    % Find closing face
    for fc = Tri{1}
      if ~any(fc.Nodes == Tri_Nodes(i))
        closing_face = fc;
        break;
      end
    end

    % Adjust the area and minor loss coefficients of the other two faces
    for fc = Tri{1}
      if fc ~= closing_face
        if isfield(fc.data,'K12')
          if isfield(closing_face.data,'K12')
            fc.data.K12 = (fc.data.K12.*fc.data.Area + ...
              closing_face.data.K12.*closing_face.data.Area)./ ...
              (fc.data.Area + closing_face.data.Area);
            fc.data.K21 = (fc.data.K21.*fc.data.Area + ...
              closing_face.data.K21.*closing_face.data.Area)./ ...
              (fc.data.Area + closing_face.data.Area);
          end
        end
        fc.data.Area = fc.data.Area + closing_face.data.Area;
      end
    end

    % Delete the face from the list
    closing_face.data.Area = 0;
    for nd = closing_face.Nodes
      nd.Faces(nd.Faces == closing_face) = [];
    end
    this.Faces(this.Faces == closing_face) = [];
  end
  %}

% Faces
% Determine the amount of Solid, Environment, Mix and Gas Faces
S_count = 0;
E_count = 0;
M_count = 0;
for Fc = this.Faces
  switch Fc.Type
    case enumFType.Solid
      S_count = S_count + 1;
    case enumFType.Mix
      M_count = M_count + 1;
    case enumFType.Environment
      E_count = E_count + 1;
  end
end
G_count = length(this.Faces) - S_count - E_count - M_count;
fprintf(['Found: ' num2str(G_count) ' Gas Faces, ' ...
  num2str(E_count) ' Environment Faces, ' ...
  num2str(M_count) ' Mixed Faces, ' ...
  num2str(S_count) ' Solid Faces\n']);
M_count = G_count + M_count;
E_count = M_count + E_count;
S_count = length(this.Faces);
G_count_backup_faces = G_count;
E_count_backup_faces = E_count;
M_count_backup_faces = M_count;
for Fc = this.Faces
  switch Fc.Type
    case enumFType.Solid
      Fc.index = S_count;
      S_count = S_count - 1;
    case enumFType.Mix
```

```
      Fc.index = M_count;
      M_count = M_count - 1;
    case enumFType.Environment
      Fc.index = E_count;
      E_count = E_count - 1;
    case enumFType.Leak

    otherwise % Gas
      Fc.index = G_count;
      G_count = G_count - 1;
  end
end

% Remove Nodal Faces that have been deleted
for iNd = this.Nodes
  keep = true(size(iNd.Faces));
  j = 1;
  for Fc = iNd.Faces
    if isempty(Fc.index) || Fc.index < 1
      keep(j) = false;
    end
    j = j + 1;
  end
  iNd.Faces = iNd.Faces(keep);
end

% Deal with input options
% 1. NodeFactor -> Already handled in initial discretization
% 2. HX Convection ->
if isfield(run,'HX_Convection') && run.HX_Convection ~= 1
  % Find all bodies which are gases, but contain source nodes
  for iGroup = this.Groups
    for iBody = iGroup.Bodies
      if iBody.matl.Phase == enumMaterial.Gas
        if ~isempty(iBody.Matrix) && ...
            isfield(iBody.Matrix.data,'SourceTemperature')
          for nd = iBody.Nodes
            if nd.Type ~= enumNType.SN
              if isfield(nd.data,'NuFunc_l')
                func = nd.data.NuFunc_l;
                if nargin(func) == 2
                  nd.data.NuFunc_l = @(Re,Pr) run.HX_Convection.*func(Re,Pr);
                else
                  nd.data.NuFunc_l = @(Re) run.HX_Convection.*func(Re);
                end
              end
              if isfield(nd.data,'NuFunc_t')
                func = nd.data.NuFunc_t;
                if nargin(func) == 2
                  nd.data.NuFunc_t = @(Re,Pr) run.HX_Convection.*func(Re,Pr);
                else
                  nd.data.NuFunc_t = @(Re) run.HX_Convection.*func(Re);
                end
              end
            end
          end
        end
      end
    end
  end
end
% 3. Regen_Convection ->
if isfield(run,'Regen_Convection') && run.Regen_Convection ~= 1
  % Find all bodies which are gases but contain solids nodes without
  % ... source nodes
  for iGroup = this.Groups
    for iBody = iGroup.Bodies
      if iBody.matl.Phase == enumMaterial.Gas
        if ~isempty(iBody.Matrix) && ...
            ~isfield(iBody.Matrix.data,'SourceTemperature')
          for nd = iBody.Nodes
```

```
            if nd.Type ~= enumNType.SN
              if isfield(nd.data,'NuFunc_l')
                func = nd.data.NuFunc_l;
                if nargin(func) == 2
                  nd.data.NuFunc_l = @(Re,Pr) run.Regen_Convection.*func(Re,Pr);
                else
                  nd.data.NuFunc_l = @(Re) run.Regen_Convection.*func(Re);
                end
              end
              if isfield(nd.data,'NuFunc_t')
                func = nd.data.NuFunc_t;
                if nargin(func) == 2
                  nd.data.NuFunc_t = @(Re,Pr) run.Regen_Convection.*func(Re,Pr);
                else
                  nd.data.NuFunc_t = @(Re) run.Regen_Convection.*func(Re);
                end
              end
            end
          end
        end
      end
    end
  end
end
% 4. Outside Matrix Convection ->
if isfield(run,'Outside_Matrix_Convection') && run.Outside_Matrix_Convection ~= 1
  % Find all bodies which contain only gas nodes
  for iGroup = this.Groups
    for iBody = iGroup.Bodies
      if iBody.matl.Phase == enumMaterial.Gas
        if isempty(iBody.Matrix)
          for nd = iBody.Nodes
            if nd.Type ~= enumNType.SN
              if isfield(nd.data,'NuoFunc_l')
                func = nd.data.NuoFunc_l;
                if nargin(func) == 2
                  nd.data.NuoFunc_l = @(Re,Pr) run.HX_Convection.*func(Re,Pr);
                else
                  nd.data.NuoFunc_l = @(Re) run.HX_Convection.*func(Re);
                end
              end
              if isfield(nd.data,'NuFunc_l')
                func = nd.data.NuFunc_l;
                if nargin(nd.data.NuFunc_l) == 2
                  nd.data.NuFunc_l = @(Re,Pr) run.HX_Convection.*func(Re,Pr);
                else
                  nd.data.NuFunc_l = @(Re) run.HX_Convection.*func(Re);
                end
              end
              if isfield(nd.data,'NuFunc_t')
                func = nd.data.NuFunc_t;
                if nargin(func) == 2
                  nd.data.NuFunc_t = @(Re,Pr) run.HX_Convection.*func(Re,Pr);
                else
                  nd.data.NuFunc_t = @(Re) run.HX_Convection.*func(Re);
                end
              end
            end
          end
        end
      end
    end
  end
end
% 5. Friction ->
if isfield(run,'Friction') && run.Friction ~= 1
  % Find all gas faces
  for Fc = this.Faces
    if Fc.Type == enumFType.Gas || Fc.Type == enumFType.MatrixTransition
      if isfield(Fc.data,'fFunc_l')
        func = Fc.data.fFunc_l;
```

```
        Fc.data.fFunc_l = @(Re) run.Friction*func(Re);
      end
      if isfield(Fc.data,'fFunc_t')
        func = Fc.data.fFunc_t;
        Fc.data.fFunc_t = @(Re) run.Friction*func(Re);
      end
    end
  end
end
% 6. Solid_Conduction ->
if isfield(run,'Solid_Conduction') && run.Solid_Conduction ~= 1
  % Find all solid and mixed faces
  for Fc = this.Faces
    if Fc.Type == enumFType.Solid
      if isfield(Fc.data,'U')
        Fc.data.U = Fc.data.U.*run.Solid_Conduction;
      end
    elseif Fc.Type == enumFType.Mix
      if isfield(Fc.data,'R')
        if run.Solid_Conduction == 0
          Fc.data.R = 1e8;
        else
          Fc.data.R = Fc.data.R./run.Solid_Conduction;
        end
      end
    end
  end
end
% 7. Axial_Mixing_Coefficient ->
if isfield(run,'Axial_Mixing_Coefficient') && run.Axial_Mixing_Coefficient ~= 1
  % Find all gas faces
  for Fc = this.Faces
    if Fc.Type == enumFType.Gas || Fc.Type == enumFType.MatrixTransition
      if isfield(Fc.data,'NkFunc_l')
        func = Fc.data.NkFunc_l;
        if nargin(Fc.data.NkFunc_l) == 2
          Fc.data.NkFunc_l = @(Re,Pr) run.Axial_Mixing_Coefficient.*func(Re,Pr);
        else
          Fc.data.NkFunc_l = @(Re) run.Axial_Mixing_Coefficient.*func(Re);
        end
      end
      if isfield(Fc.data,'NkFunc_t')
        func = Fc.data.NkFunc_t;
        if nargin(Fc.data.NkFunc_t) == 2
          Fc.data.NkFunc_t = @(Re,Pr) run.Axial_Mixing_Coefficient.*func(Re,Pr);
        else
          Fc.data.NkFunc_t = @(Re) run.Axial_Mixing_Coefficient.*func(Re);
        end
      end
    end
  end
end
for iGroup = this.Groups
  for iBody = iGroup.Bodies
    if ~isempty(iBody.Matrix) && ...
            iBody.Matrix.Geometry == enumMatrix.HeatExchanger && ...
            strcmp(iBody.Matrix.data.Classification,'Custom HX')
      if isfield(run,'HX_C1')
        iBody.Matrix.data.C1 = run.HX_C1;
      end
      if isfield(run,'HX_C2')
        iBody.Matrix.data.C2 = run.HX_C2;
      end
      if isfield(run,'HX_C3')
        iBody.Matrix.data.C3 = run.HX_C3;
      end
      if isfield(run,'HX_C4')
        iBody.Matrix.data.C4 = run.HX_C4;
      end
      if isfield(run,'HX_SA_V')
        iBody.Matrix.data.SA_V = run.HX_SA_V;
```

```
      end
    end
    if ~isempty(iBody.Matrix) && ...
            iBody.Matrix.Geometry == enumMatrix.CustomRegen
      if isfield(run,'Regen_C1')
        iBody.Matrix.data.C1 = run.Regen_C1;
      end
      if isfield(run,'Regen_C2')
        iBody.Matrix.data.C2 = run.Regen_C2;
      end
      if isfield(run,'Regen_C3')
        iBody.Matrix.data.C3 = run.Regen_C3;
      end
      if isfield(run,'Regen_C4')
        iBody.Matrix.data.C4 = run.Regen_C4;
      end
      if isfield(run,'Regen_Porosity')
        iBody.Matrix.data.Porosity = run.Regen_Porosity;
      end
      if isfield(run,'Regen_SA_V')
          iBody.Matrix.data.SA_V = run.Regen_SA_V;
      end
    end
  end
end

%% Vectorizing Nodes
progressbar('Vectorizing Nodes');
% Generic Properties
Sim.dT_dU = zeros(S_count_backup,1);
Sim.u = Sim.dT_dU;
Sim.T = Sim.dT_dU;
Sim.CondFlux = Sim.dT_dU;

% Environment Additional Properties
Sim.P = zeros(E_count_backup,1);
Sim.dP = Sim.P;
Sim.dh_dT = Sim.P;
Sim.rho = Sim.P;
Sim.m = Sim.dT_dU;
Sim.vol = Sim.T;
Sim.dV_dt = Sim.P;

% Gas Node Additional Properties
Sim.k = Sim.P;
Sim.mu = Sim.P;
Sim.Dh = zeros(G_count_backup,1);
Sim.Nu = Sim.Dh;
Sim.NuFunc_l = cell(G_count_backup,1);
Sim.NuFunc_t = Sim.NuFunc_l;
Sim.isDynVol = Sim.P;
Sim.DynVol = zeros(6,0);
% Interpolated from Faces
Sim.RE = Sim.Dh;
Sim.U = Sim.Dh;
Sim.f = Sim.Dh;
% Turbulence
Sim.useTurbulenceNd = false(length(Sim.P)-1,1);
Sim.turb = Sim.P;
Sim.dturb = Sim.P;
Sim.Area = zeros(2,length(Sim.Dh));
Sim.Va = Sim.Dh;
Sim.to = Sim.Dh;

% Gas Regions
% Growth algorithm propegating through gas faces that are always open
region = zeros(length(Sim.P),1);
region_count = 0;
for Nd = this.Nodes
  if Nd.index <= length(region) && region(Nd.index) == 0
    region_count = region_count + 1;
```

```
    region = PropegateRegion(Nd,region,region_count);
    if all(region > 0); break; end
  end
end

% Define Functions
DynVol_n = 1;
DynDh_n = 1;
Rs = Sim.P;
for Nd = this.Nodes
  if isfield(Nd.data,'matl')
    if Nd.data.matl.Phase ~= enumMaterial.Solid
      matl = Material(Nd.data.matl.name);
    else
      matl = Nd.data.matl;
    end
  else
    if Nd.Body.matl.Phase ~= enumMaterial.Solid
      matl = Material(Nd.Body.matl.name);
    else
      matl = Nd.Body.matl;
    end
  end
  switch Nd.Type
    case enumNType.SN
      % Sim.dU(Nd.index) = 0; - Needs to be zeroed
      Sim.m(Nd.index) = Nd.vol()*matl.Density;
      if matl.dT_du <= 0
        Sim.dT_dU(Nd.index) = 0;
      else
        Sim.dT_dU(Nd.index) = matl.dT_du;
      end
      Sim.T(Nd.index) = Nd.data.T;
      Sim.u(Nd.index) = matl.initialInternalEnergy(Nd.data.T);
      Sim.vol(Nd.index) = Nd.vol();

      % Static Volume Gas Node %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    case {enumNType.SVGN, enumNType.VVGN, enumNType.SAGN}
      V = Nd.vol();
      Nd.recalc_Dh();
      if isempty(Nd.Body.Matrix)
        if ~isscalar(V)
          Sim.useTurbulenceNd(Nd.index) = true;
        else
          Sim.useTurbulenceNd(Nd.index) = false;
        end
      else
        Sim.useTurbulenceNd(Nd.index) = true;
      end

      if isscalar(V)
        Sim.vol(Nd.index) = V;
      else
        Sim.vol(Nd.index) = V(1);
        Sim.isDynVol(Nd.index) = DynVol_n;
        Sim.DynVol(1,DynVol_n) = Nd.index;
        Sim.DynVol(2,DynVol_n) = Sim.Dyn;
        DynVol_n = DynVol_n + 1;
        Sim.Dynamic(Sim.Dyn,:) = V;
        Sim.Dyn = Sim.Dyn + 1;
      end
      if isscalar(Nd.data.Dh)
        Sim.Dh(Nd.index) = Nd.data.Dh;
      else
        Sim.DynDh(1,DynDh_n) = Nd.index;
        Sim.DynDh(2,DynDh_n) = Sim.Dyn;
        DynDh_n = DynDh_n + 1;
        Sim.Dynamic(Sim.Dyn,:) = Nd.data.Dh;
        Sim.Dyn = Sim.Dyn + 1;
      end
      Sim.dT_dU(Nd.index) = 1;
```

```
            Sim.dT_duFunc{region(Nd.index)} = matl.dT_duFunc;
            try
              Sim.dh_dTFunc{region(Nd.index)} = matl.dh_dTFunc; % Additions
            catch
              matl.Configure(matl.name);
              Sim.dh_dTFunc{region(Nd.index)} = matl.dh_dTFunc; % Additions
            end
            Sim.u2T{region(Nd.index)} = matl.u2T;
            Sim.T(Nd.index) = Nd.data.T;

            Sim.P(Nd.index) = Nd.data.P;
            Sim.rho(Nd.index) = Nd.data.P/(matl.R*Nd.data.T);
            Sim.u(Nd.index) = matl.initialInternalEnergy(Nd.data.T);% +
Nd.data.P/Sim.rho(Nd.index);
            Sim.m(Nd.index) = Sim.rho(Nd.index)*Sim.vol(Nd.index);

            Sim.kFunc{region(Nd.index)} = matl.kFunc;
            Sim.muFunc{region(Nd.index)} = matl.muFunc;
            Rs(Nd.index) = matl.R;

            if isfield(Nd.data,'NuoFunc_l')
              Sim.NuFunc_l{Nd.index} = Nd.data.NuoFunc_l;
            else
              Sim.NuFunc_l{Nd.index} = Nd.data.NuFunc_l;
            end
            Sim.NuFunc_t{Nd.index} = Nd.data.NuFunc_t;
            % Environment Node (Static Properties Node) %%%%%%%%%%%%%%%%%%%
          case enumNType.EN
            Sim.dT_dU(Nd.index) = 0;
            Sim.T(Nd.index) = Nd.Body.Temperature;
            Sim.u2T{region(Nd.index)} = matl.u2T;
            Sim.kFunc{region(Nd.index)} = matl.kFunc;
            Sim.muFunc{region(Nd.index)} = matl.muFunc;
            Sim.dT_duFunc{region(Nd.index)} = matl.dT_duFunc;
            try
              Sim.dh_dTFunc{region(Nd.index)} = matl.dh_dTFunc; % Additions
            catch
              matl.Configure(matl.name);
              Sim.dh_dTFunc{region(Nd.index)} = matl.dh_dTFunc; % Additions
            end
            Rs(Nd.index) = matl.R;
            Sim.k(Nd.index) = matl.kFunc(Nd.data.T);
            Sim.mu(Nd.index) = matl.muFunc(Nd.data.T);
            Sim.u(Nd.index) = matl.initialInternalEnergy(Nd.data.T);% + Nd.data.P/Nd.data.rho;
            Sim.P(Nd.index) = Nd.data.P;
            Sim.rho(Nd.index) = Nd.data.rho;
            Sim.vol(Nd.index) = Inf;
            Sim.m(Nd.index) = Inf;
            Sim.turb(Nd.index) = 0;
        end
      end

      %% Vectorizing Faces
      progressbar('Vectorizing Faces');

      Sim.Fc_Nd = zeros(length(this.Faces),2);
      Sim.Fc_U = zeros(G_count_backup_faces,1);
      Sim.Fc_PR = Sim.Fc_U;
      Sim.Fc_dx = Sim.Fc_U;
      Sim.Fc_RE = Sim.Fc_U;
      Sim.Fc_f = Sim.Fc_U;
      Sim.Fc_R = zeros(1,M_count_backup_faces);
      Sim.Fc_fFunc_l = cell(G_count_backup_faces,1);
      Sim.Fc_fFunc_t = Sim.Fc_fFunc_l;
      Sim.Fc_NkFunc_l = Sim.Fc_fFunc_l;
      Sim.Fc_NkFunc_t = Sim.Fc_fFunc_l;
      Sim.Fc_Dist = Sim.Fc_U;
      Sim.Fc_Cond_Dist = Sim.Fc_U;
      Sim.Fc_K12 = Sim.Fc_U;
      Sim.Fc_K21 = Sim.Fc_U;
      Sim.Fc_u = Sim.Fc_U;
```

```
%       Sim.dL_dt = Sim.Fc_U;
%       Sim.dD_dt = Sim.Fc_U;
        Sim.KpU_2A = Sim.Fc_U;
        Sim.Fc_V = Sim.Fc_U;
        Sim.Fc_dP = Sim.Fc_U;
        Sim.Fc_V_backup = Sim.Fc_U;
        Sim.Fc_W = Sim.Fc_U;

        % For gas-gas, mix and environment faces
        Sim.Fc_Area = zeros(E_count_backup_faces,1);
        Sim.Fc_Dh = Sim.Fc_U;
        Sim.Fc_Cond = Sim.Fc_Area;
        Sim.Fc_T = Sim.Fc_U;
        Sim.Fc_k = Sim.Fc_U;
        Sim.Fc_mu = Sim.Fc_U;
        Sim.Fc_rho = Sim.Fc_U;
        Sim.Fc_Vel_Factor = Sim.Fc_U;
        Sim.Fc_Shear_Factor = Sim.Fc_U;

        % Turbulence
        Sim.Fc_turb = Sim.Fc_U;
        Sim.Fc_to = Sim.Fc_U;
        Sim.useTurbulenceFc = true(G_count_backup_faces,1);

        % Flux Limiters
        Sim.Fc_Nd03 = Sim.Fc_Nd;
        Sim.Fc_A = Sim.Fc_U;
        Sim.Fc_B = Sim.Fc_U;
        Sim.Fc_C = Sim.Fc_U;
        Sim.Fc_D = Sim.Fc_U;

        % Find V and S for the faces
        for Fc = this.Faces
          [V, S, SContact] = FaceMotion(Fc);
          if ~isempty(V); Fc.data.V = V; end
          if ~isempty(S)
            Fc.data.S = S;
            if ~isempty(SContact)
              this.ShearContacts = [this.ShearContacts SContact];
            end
          end
        end

        %% Creating Shear/Pressure Contacts
        progressbar('Creating Shear/Pressure Contacts');

        % For all Faces, attempt to make a PressureContact
        for Fc = this.Faces
          if Fc.Type == enumFType.Mix
            PContact = Fc.getPressureContact();
            if ~isempty(PContact)
              this.PressureContacts = [this.PressureContacts PContact];
            end
          elseif (Fc.Nodes(1).Type == enumNType.SN && ...
              Fc.Nodes(2).Type == enumNType.EN) || ...
              (Fc.Nodes(1).Type == enumNType.EN && ...
              Fc.Nodes(2).Type == enumNType.SN)
            PContact = Fc.getPressureContact();
            if ~isempty(PContact)
              this.PressureContacts = [this.PressureContacts PContact];
            end
          end
        end

        % For all Faces, distribute the friction length to neighbours if
        % ... K enabled.
        for Fc = this.Faces
          if isfield(Fc.data,'Dist')
            Fc.data.Cond_Dist = Fc.data.Dist;
            if isfield(Fc.data,'dx') && isfield(Fc.data, 'K12')
              if any(Fc.data.K12 > 0) || any(Fc.data.K21 > 0)
```

```
% Will only run this code if:
% ... It is a gas face
% ... It has a minor loss coefficient

% This face will not utilize the value of Dist
Fc.data.Dist = 0;

% Get the location of the center of this face
x = getCenterOfOverlapRegion(...
  Fc.Nodes(1).xmin, Fc.Nodes(2).xmin,...
  Fc.Nodes(1).xmax, Fc.Nodes(2).xmax);
y = getCenterOfOverlapRegion(...
  Fc.Nodes(1).ymin, Fc.Nodes(2).ymin,...
  Fc.Nodes(1).ymax, Fc.Nodes(2).ymax);

% Find all neighbours
for nd = Fc.Nodes
  ndx = (nd.xmin + nd.xmax)/2;
  ndy = (nd.ymin + nd.ymax)/2;
  count = 0;
  for fci = nd.Faces
    if fci ~= Fc
      if isfield(fci.data,'Dist') && (...
          (isfield(Fc.data, 'K12') && all(Fc.data.K12 == 0)) || ...
          ~isfield(Fc.data, 'K12'))
        count = count + 1;
      end
    end
  end
  if count < 2
    % Will only run if this node has only one other gas face
    for fci = nd.Faces
      if fci ~= Fc
        if isfield(fci.data,'Dist') && (...
            (isfield(Fc.data, 'K12') && all(Fc.data.K12 == 0)) || ...
            ~isfield(Fc.data, 'K12'))
          % Will only run if this face can use it
          % Determine orientation of fci
          if fci.Nodes(1).xmin == fci.Nodes(2).xmax
            dDist = abs(ndx - x);
            % If the connection is actually closer than
            % ... assumed then the distance is negative
            if abs(fci.Nodes(1).xmin - x) < ...
                abs(fci.Nodes(1).xmin - ndx)
              dDist = -dDist;
            end
          elseif fci.Nodes(1).xmax == fci.Nodes(2).xmin
            dDist = abs(ndx - x);
            % If the connection is actually closer than
            % ... assumed then the distance is negative
            if abs(fci.Nodes(2).xmin - x) < ...
                abs(fci.Nodes(2).xmin - ndx)
              dDist = -dDist;
            end
          elseif all(fci.Nodes(1).ymin == fci.Nodes(2).ymax)
            dDist = abs(ndy - y);
            % If the connection is actually closer than
            % ... assumed then the distance is negative
            if abs(fci.Nodes(1).ymin - y) < ...
                abs(fci.Nodes(1).ymin - ndy)
              dDist = -dDist;
            end
          else
            dDist = abs(ndy - y);
            % If the connection is actually closer than
            % ... assumed then the distance is negative
            if abs(fci.Nodes(2).ymin - y) < ...
                abs(fci.Nodes(2).ymin - ndy)
              dDist = -dDist;
            end
          end
```

```
                fci.data.Dist = CollapseVector(fci.data.Dist + dDist);
                if any(fci.data.Dist <= 0)
                  fprintf('XXX Negative Distance Detected. \n');
                end
              end
            end
          end
        end
      end
    end
  end
end

% Vectorize all Faces
MF_n = 1;
Fc_DynCond_n = 1;
Fc_DynArea_n = 1;
Fc_DynDist_n = 1;
Fc_DynCond_Dist_n = 1;
Fc_Dyndx_n = 1;
Fc_DynDh_n = 1;
Fc_DynK12_n = 1;
Fc_DynK21_n = 1;
Fc_DynVel_Factor_n = 1;
Fc_DynShear_Factor_n = 1;
Fc_DynA_n = 1; Fc_DynB_n = 1; Fc_DynC_n = 1; Fc_DynD_n = 1;
IsApprox = false(length(this.Faces),1);
ApproxCount = 1;
for Fc = this.Faces
  N1 = Fc.Nodes(1);
  N2 = Fc.Nodes(2);
  Sim.Fc_Nd(Fc.index,1) = N1.index;
  Sim.Fc_Nd(Fc.index,2) = N2.index;

  % Solid Faces
  switch Fc.Type
    case enumFType.Solid % Solid and Solid-Environment Faces
      % Conductance
      if isscalar(Fc.data.U)
        Sim.Fc_Cond(Fc.index) = Fc.data.U;
      else
        Sim.Dynamic(Sim.Dyn,:) = Fc.data.U;
        Sim.Fc_DynCond(1,Fc_DynCond_n) = Fc.index;
        Sim.Fc_DynCond(2,Fc_DynCond_n) = Sim.Dyn;
        Fc_DynCond_n = Fc_DynCond_n + 1;
        Sim.Dyn = Sim.Dyn + 1;
      end
    case enumFType.Mix % Gas-Solid Faces
      Sim.Mix_Fc(MF_n) = Fc.index; % A list of Fc_indexes
      if N2.Type ~= enumNType.SN
        % Switch direction, Gas First, Solid Second
        Sim.Fc_Nd(Fc.index,1) = N2.index;
        Sim.Fc_Nd(Fc.index,2) = N1.index;
        temp = N1;
        N1 = N2;
        N2 = temp;
      end
      if isscalar(Fc.data.Area) && isscalar(Fc.data.R)
        % Solid Resistance
        Sim.Fc_R(Fc.index) = Fc.data.R;
        % Surface Area
        Sim.Fc_Area(Fc.index) = Fc.data.Area;
      elseif ~isscalar(Fc.data.Area)
        % Solid Resistance
        temp = Fc.data.R;
        temp = temp(~isnan(temp));
        Sim.Fc_R(Fc.index) = temp(1);
        % Surface Area
        Sim.Dynamic(Sim.Dyn,:) = Fc.data.Area;
        Sim.Fc_DynArea(1,Fc_DynArea_n) = Fc.index;
```

```
            Sim.Fc_DynArea(2,Fc_DynArea_n) = Sim.Dyn;
            Fc_DynArea_n = Fc_DynArea_n + 1;
            Sim.Dyn = Sim.Dyn + 1;
          else
            Fc.data.R = Fc.data.R(~isnan(Fc.data.R));
            Fc.data.R = Fc.data.R(1);
            Sim.Fc_R(Fc.index) = Fc.data.R;
            Sim.Fc_Area(Fc.index) = Fc.data.Area;
          end
          % Look at the mixed face and determine if it can be
          % ... approximated
          %{
          if isfield(N2.data,'matl')
            if N2.data.matl.Phase ~= enumMaterial.Solid
              matl = Material(N2.data.matl.name);
            else
              matl = N2.data.matl;
            end
          else
            if N2.Body.matl.Phase ~= enumMaterial.Solid
              matl = Material(N2.Body.matl.name);
            else
              matl = N2.Body.matl;
            end
          end
          if matl.dT_du < 0; matl.dT_du = 1e-8; end
          if length(N2.Faces) == 1
            % True for most regenerators and heat exchangers
            if any((Fc.data.Area./Fc.data.R)./(N2.vol().*matl.Density./matl.dT_du)*1.e-4 >
0.25)
              IsApprox(Fc.index) = true;
              Sim.FcApprox(ApproxCount) = Fc.index;
              ApproxCount = ApproxCount + 1;
            end
          else
            CU = 0;
            Cother = 0;
            for fc = N2.Faces
              if fc == Fc
                CU = fc.data.Area./fc.data.R;
                if double(sum(CU < Cother))/...
                    double(max(length(CU),length(Cother))) > 0.5
                  CU = 0;
                  break;
                end
              else
                if fc.Type == enumFType.Mix
                  Cother = Cother + fc.data.Area./fc.data.R;
                  if any(CU ~= 0) && ...
                      double(sum(CU < Cother))/...
                      double(max(length(CU),length(Cother))) > 0.5
                    CU = 0;
                    break;
                  end
                end
              end
            end
            if CU ~= 0
              if any((Fc.data.Area./Fc.data.R)./(N2.vol().*matl.Density./matl.dT_du)*1.e-4 >
0.25)
                IsApprox(Fc.index) = true;
                Sim.FcApprox(ApproxCount) = Fc.index;
                ApproxCount = ApproxCount + 1;
              end
            end
          end

          %}
          MF_n = MF_n + 1;
        case {enumFType.Gas, enumFType.MatrixTransition} % Gas-Gas, Gas-Environment Faces
          Fc.recalc_Area_Dh();
```

```
% Create Fc_Fcs array
[A,B,C,D] = populate_Fc_ABCD(Sim, Fc);

% Create Fc_A array
if isscalar(A)
  Sim.Fc_A(Fc.index) = A;
else
  Sim.Dynamic(Sim.Dyn,:) = A;
  Sim.Fc_DynA(1,Fc_DynA_n) = Fc.index;
  Sim.Fc_DynA(2,Fc_DynA_n) = Sim.Dyn;
  Fc_DynA_n = Fc_DynA_n + 1;
  Sim.Dyn = Sim.Dyn + 1;
end
% Create Fc_B array
if isscalar(B)
  Sim.Fc_B(Fc.index) = B;
else
  Sim.Dynamic(Sim.Dyn,:) = B;
  Sim.Fc_DynB(1,Fc_DynB_n) = Fc.index;
  Sim.Fc_DynB(2,Fc_DynB_n) = Sim.Dyn;
  Fc_DynB_n = Fc_DynB_n + 1;
  Sim.Dyn = Sim.Dyn + 1;
end
% Create Fc_C array
if isscalar(C)
  Sim.Fc_C(Fc.index) = C;
else
  Sim.Dynamic(Sim.Dyn,:) = C;
  Sim.Fc_DynC(1,Fc_DynC_n) = Fc.index;
  Sim.Fc_DynC(2,Fc_DynC_n) = Sim.Dyn;
  Fc_DynC_n = Fc_DynC_n + 1;
  Sim.Dyn = Sim.Dyn + 1;
end
% Create Fc_B array
if isscalar(D)
  Sim.Fc_D(Fc.index) = D;
else
  Sim.Dynamic(Sim.Dyn,:) = D;
  Sim.Fc_DynD(1,Fc_DynD_n) = Fc.index;
  Sim.Fc_DynD(2,Fc_DynD_n) = Sim.Dyn;
  Fc_DynD_n = Fc_DynD_n + 1;
  Sim.Dyn = Sim.Dyn + 1;
end

% Area
if isscalar(Fc.data.Area)
  Sim.Fc_Area(Fc.index) = Fc.data.Area;
else
  Sim.Dynamic(Sim.Dyn,:) = Fc.data.Area;
  Sim.Fc_DynArea(1,Fc_DynArea_n) = Fc.index;
  Sim.Fc_DynArea(2,Fc_DynArea_n) = Sim.Dyn;
  Fc_DynArea_n = Fc_DynArea_n + 1;
  Sim.Dyn = Sim.Dyn + 1;
end
% Length / Friction Length
if isscalar(Fc.data.Dist)
  Sim.Fc_Dist(Fc.index) = Fc.data.Dist;
else
  Sim.Dynamic(Sim.Dyn,:) = Fc.data.Dist;
  Sim.Fc_DynDist(1,Fc_DynDist_n) = Fc.index;
  Sim.Fc_DynDist(2,Fc_DynDist_n) = Sim.Dyn;
  Fc_DynDist_n = Fc_DynDist_n + 1;
  Sim.Dyn = Sim.Dyn + 1;
end
if isscalar(Fc.data.Cond_Dist)
  Sim.Fc_Cond_Dist(Fc.index) = Fc.data.Cond_Dist;
else
  Sim.Dynamic(Sim.Dyn,:) = Fc.data.Cond_Dist;
  Sim.Fc_DynCond_Dist(1,Fc_DynCond_Dist_n) = Fc.index;
  Sim.Fc_DynCond_Dist(2,Fc_DynCond_Dist_n) = Sim.Dyn;
  Fc_DynCond_Dist_n = Fc_DynCond_Dist_n + 1;
```

```
        Sim.Dyn = Sim.Dyn + 1;
      end
      if isscalar(Fc.data.dx)
        Sim.Fc_dx(Fc.index) = Fc.data.dx;
      else
        Sim.Dynamic(Sim.Dyn,:) = Fc.data.dx;
        Sim.Fc_Dyndx(1,Fc_Dyndx_n) = Fc.index;
        Sim.Fc_Dyndx(2,Fc_Dyndx_n) = Sim.Dyn;
        Fc_Dyndx_n = Fc_Dyndx_n + 1;
        Sim.Dyn = Sim.Dyn + 1;
      end
      % Hydraulic Diameter
      if isscalar(Fc.data.Dh)
        Sim.Fc_Dh(Fc.index) = Fc.data.Dh;
      else
        Sim.Dynamic(Sim.Dyn,:) = Fc.data.Dh;
        Sim.Fc_DynDh(1,Fc_DynDh_n) = Fc.index;
        Sim.Fc_DynDh(2,Fc_DynDh_n) = Sim.Dyn;
        Fc_DynDh_n = Fc_DynDh_n + 1;
        Sim.Dyn = Sim.Dyn + 1;
      end
      % Friction Function
      if isfield(Fc.data,'K12') && any(Fc.data.K12 > 0) && any(Fc.data.K21 > 0)
        if isscalar(Fc.data.K12)
          Sim.Fc_K12(Fc.index) = Fc.data.K12;
        else
          Sim.Dynamic(Sim.Dyn,:) = Fc.data.K12;
          Sim.Fc_DynK12(1,Fc_DynK12_n) = Fc.index;
          Sim.Fc_DynK12(2,Fc_DynK12_n) = Sim.Dyn;
          Fc_DynK12_n = Fc_DynK12_n + 1;
          Sim.Dyn = Sim.Dyn + 1;
        end
        if isscalar(Fc.data.K21)
          Sim.Fc_K21(Fc.index) = Fc.data.K21;
        else
          Sim.Dynamic(Sim.Dyn,:) = Fc.data.K21;
          Sim.Fc_DynK21(1,Fc_DynK21_n) = Fc.index;
          Sim.Fc_DynK21(2,Fc_DynK21_n) = Sim.Dyn;
          Fc_DynK21_n = Fc_DynK21_n + 1;
          Sim.Dyn = Sim.Dyn + 1;
        end
      else
        Sim.Fc_fFunc_l{Fc.index} = Fc.data.fFunc_l;
        Sim.Fc_fFunc_t{Fc.index} = Fc.data.fFunc_t;
      end
      % Mixing Function
      Sim.Fc_NkFunc_l{Fc.index} = Fc.data.NkFunc_l;
      Sim.Fc_NkFunc_t{Fc.index} = Fc.data.NkFunc_t;
      % Shear Speed Factor
      if isfield(Fc.data,'S')
        Sim.Dynamic(Sim.Dyn,:) = Fc.data.S;
        Sim.Fc_DynShear_Factor(1,Fc_DynShear_Factor_n) = Fc.index;
        Sim.Fc_DynShear_Factor(2,Fc_DynShear_Factor_n) = Sim.Dyn;
        Fc_DynShear_Factor_n = Fc_DynShear_Factor_n + 1;
        Sim.Dyn = Sim.Dyn + 1;
      end
      % Face Speed Factor
      if isfield(Fc.data,'V')
        Sim.Dynamic(Sim.Dyn,:) = Fc.data.V;
        Sim.Fc_DynVel_Factor(1,Fc_DynVel_Factor_n) = Fc.index;
        Sim.Fc_DynVel_Factor(2,Fc_DynVel_Factor_n) = Sim.Dyn;
        Fc_DynVel_Factor_n = Fc_DynVel_Factor_n + 1;
        Sim.Dyn = Sim.Dyn + 1;
      end
    case enumFType.Leak % Gas-Gas Leaks
      % Do nothing, this is handled elsewhere
  end
end

Sim.Dynamic = Sim.Dynamic';
```

```
%% Creating Face - Use Turbulence
progressbar('Creating Face - Use Turbulence');

L = G_count_backup_faces + 1;
for Fc = this.Faces
  if Fc.index < L
    % Don't use turbulence if
    % Matrix exist in either connected node
    % Either Node is variable volume
    for Nd = Fc.Nodes
      if ~Sim.Fc_K12(Fc.index)
        if Sim.isDynVol(Nd.index)
          Sim.useTurbulenceFc(Fc.index) = false;
          break;
        end
        if isa(Nd.Body,'Body')
          if ~isempty(Nd.Body.Matrix)
            Sim.useTurbulenceFc(Fc.index) = false;
            break;
          end
        else
          Sim.useTurbulenceFc(Fc.index) = false;
          break;
        end
      end
    end
  end
end

%% Defining Max Time Step
progressbar('Defining Max Time Step');

BoundaryNodes = [];
NGas = length(Sim.P);
NGas = NGas - 1;
NSolid = length(Sim.T) - NGas;
MixFcs = cell(NSolid,1);
ACond = zeros(NSolid,NSolid);
bCond = zeros(NSolid,1);

for nd = this.Nodes
  if nd.Type == enumNType.SN
    if (isfield(nd.data,'matl') && nd.data.matl.dT_du < 0) || ...
        nd.Body.matl.dT_du < 0
      % Do not give these any sort of special privileges as they are
      % ... no different than an environment node.
      continue;
    end
    added = false;
    for fc = nd.Faces
      if fc.Type == enumFType.Mix
        if ~added
          added = true;
          BoundaryNodes(length(BoundaryNodes)+1,1) = nd.index - NGas;
        end
        MixFcs{nd.index - NGas} = [MixFcs{nd.index - NGas} fc.index];
      end
    end
  end
end

fprintf(['Number of Solid Nodes + 1 Env node: ' num2str(NSolid) '\n']);

for nd = this.Nodes
  if nd.index > NGas
    row = nd.index-NGas;
    if nd.Type == enumNType.SN
      if (isfield(nd.data,'matl') && nd.data.matl.dT_du < 0) || ...
          nd.Body.matl.dT_du < 0
        ACond(row,row) = 1;
        bCond(row) = nd.data.T;
```

```
      else
        for fc = nd.Faces
          if fc.Type ~= enumFType.Mix
            avgCond = mean(fc.data.U);
            if fc.Nodes(1) == nd
              col = fc.Nodes(2).index - NGas;
            else
              col = fc.Nodes(1).index - NGas;
            end
            ACond(row, row) = ACond(row, row) + avgCond;
            ACond(row, col) = ACond(row, col) - avgCond;
          end
        end
      end
    else
      if nd.Type == enumNType.EN
        ACond(row,row) = 1;
        bCond(row) = nd.Body.Temperature;
      else
        fprintf(['XXX Undefined node type during ACond and bCond ' ...
          'pre-calculation XXX/n']);
      end
    end
  end
end

Sim.ACond = ACond;
Sim.bCond = bCond;
Sim.CondEff = zeros(M_count_backup_faces,1);
Sim.CondTempEff = zeros(M_count_backup_faces,1);
Sim.BoundaryNodes = BoundaryNodes';
Sim.MixFcs = MixFcs;
Sim.CycleTime = 0;

a = 1000;
Sim.Solid_dt_max = a(ones(1,Frame.NTheta));
Sim.Nd_Solid_dt = a(ones(size(Sim.T)));
for fc = this.Faces
  if ~IsApprox(fc.index)
    if fc.Type == enumFType.Solid
      for nd = fc.Nodes
        if isfield(nd.data,'matl'); matl = nd.data.matl;
        else; matl = nd.Body.matl;
        end
        if isa(nd.Body,'Body')
          if matl.dT_du > 0
            timesteps = (this.MaxFourierNumber*nd.vol()*matl.Density/...
              matl.dT_du)./fc.data.U;
            if length(timesteps) == 1
              Sim.Solid_dt_max(Sim.Solid_dt_max > timesteps) = timesteps;
            else
              if iscolumn(timesteps)
                timesteps = timesteps';
              end
              Sim.Solid_dt_max = min([Sim.Solid_dt_max; timesteps]);
            end
            Sim.Nd_Solid_dt(nd.index) = min(Sim.Nd_Solid_dt(nd.index), min(timesteps));
          end
        end
      end
    end
  end
end

%% Defining Conduction/Transport Network
progressbar('Defining Conduction/Transport Network');

% SolidNds
% Sim.Cond_Nds = all nodes except the environment, which is
% ... automatically excluded
Sim.Cond_Nds = [1:G_count_backup E_count_backup+1:S_count_backup];
```

```
%Sim.Cond_Fcs = Sim.Solid_Fc;
Sim.Cond_Fcs = 1:length(this.Faces);
Sim.Cond_Fcs(IsApprox) = []; % Remove faces that are approximated by a different method.
Nds1 = Sim.Fc_Nd(Sim.Cond_Fcs,1);
Nds2 = Sim.Fc_Nd(Sim.Cond_Fcs,2);
Sim.Cond_Nds1 = Nds1;
Sim.Cond_Nds2 = Nds2;
Nds1(Sim.dT_dU(Nds1)<0) = 0;
Nds2(Sim.dT_dU(Nds2)<0) = 0;
% Determine set of element sets with sign
i = 1;
% Node 1's
if any(Nds1~=0); N1 = mode(Nds1(Nds1~=0)); N1 = sum(Nds1(:)==N1);
else; N1 = 0; end
if any(Nds2~=0); N2 = mode(Nds2(Nds2~=0)); N2 = sum(Nds2(:)==N2);
else; N2 = 0; end
Temp = cell(1,3*(N1+N2));
if N1 ~= 0
  % First element = sign
  % Second element = nodes
  % Third element = faces
  for k = 1:N1
    % Q is flow into Node 1
    N = length(unique(Nds1(Nds1>0)));
    Temp{i} = -1;
    Temp{i+1} = zeros(1,N);
    Temp{i+2} = zeros(1,N);
    el = 1;
    for x = 1:length(Nds1)
      if Nds1(x) > 0
        if ~any(Temp{i+1}(1:el-1) == Nds1(x))
          Temp{i+1}(el) = Nds1(x);
          Temp{i+2}(el) = x; % index with respect to Fc_Cond
          Nds1(x) = 0;
          el = el + 1;
        end
      end
    end
    i = i + 3;
  end
end
% Node 2's
if N2 ~= 0
  % First element = sign
  % Second element = nodes
  % Third element = faces
  for k = 1:N2
    % Q is flow into Node 1
    N = length(unique(Nds2(Nds2>0)));
    Temp{i} = 1;
    Temp{i+1} = zeros(1,N);
    Temp{i+2} = zeros(1,N);
    el = 1;
    for x = 1:length(Nds2)
      if Nds2(x) > 0
        if ~any(Temp{i+1}(1:el-1) == Nds2(x))
          Temp{i+1}(el) = Nds2(x);
          Temp{i+2}(el) = x; % index with respect to Fc_Cond
          Nds2(x) = 0;
          el = el + 1;
        end
      end
    end
    i = i + 3;
  end
end
Sim.CondNet = Temp;

% GasNds
Sim.Trans_Fcs = 1:length(Sim.Fc_U);
Nds1 = Sim.Fc_Nd(Sim.Trans_Fcs,1);
```

```
Nds2 = Sim.Fc_Nd(Sim.Trans_Fcs,2);
Nds1(Sim.dT_dU(Nds1)==0) = 0;
Nds2(Sim.dT_dU(Nds2)==0) = 0;
% Determine the set of element sets with sign
i = 1;
% Node 1's
if any(Nds1~=0); N1 = mode(Nds1(Nds1~=0)); N1 = sum(Nds1(:)==N1);
else; N1 = 0; end
if any(Nds2~=0); N2 = mode(Nds2(Nds2~=0)); N2 = sum(Nds2(:)==N2);
else; N2 = 0; end
Temp = cell(1,3*(N1+N2));
if N1 ~= 0
  Excluded = false(1,length(Nds1)); Excluded(Nds1==0) = true;
  % First element = sign
  % Second element = nodes
  % Third element = faces
  for k = 1:N1
    % Q is flow into Node 1
    N = length(unique(Nds1(~Excluded)));
    Temp{i} = -1;
    Temp{i+1} = zeros(1,N);
    Temp{i+2} = zeros(1,N);
    el = 1;
    for x = 1:length(Nds1)
      if ~Excluded(x) && ~any(Temp{i+1}(1:el-1) == Nds1(x))
        Temp{i+1}(el) = Nds1(x); % Target Node
        Temp{i+2}(el) = x; % index with respect to Fc_Cond
        Excluded(x) = true;
        el = el + 1;
      end
    end
    i = i + 3;
  end
end
% Node 2's
if N2 ~= 0
  Excluded = false(1,length(Nds2)); Excluded(Nds2==0) = true;
  % First element = sign
  % Second element = nodes
  % Third element = faces
  for k = 1:N2
    % Q is flow into Node 1
    N = length(unique(Nds2(~Excluded)));
    Temp{i} = 1;
    Temp{i+1} = zeros(1,N);
    Temp{i+2} = zeros(1,N);
    el = 1;
    for x = 1:length(Nds2)
      if ~Excluded(x) && ~any(Temp{i+1}(1:el-1) == Nds2(x))
        Temp{i+1}(el) = Nds2(x);
        Temp{i+2}(el) = x; % index with respect to Fc_Cond
        Excluded(x) = true;
        el = el + 1;
      end
    end
    i = i + 3;
  end
end
Sim.TransNet = Temp;

%% Creating Lookup Tables, Regions and Loops For Solver
progressbar('Creating Regions and Loops For Solver');

%% Group functions
% Laminar Nusselt
novel = true(size(Sim.P));
novel(end) = [];
nodes = zeros(size(Sim.P));
Sim.NuFunc_l_el = cell(0);
x = 1;
for i = 1:length(Sim.P)-2
```

```
  if novel(i)
    func = Sim.NuFunc_l{i}; k = 1; nodes(k) = i;
    for j = i+1:length(Sim.P)-1
      if novel(j)
        if nargin(func) == nargin(Sim.NuFunc_l{j})
          if nargin(func) == 1
            x1 = rand(1);
            if func(x1) == Sim.NuFunc_l{j}(x1)
              k = k + 1; nodes(k) = j; novel(j) = false;
            end
          else
            x1 = rand(1); x2 = rand(1);
            if func(x1,x2) == Sim.NuFunc_l{j}(x1,x2)
              k = k + 1; nodes(k) = j; novel(j) = false;
            end
          end
        end
      end
    end
    Sim.NuFunc_l_el{x} = nodes(1:k);
    x = x + 1;
  end
end
if novel(end); Sim.NuFunc_l_el{x} = length(novel); end
Sim.NuFunc_l(~novel) = [];

% Turbulent Nusselt
novel(:) = true;
nodes = zeros(size(Sim.P));
Sim.NuFunc_t_el = cell(0);
x = 1;
for i = 1:length(Sim.P)-2
  if novel(i)
    func = Sim.NuFunc_t{i}; k = 1; nodes(k) = i;
    for j = i+1:length(Sim.P)-1
      if novel(j)
        if nargin(func) == nargin(Sim.NuFunc_t{j})
          if nargin(func) == 1
            x1 = rand(1);
            if func(x1) == Sim.NuFunc_t{j}(x1)
              k = k + 1; nodes(k) = j; novel(j) = false;
            end
          else
            x1 = rand(1); x2 = rand(1);
            if func(x1,x2) == Sim.NuFunc_t{j}(x1,x2)
              k = k + 1; nodes(k) = j; novel(j) = false;
            end
          end
        end
      end
    end
    Sim.NuFunc_t_el{x} = nodes(1:k);
    x = x + 1;
  end
end
if novel(end); Sim.NuFunc_t_el{x} = length(novel); end
Sim.NuFunc_t(~novel) = [];

% Laminar Conduction
novel = true(size(Sim.Fc_U));
nodes = zeros(size(Sim.Fc_U));
Sim.Fc_NkFunc_l_el = cell(0);
x = 1;
if ~isempty(novel)
  for i = 1:length(Sim.Fc_U)-1
    if novel(i)
      func = Sim.Fc_NkFunc_l{i}; k = 1; nodes(k) = i;
      for j = i+1:length(Sim.Fc_U)
        if novel(j)
          if nargin(func) == nargin(Sim.Fc_NkFunc_l{j})
            if nargin(func) == 1
```

```
            x1 = rand(1);
            if func(x1) == Sim.Fc_NkFunc_l{j}(x1)
              k = k + 1; nodes(k) = j; novel(j) = false;
            end
          else
            x1 = rand(1); x2 = rand(1);
            if func(x1,x2) == Sim.Fc_NkFunc_l{j}(x1,x2)
              k = k + 1; nodes(k) = j; novel(j) = false;
            end
          end
        end
      end
      Sim.Fc_NkFunc_l_el{x} = nodes(1:k);
      x = x + 1;
    end
  end
  if novel(end); Sim.Fc_NkFunc_l_el{x} = length(novel); end
  Sim.Fc_NkFunc_l(~novel) = [];
end

% Turbulent Conduction
novel(:) = true;
nodes = zeros(size(Sim.Fc_U));
Sim.Fc_NkFunc_t_el = cell(0);
x = 1;
if ~isempty(novel)
  for i = 1:length(Sim.Fc_U)-1
    if novel(i)
      func = Sim.Fc_NkFunc_t{i}; k = 1; nodes(k) = i;
      for j = i+1:length(Sim.Fc_U)
        if novel(j)
          if nargin(func) == nargin(Sim.Fc_NkFunc_t{j})
            if nargin(func) == 1
              x1 = rand(1);
              if func(x1) == Sim.Fc_NkFunc_t{j}(x1)
                k = k + 1; nodes(k) = j; novel(j) = false;
              end
            else
              x1 = rand(1); x2 = rand(1);
              if func(x1,x2) == Sim.Fc_NkFunc_t{j}(x1,x2)
                k = k + 1; nodes(k) = j; novel(j) = false;
              end
            end
          end
        end
      end
      Sim.Fc_NkFunc_t_el{x} = nodes(1:k);
      x = x + 1;
    end
  end
  if novel(end); Sim.Fc_NkFunc_t_el{x} = length(novel); end
  Sim.Fc_NkFunc_t(~novel) = [];
end

% region now represents how the engine is divided up
regions = cell(region_count,1);
isEnvironmentRegion = false(region_count,1);
isEnvironmentRegion(region(end)) = true;
loop_ind_cell = cell(region_count,1);
loops_cell = cell(region_count,1);
regionFcCount = zeros(region_count,1);
regionFcs = cell(region_count,1);
Sim.ActiveRegionFcs = cell(region_count,1);
Sim.A_Press = cell(region_count,1);

for i = 1:region_count
  % loop_ind = [ start end condition ]
  %            [ ...   ... ind or 0  ]
  loop_ind_cell{i} = zeros(3,0);
  % loops = [nd1, fc12, sign]
```

```
  loops_cell{i} = zeros(3,0);
end
% Make a list of nodes that are under this region
for i = 1:region_count
  c = 1;
  regions{i} = zeros(length(region),1);
  for k = 1:length(region)-1
    if region(k) == i; regions{i}(c) = k; c = c + 1; end
  end
  if isEnvironmentRegion(i)
    regions{i}(c) = length(region);
    c = c + 1;
  end
  if c <= length(region); regions{i}(c:end) = []; end
end

% Take a count of faces that are under this region
% ... This will tell us how many loops we need to define
% ... May not be necassary

%       extfc = cell(n,2);
for Fc = this.Faces
  if isfield(Fc.data,'dx')
    if region(Fc.Nodes(1).index) == region(Fc.Nodes(2).index)
      r = region(Fc.Nodes(1).index);
      regionFcCount(r) = regionFcCount(r) + 1;
      regionFcs{r}(end+1) = Fc.index;
    end
  end
end
%       Sim.extfc = extfc;

% Find Loops in each region
LEN = length(Sim.Fc_U);
% Make visited/closed any string who goes to a dead end
Closed_Edge = TrimFaces(this,region,false(LEN,1));

% What is left is all the nodes that could possibly be a part of a
% ... loop.
% Create Loops using the available faces and nodes
open = LoopNode.empty;
for i = 1:region_count
  lequ = 1;
  lcount = 0;
  %         TimesVisited = zeros(length(Sim.Fc_dx),1);
  % Find the edges that close during the cycle. These are classified
  % ... as holes.
  holes = Face.empty;
  for Fc = this.Faces
    if Fc.index <= LEN && ...
        region(Fc.Nodes(1).index) == i && ...
        region(Fc.Nodes(2).index) == i && ...
        any(Fc.data.Area == 0)
      % This is a node that is transient, used to trim loops
      holes(end+1) = Fc;
      Closed_Edge(Fc.index) = true;
    end
  end

  % We have defined all the "holes", the first n loops will be
  % ... dedicated to covering those holes.
  % NIndependent_Equations = # of Nodes - 1
  % N loops = Unknowns - NIndependent_Equations - Environment_Node
  % Nloops = (regionFcCount(i)-length(regions{i})+1-isEnvironmentRegion(i));
  for k = 1:(regionFcCount(i)-length(regions{i})+1)
    Vis_Edge = Closed_Edge;
    % Get a starting Point
    if k <= length(holes)
      % Find loops that cover these holes
      Fc = holes(k);
    else
```

```
  % Find open edges, and find loops that cover them
  found = false;
  for Fc = this.Faces
    if Fc.index <= LEN && ~Closed_Edge(Fc.index) && ...
        region(Fc.Nodes(1).index) == i  && ...
        region(Fc.Nodes(2).index) == i
      found = true; break;
    end
  end
  if ~found
    fprintf('XXX No valid Loop Starting Point! XXX\n'); return;
  end
  Closed_Edge(Fc.index) = true; Vis_Edge(Fc.index) = true;
end
closed = LoopNode(LoopNode.empty, Face.empty, Fc.Nodes(1));
target = Fc.Nodes(1);
open = LoopNode(closed(1), Fc, Fc.Nodes(2));
% EdgeClosed = Fc;

% Use open as a starting point and path to the closed
% ... "target" is the end node
% ... Do not path though Closed_Edge's
done = false;
while ~(isempty(open) || done)
  len = length(open);
  for x = len:-1:1
    % Expand it
    LpNd = open(x);
    for Fc = LpNd.Nd.Faces
      if Fc.index <= length(Vis_Edge) && ...
          region(Fc.Nodes(1).index) == i && ...
          region(Fc.Nodes(2).index) == i && ...
          ~Vis_Edge(Fc.index)
        Vis_Edge(Fc.index) = true;
        % Add it to the open list
        if Fc.Nodes(1) == LpNd.Nd; newNd = Fc.Nodes(2);
        else; newNd = Fc.Nodes(1); end
        if newNd == target
          done = true;
          closed(end+1) = LoopNode(LpNd,Fc,newNd);
          break;
        else
          open(end+1) = LoopNode(LpNd,Fc,newNd);
        end
      end
    end
    if done; break; end
  end
  if ~done; open = open(len+1:end); end
end

% The loop should of reached its target.
if done
  % Backtrace the loop
  current = closed(end);
  lcount = lcount + 1;
  loop_ind_cell{i}(1,lcount) = lequ;
  while ~isempty(current.parent)
    loops_cell{i}(1,lequ) = current.Nd.index;
    loops_cell{i}(2,lequ) = current.parentFc.index;
    if current.parentFc.Nodes(1) == current.Nd
      loops_cell{i}(3,lequ) = 1;
    else
      loops_cell{i}(3,lequ) = -1;
    end
    lequ = lequ + 1;
    current = current.parent;
  end
  loop_ind_cell{i}(2,lcount) = lequ - 1;
  % closed(end) is the start node
  % Determine if the loop has a condition
```

```
      if k <= length(holes)
        % This one is connected to the area state of holes(k)
        loop_ind_cell{i}(3,lcount) = holes(k).index;
      else
        % This one is unnconnected to a hole
        loop_ind_cell{i}(3,lcount) = 0;
      end

      % Close all edges that run into the "EdgeClosed"
      if k >= length(holes)
        Closed_Edge = TrimFaces(this, region, Closed_Edge);
      end

    else
      fprintf(['XXX Failed to complete a loop. Loop: ' num2str(k) ' XXX\n']);
    end
  end

end

% Find ActiveFaces
Vis_Node = false(length(region),1);
for i = 1:region_count
  k = 0;
  Temp = zeros(regionFcCount(i),1);
  for Nd = this.Nodes
    if Nd.index <= length(region) && ...
        ~Vis_Node(Nd.index) && ...
        region(Nd.index) == i
      [k,Temp,Vis_Node] = PropegateActiveFaces(Nd,Vis_Node,k,Temp);
      break;
    end
  end
  Temp(k+1:end) = [];
  Sim.ActiveRegionFcs{i} = Temp;
end

% Find A-PressureLoss
for i = 1:region_count
  Sim.A_Press{i} = zeros(length(regions{i}));
  for x = 1:length(Sim.ActiveRegionFcs{i})
    Fc = Sim.ActiveRegionFcs{i}(x);
    % n1 = +ve;
    % n2 = -ve;
    temp = Sim.Fc_Nd(Fc,1);
    for k = 1:length(regions{i})
      if temp == regions{i}(k)
        Sim.A_Press{i}(x,k) = 1;
        break;
      end
    end
    temp = Sim.Fc_Nd(Fc,2);
    for k = 1:length(regions{i})
      if temp == regions{i}(k)
        Sim.A_Press{i}(x,k) = -1;
        break;
      end
    end
  end
end

% Calculate what the gas constant would be
% We have Rs
for i = 1:region_count
  if isEnvironmentRegion(i)
    Sim.R(i) = Rs(end);
  else
    % Pick the most common
    Sim.R(i) = mode(Rs(regions{i}));
  end
  for j = regions{i}
```

```
    if Rs(j) ~= Sim.R(i)
      fprintf(['XXX Node in region ' num2str(i) ...
        ' found that had a different gas than the bulk. XXX\n']);
      fprintf(['XXX ... Region is of size: ' ...
        num2str(length(regions{i})) '. XXX\n']);
    end
  end
end
Sim.Rs = Rs;

% loops_cell
% loop_ind_cell
% regions (cell array containing all nodes separated by a region)
Sim.Regions = regions;
Sim.isEnvironmentRegion = isEnvironmentRegion;

Sim.RegionFcs = regionFcs;
for i = 1:length(regionFcs)
  Sim.Fc2Col(regionFcs{i}(:)) = 1:length(regionFcs{i});
end
Sim.RegionFcCount = regionFcCount;
Sim.RegionLoops = loops_cell;
Sim.RegionLoops_Ind = loop_ind_cell;
for list = loop_ind_cell
  count = count + size(list{1},2);
end
fprintf(['Found ' num2str(count) ' loops. \n']);

% Collapse F2C for the limited set
%   Sim.isLoopRegionFcs = cell(size(Sim.RegionFcs));
%   Sim.Fc2Col_loop = zeros(size(Sim.Fc_V));
%   for i = 1:region_count
%     if ~isempty(Sim.RegionLoops{i})
%       Sim.isLoopRegionFcs{i} = false(size(Sim.RegionFcs{i}));
%       for x = 1:size(Sim.RegionLoops{i},2)
%         Sim.isLoopRegionFcs{i}(Sim.RegionLoops{i}(2,x)) = true;
%       end
%     end
%   end

Sim.Faces = cell(length(Sim.Dh),1);

% Define "Sim.Faces"
for Nd = this.Nodes
  if Nd.index <= length(Sim.Dh)
    Fcs = Face.empty;
    % It is a gas node
    % ... Get list of gas faces for this node
    for Fc = Nd.Faces
      if isfield(Fc.data,'dx')
        Fcs(end+1) = Fc;
      end
    end
    if ~isempty(Fcs)
      % This node has many gas faces
      Sim.Faces{Nd.index} = zeros(length(Fcs),3);
      for i = 1:length(Fcs)
        if Fcs(i).Nodes(1) == Nd
          dir = -1;
        else
          dir = 1;
        end
        Sim.Faces{Nd.index}(i,:) = [Fcs(i).index dir...
          region(Fcs(i).Nodes(1).index) ~= region(Fcs(i).Nodes(2).index)];
      end
    else
      Sim.Faces{Nd.index} = zeros(0,3);
    end
  end
end
```

```
      % So we have faces, which has an entry for each node
      % ... List of Face Indexes
      % ... List of BValues
      % ... List of signs (-1 for outlet, 1 for inlet)
      % ... List of 0 = implicit, 1 = explicit

      % Need to make a list of implicit velocities that need to be
      % ... calculated, use region pressure
      Sim.ExplicitLeak = zeros(0,5);
      Sim.ExplicitNorm = zeros(0,3);
      for Fc = this.Faces
        if isfield(Fc.data,'dx')
          if region(Fc.Nodes(1).index) ~= region(Fc.Nodes(2).index)
            % Add to list
            if Fc.Type == enumFType.Leak
              % FAVAD equation
              % ... V = C * (dP) ^ N
              Sim.ExplicitLeak = [Sim.ExplicitLeak; [Fc.index Fc.data.C Fc.data.N
region(Fc.Nodes(1).index) region(Fc.Nodes(2).index)]];
            else
              Sim.ExplicitNorm = [Sim.ExplicitNorm; [Fc.index region(Fc.Nodes(1).index)
region(Fc.Nodes(2).index)]];
            end
          end
        end
      end

      % Flow Network
      % NEED EXTERNAL FACES TO BE LABELLED
      % ... explicit faces
      % ... ... Between regions, sources, sinks, leaks.. etc
      % ... ... Used on region scale for mass change
      % ... ... Used on local scale
      % ... implicit faces
      % ... ... Internal to region,
      % NEED FACES AND NODES ORGANIZED BY REGION

      %% Pressure/Shear Contacts, Sensors, PVoutputs
      progressbar('Pressure/Shear Contacts, Sensors, PVoutputs');

      % Pressure Contacts
      PC_n = 1;
      for PC = this.PressureContacts
        addto = true;
        for i = 1:PC_n-1
          if PC.GasNode == Sim.Press_Contact(3,i) && ...
              PC.Area == Sim.Press_Contact(2,i) && ...
              PC.MechanismIndex == Sim.Press_Contact(1,i)
            addto = false;
          end
        end
        if addto
          Sim.Press_Contact(1,PC_n) = PC.ConverterIndex;
          Sim.Press_Contact(2,PC_n) = PC.MechanismIndex;
          Sim.Press_Contact(3,PC_n) = PC.Area;
          Sim.Press_Contact(4,PC_n) = PC.GasNode.index;
          PC_n = PC_n + 1;
        end
      end
      this.PressureContacts = PressureContact.empty;

      % Shear Contacts
      SC_n = 1;
      SC_Active_n = 1;
      for SC = this.ShearContacts
        addto = true;
        for i = 1:SC_n-1
          if SC.UpperNode.index == Sim.Shear_Contact(4,i) && ...
              SC.LowerNode.index == Sim.Shear_Contact(3,i) && ...
              SC.Area == Sim.Shear_Contact(2,i) && ...
              SC.MechanismIndex == Sim.Shear_Contact(1,i)
```

```
      addto = false;
    end
  end
  if addto
    if any(SC.ActiveTimes)
      Sim.Shear_Contact(1,SC_n) = SC.ConverterIndex;
      Sim.Shear_Contact(2,SC_n) = SC.MechanismIndex;
      Sim.Shear_Contact(3,SC_n) = SC.Area;
      Sim.Shear_Contact(4,SC_n) = SC.LowerNode.index;
      Sim.Shear_Contact(5,SC_n) = SC.UpperNode.index;
      Sim.Shear_Contact(6,SC_n) = 1;
      if ~all(SC.ActiveTimes)
        if size(SC.ActiveTimes,2) ~= 1
          SC.ActiveTimes = SC.ActiveTimes';
        end
        Sim.Dynamic(:,Sim.Dyn) = SC.ActiveTimes;
        Sim.SC_Active(1,SC_Active_n) = SC_n;
        Sim.SC_Active(2,SC_Active_n) = Sim.Dyn;
        SC_Active_n = SC_Active_n + 1;
        Sim.Dyn = Sim.Dyn + 1;
      end
      SC_n = SC_n + 1;
    end
  end
end
this.ShearContacts = ShearContact.empty;

% Sensors
for i = length(this.Sensors):-1:1
  if ~isValid(this.Sensors(i))
    len = length(this.Sensors);
    this.Sensors(i).deReference()
    if len == length(this.Sensors)
      this.Sensors(i) = [];
    end
  end
end
if ~isempty(this.Sensors)
  for iSense = this.Sensors
    iSense.update();
  end
end
if ~isempty(this.PVoutputs)
  for iPVoutput = this.PVoutputs; iPVoutput.update(region); end
end
Sim.PRegion = zeros(length(Sim.Regions),1);
Sim.PRegionTime = 0;

progressbar(12/13);
progressbar('Defining Area for Turbulence');

% Node Faces For Turbulent Decay and Generation
Len = 1 + size(Sim.Area,2);
for Nd = this.Nodes
  if Nd.index < Len
    if Nd.Body.divides(1) > Nd.Body.divides(2)
      % It is divides along by cylindrical shells
      % Look for two dynamic Dh faces that have the same motion
      % ... Pattern

      % 1 and 2 dynamic face pairs within body
      if (~isscalar(Nd.ymax) || ~isscalar(Nd.ymin)) && ...
          ~all(Nd.ymax-Nd.ymin == Nd.ymax(1)-Nd.ymin(1))
        startindex = 1;
        count = 0;
        while startindex ~= 0 && startindex <= length(Nd.Faces)
          Pattern = 0;
          oldstartindex = startindex;
          startindex = 1;
          i = 0;
          for Fc = Nd.Faces(startindex:end)
```

```
      i = i + 1;
      if Fc.Type ~= enumFType.Mix
        if ~isscalar(Fc.data.Dh) && isempty(Fc.Connection)
          count = count + 1;
          if ~any(Pattern)
            Pattern = Fc.data.Dh;
            startindex = i;
          else
            temp = Pattern./Fc.data.Dh;
            if all(temp == temp(1))
              % Simply take the average of the faces
              Sim.Area(1,Nd.index) = Fc.index;
              Sim.Area(2,Nd.index) = (temp(1)+1)/2;
              startindex = 0;
              break;
            end
          end
        end
      end
    end
    if oldstartindex == startindex
      startindex = 0;
    elseif startindex ~= 0
      startindex = startindex + 1;
    end
  end
  if count == 1
    % There is only one non-Connection Face
    for Fc = Nd.Faces
      if Fc.Type ~= enumFType.Mix && ~isscalar(Fc.data.Dh) && isempty(Fc.Connection)
        if all(temp == temp(1))
          % Simply take the average of the faces
          Sim.Area(1,Nd.index) = Fc.index;
          Sim.Area(2,Nd.index) = 1;
          break;
        end
      end
    end
  end
end

% 1 and 2 static face pairs within body
if ~Sim.Area(2,Nd.index)
  % No two faces were found
  % Find a face that is static and not a connection
  count = 0;
  for Fc = Nd.Faces
    if Fc.Type ~= enumFType.Mix
      if isscalar(Fc.data.Dh) && isempty(Fc.Connection)
        count = count + 1;
      end
    end
  end
  if count == 2
    for Fc = Nd.Faces
      if Fc.Type ~= enumFType.Mix
        if isscalar(Fc.data.Area) && isempty(Fc.Connection)
          Sim.Area(2,Nd.index) = Sim.Area(2,Nd.index) + 0.5*Fc.data.Area;
        end
      end
    end
  end
  if count == 1
    for Fc = Nd.Faces
      if Fc.Type ~= enumFType.Mix
        if isscalar(Fc.data.Area) && isempty(Fc.Connection)
          Sim.Area(2,Nd.index) = Sim.Area(2,Nd.index) + Fc.data.Area;
        end
      end
    end
  end
```

```
      end

      %
      if ~Sim.Area(2,Nd.index)
        fprintf('XXX Deficiency in Node Face Calculation in Model XXX');
      end
    else
      % It is divided by horizontal planes or not divided,
      % ... simply take the radius of the shape
      Sim.Area(1,Nd.index) = 0;
      Sim.Area(2,Nd.index) = pi*Nd.xmax^2;
    end
  end
end

if isempty(this.MechanicalSystem)
  Sim.MechanicalSystem = ...
    MechanicalSystem(this,this.Converters,[],...
    1,function_handle.empty);
else
  Sim.MechanicalSystem = ...
    MechanicalSystem(this,this.Converters,[],...
    this.MechanicalSystem.Inertia,this.MechanicalSystem.LoadFunction);
end

%% Defining Energy Statistics Handlers
progressbar('Defining Energy Statistics Handlers');

% Statistics
% Find all Solid Faces that go to the Environment
Sim.ToEnvironmentSolid = zeros(2,length(this.surroundings.Node.Faces));
Sim.ToEnvironmentGas = zeros(2,length(this.surroundings.Node.Faces));
nS = 1; nG = 1;
for Fc = this.surroundings.Node.Faces
  if Fc.Nodes(1).Type == enumNType.SN
    % It is a solid-envionment face
    Sim.ToEnvironmentSolid(1,nS) = Fc.index;
    Sim.ToEnvironmentSolid(2,nS) = -1;
    nS = nS + 1;
  elseif Fc.Nodes(2).Type == enumNType.SN
    % It is a solid-envionment face
    Sim.ToEnvironmentSolid(1,nS) = Fc.index;
    Sim.ToEnvironmentSolid(2,nS) = 1;
    nS = nS + 1;
  elseif Fc.Nodes(1).Type == enumNType.EN
    % It is a gas-envionment face
    Sim.ToEnvironmentGas(1,nG) = Fc.index;
    Sim.ToEnvironmentGas(2,nG) = 1;
    nG = nG + 1;
  else
    % It is a gas-envionment face
    Sim.ToEnvironmentGas(1,nG) = Fc.index;
    Sim.ToEnvironmentGas(2,nG) = -1;
    nG = nG + 1;
  end
end
Sim.ToEnvironmentSolid = Sim.ToEnvironmentSolid(:,1:nS-1);
Sim.ToEnvironmentGas = Sim.ToEnvironmentGas(:,1:nG-1);

% Find all Faces that go to a Source
isToSourceOrSink = false(1, length(this.Faces));
isSourceOrSink = false(1, length(this.Nodes));
for Nd = this.Nodes
  if Nd.Type == enumNType.SN && ...
      (strcmp(Nd.Body.matl.name, 'Constant Temperature') || (...
      isfield(Nd.data,'matl') && ...
      strcmp(Nd.data.matl.name, 'Constant Temperature')) ...
      )
    isSourceOrSink(Nd.index) = true;
    for Fc = Nd.Faces
      isToSourceOrSink(Fc.index) = ~isToSourceOrSink(Fc.index);
```

```
    end
  end
end

temp = 1:length(this.Faces);
Subject_Faces = temp(isToSourceOrSink);
temp = 1:length(this.Nodes);
Subject_Nodes = temp(isSourceOrSink);

% Get Average Temperatures
T = mean(Sim.T(isSourceOrSink));
Sim.ToSource = zeros(2,length(this.Faces));
nSr = 1;
Sim.ToSink = zeros(2,length(this.Faces));
nSi = 1;
IsSource = false(1, length(this.Nodes));
if T > this.surroundings.Temperature
  IsSource(Subject_Nodes) = Sim.T(Subject_Nodes) >= T;
else
  IsSource(Subject_Nodes) = Sim.T(Subject_Nodes) > T;
end
for findex = Subject_Faces
  if isSourceOrSink(Sim.Fc_Nd(findex,1))
    if IsSource(Sim.Fc_Nd(findex,1))
      Sim.ToSource(1,nSr) = findex;
      Sim.ToSource(2,nSr) = -1;
      nSr = nSr + 1;
    else
      Sim.ToSink(1,nSi) = findex;
      Sim.ToSink(2,nSi) = -1;
      nSi = nSi + 1;
    end
  else
    if IsSource(Sim.Fc_Nd(findex,2))
      Sim.ToSource(1,nSr) = findex;
      Sim.ToSource(2,nSr) = 1;
      nSr = nSr + 1;
    else
      Sim.ToSink(1,nSi) = findex;
      Sim.ToSink(2,nSi) = 1;
      nSi = nSi + 1;
    end
  end
end
Sim.ToSource = Sim.ToSource(:,1:nSr-1);
Sim.ToSink = Sim.ToSink(:,1:nSi-1);
Sim.Sources = temp(IsSource);
Sim.Sinks = temp(and(isSourceOrSink, ~IsSource));

% identify shearing faces
% All Mixed Faces, All Solid Faces
if ~isempty(Sim.Fc_DynArea)
  ShuttleFaces = Sim.Fc_DynArea(1,:);%[Sim.Fc_DynArea(1,:) Sim.Fc_DynCond(1,:)];
else
  ShuttleFaces = zeros(1,0);
end
if ~isempty(Sim.Fc_DynCond)
  ShuttleFaces = [ShuttleFaces Sim.Fc_DynCond(1,:)];
end
% Exclude Gas Faces
Sim.ShuttleFaces = ShuttleFaces(ShuttleFaces>length(Sim.Fc_U));

% idenfity static faces
% All Mixed Faces, All Solid Faces
% Exclude Gas Faces
Sim.StaticFaces = 1:length(Sim.Fc_Cond);
Sim.StaticFaces(Sim.ShuttleFaces) = [];

Sim.ExergyLossShuttle = 0;
Sim.ExergyLossStatic = 0;
```

```
  this.Simulations = Sim;

  this.isStateDiscretized = true;

  Sim.Fc_K12(isnan(Sim.Fc_K12)) = 1;
  Sim.Fc_K21(isnan(Sim.Fc_K21)) = 1;
  Sim.Dynamic(isnan(Sim.Dynamic)) = 0;

  progressbar(1);
end

function [success] = Run(ME, runs)
  success = false;
  backup_path = ME.outputPath;
  if nargin > 1
    tests = length(runs);
    ME.showLivePV = true;
    ME.showPressureAnimation = true;
    ME.recordPressure = true;
    ME.showTemperatureAnimation = true;
    ME.recordTemperature = true;
    ME.showVelocityAnimation = true;
    ME.recordVelocity = true;
    ME.showTurbulenceAnimation = true;
    ME.recordTurbulence = true;
    ME.showConductionAnimation = true;
    ME.recordConductionFlux = true;
    ME.showPressureDropAnimation = true;
    ME.recordPressureDrop = true;
    ME.recordOnlyLastCycle = true;
    ME.recordStatistics = true;
    for i = 1:length(runs)
      runs(i).isManual = false;
    end
  else
    tests = 1;
    crun = struct(...
      'isManual',true,...
      'Model',ME.name,...
      'title',[ME.name ' Test- ' date], ...
      'NodeFactor',ME.deRefinementFactorInput);
  end
  for Nt = 1:tests
    if nargin > 1
      crun = runs(Nt);
    end
    % If it has a steady state end condition and only the last cycle is
    % ... important then use the Multi-Grid Formulation.
    useTrials = nargin > 1 && crun.SS == true && ME.recordOnlyLastCycle;
    ntrials = 1;

    [status] = mkdir('../Runs',crun.title);
    if status
      ME.outputPath = ['../Runs/' crun.title];
    else
      msgbox(['Please create file: ../Runs/' crun.title])
    end
    for trial = 1:ntrials
      % Only do warmup when starting from scratch
      do_warmup = (Nt == 1 && trial == 1);

      ME.resetDiscretization();

      %% Apply Geometry Modifications
      % Uniform Scale Modification
      if nargin > 1
        if isfield(crun,'Uniform_Scale')
          % Scale the connections
          for iGroup = ME.Groups
            for iCon = iGroup.Connections
              iCon.x = iCon.x*crun.Uniform_Scale;
```

```
      end
      % Scale the positions
      iGroup.Position.x = iGroup.Position.x*crun.Uniform_Scale;
      iGroup.Position.y = iGroup.Position.y*crun.Uniform_Scale;
    end

    % Scale the bridge offsets
    for iBridge = ME.Bridges
      iBridge.x = iBridge.x*crun.Uniform_Scale;
    end

    % Scale the mechanisms
    for iLRM = ME.Converters
      iLRM.Uniform_Scale(crun.Uniform_Scale);
    end

    % Scale the view window
    XL = get(ME.AxisReference, 'XLim');
    YL = get(ME.AxisReference, 'YLim');
    set(ME.AxisReference,'XLim', XL*crun.Uniform_Scale);
    set(ME.AxisReference,'YLim', YL*crun.Uniform_Scale);
  end
end

%% Run
ME.update();

% Discretize according to the Multigrid Optimization
if useTrials
  if isfield(crun,'NodeFactor') && crun.NodeFactor ~= 1
    islast = true;
    ss_tolerance = 0.01;
  else
    if trial == ntrials % 3/3 or 2/2 or 1/1
      islast = true;
      ss_tolerance = 0.01;
    else
      islast = false;
      if ntrials - trial == 1 % 2/3 or 1/2
        crun.NodeFactor = crun.NodeFactor*0.1;
        ss_tolerance = 0.01;
      else % 1/3
        crun.NodeFactor = crun.NodeFactor*0.001;
        ss_tolerance = 0.025;
      end
    end
  end
else
  islast = true;
  ss_tolerance = 0.01;
end

ME.discretize(crun);

% If discretization was successful
if ME.isStateDiscretized
  % Apply Snapshot
  % ... Which Snapshot would the user like to use?
  if ~isempty(ME.SnapShots)
    names = cell(length(ME.SnapShots)+1,1);
    if nargin < 2
      % Have the user pick a starting Snap-Shot
      for i = 1:length(ME.SnapShots)
        names{i} = ME.SnapShots{i}.Name;
      end
      names{end} = '... From Scratch';
      [answer, selectionMade] = listdlg(...
        'PromptString','Select a SnapShot',...
        'ListString',names,...
        'SelectionMode','single');
    else
```

```
    % Try to find a snapshot with matching name
    selectionMade = true;
    found = false;
    for i = 1:length(ME.SnapShots)
      if strcmp(ME.SnapShots{i}.Name, crun.title)
        found = true;
        answer = i;
        break;
      end
    end

    % If it did not find a match then take the last one listed
    if ~found
      answer = length(ME.SnapShots);
    end

  end

  % Apply the snapshot if it is selected
  if selectionMade && answer ~= length(names)
    SS = ME.SnapShots{answer};
    ME.assignSnapShot(SS);
  end
end

if nargin > 1 && ...
    crun.movement_option == 'V' && ...
    crun.SS && ...
    ME.recordStatistics && ...
    ME.recordOnlyLastCycle
  dynamic = true;
  record_P_backup = ME.recordPressure;
  record_T_backup = ME.recordTemperature;
  record_t_backup = ME.recordTurbulence;
  ME.recordPressure = true;
  ME.recordTemperature = true;
  ME.recordTurbulence = true;
  crun.movement_option = 'C';
  ss_tolerance = 0.01;
else
  dynamic = false;
end

tic;
[ME.Results, success] = ME.Simulations(1).Run(...
  islast, do_warmup, ss_tolerance, crun);
if isempty(ME.Results)
      ME.CurrentSim(:) = [];
      ME.Results(:) = [];
      ME.resetDiscretization();
    return;
end

if dynamic
  % Reset Settings
  crun.movement_option = 'V';
  crun.set_Load = mean(ME.Results.Data.Power)/mean(ME.Results.Data.dA);
  % Save and Reload Snapshot
  ME.Results.getSnapShot(ME,'Temp');
  ME.assignSnapShot(ME.SnapShots{end});
  ME.SnapShots(end) = [];
  ME.recordPressure = record_P_backup;
  ME.recordTemperature = record_T_backup;
  ME.recordTurbulence = record_t_backup;
  % Run
  [ME.Results, success] = ME.Simulations(1).Run(...
    islast, do_warmup, ss_tolerance, crun);
end
toc;

if ~success || isempty(ME.Results); return; end
```

```
            % If it is a recording set then ready the display matricies and
            %    record everything
            if islast
              % Calculate Node Locations
              if ME.showPressureAnimation || ...
                  ME.showTemperatureAnimation || ...
                  ME.showTurbulenceAnimation || ...
                  ME.showConductionAnimation || ...
                  ME.showPressureDropAnimation
                cpnts = cell(1,length(ME.Nodes));
                nodesleft = 0;
                for Nd = ME.Nodes
                  if nodesleft == 0
                    if isa(Nd.Body,'Body')
                      iGroup = Nd.Body.Group;
                      Rot = RotMatrix(iGroup.Position.Rot - pi/2);
                      Trans = [iGroup.Position.x; iGroup.Position.y];
                      AxisAligned = (iGroup.Position.Rot == pi/2);
                      nodesleft = length(iGroup.Nodes)-1;
                    else
                      Rot = [1 0; 0 1];
                      Trans = [0; 0];
                      AxisAligned = true;
                      % nodesleft = 0;
                    end
                  else
                    nodesleft = nodesleft - 1;
                  end
                  % Corner points

                  % Type 1 (static) ,4 (dynamic): Translation Only
                  % ... [Type d1x d2x d3x cx ... ]
                  % ... [ --  d1y d2y d3y cy ... ]
                  % ... c is the center of the node
                  % ... d1 is the diagonal between the center and top right corner
                  % ... d2 is the diagonal between the center and the bottom right corner
                  % ... d3 is the vector between centers of the ring, (0,0) if node is centered

                  % Type 2: Stretching in One Direction
                  % ... [Type cx d1x d2x d3x ... ]
                  % ... [ --  cy d1y d2y d3y ... ]
                  % ... c is the bottom left corner
                  % ... d1 is the vector to the bottom right corner from c
                  % ... d2 is the vector to the bottom right corner of the other side
                  % ... ... (0,0) if the node is centered
                  % ... d3 is the vector to the top left corner

                  % Type 3: Movement of both ybounds
                  % ... [Type d1x cx  ... ]
                  % ... [ --  d1y cy  ... ]
                  % ... [ --  d2x d3x ... ]
                  % ... [ --  d2y d3y ... ]
                  % ... c is the bottom left corner
                  % ... d1 is the vector to the bottom right corner from c
                  % ... d2 is the vector to the bottom right corner of the other side
                  % ... ... (0,0) if the node is centered
                  % ... d3 is the vector to the top left corner

                  if isscalar(Nd.ymin)
                    if isscalar(Nd.ymax)
                      Type = 1;
                      if Nd.xmin == 0
                        pnts = [Type Nd.xmax              Nd.xmax             0  0
; ...
                          0    (Nd.ymax-Nd.ymin)/2 -(Nd.ymax-Nd.ymin)/2 0 (Nd.ymax+Nd.ymin)/2];
                      else
                        pnts = [Type (Nd.xmax-Nd.xmin)/2 (Nd.xmax-Nd.xmin)/2  -(Nd.xmin+Nd.xmax)
(Nd.xmax+Nd.xmin)/2; ...
                          0    (Nd.ymax-Nd.ymin)/2 -(Nd.ymax-Nd.ymin)/2 0
(Nd.ymax+Nd.ymin)/2];
```

```
                    end
                    % Rotate
                    if ~AxisAligned; pnts(:,2:5) = Rot*pnts(:,2:5); end
                    pnts(:,5) = pnts(:,5) + Trans;
                  else
                    Type = 2;
                    pnts = zeros(2,4+length(Nd.ymax));
                    % Nd.ymax is dynamic
                    if Nd.xmin == 0
                      pnts(:,1:4) = [Type -Nd.xmax 2*Nd.xmax 0; ...
                        0    Nd.ymin  0         0];
                    else
                      pnts(:,1:4) = [Type Nd.xmin Nd.xmax-Nd.xmin -Nd.xmax-Nd.xmin; ...
                        0    Nd.ymin 0               0               ];
                    end
                    pnts(1,5:end) = 0;
                    pnts(2,5:end) = Nd.ymax - pnts(2,2);
                    % Rotate
                    if ~AxisAligned; pnts(:,2:end) = Rot*pnts(:,2:end); end
                    pnts(:,2) = pnts(:,2) + Trans;
                  end
                else
                  if isscalar(Nd.ymax)
                    Type = 2;
                    pnts = zeros(2,4+length(Nd.ymin));
                    % Nd.ymin is dynamic
                    if Nd.xmin == 0
                      pnts(:,1:4) = [Type -Nd.xmax 2*Nd.xmax 0; ...
                        0    Nd.ymax  0         0];
                    else
                      pnts(:,1:4) = [Type Nd.xmin Nd.xmax-Nd.xmin -Nd.xmax-Nd.xmin; ...
                        0    Nd.ymax 0               0               ];
                    end
                    pnts(1,5:end) = 0;
                    pnts(2,5:end) = Nd.ymin - pnts(2,2);
                    % Rotate
                    if ~AxisAligned; pnts(:,2:end) = Rot*pnts(:,2:end); end
                    pnts(:,2) = pnts(:,2) + Trans;
                  else
                    if isfield(Nd.data,'matl'); matl = Nd.data.matl;
                    else; matl = Nd.Body.matl;
                    end
                    if matl.Phase == enumMaterial.Solid
                      % ... [Type d1x d2x d3x cx ... ]
                      % ... [ --  d1y d2y d3y cy ... ]
                      Type = 4; % Stretching is impossible
                      pnts = zeros(2,4+length(Nd.ymax));
                      if Nd.xmin == 0
                        pnts(:,1:4) = [Type Nd.xmax                    Nd.xmax
0; ...
                          0    (Nd.ymax(1)-Nd.ymin(1))/2 -(Nd.ymax(1)-Nd.ymin(1))/2 0];
                        x = 0;
                      else
                        pnts(:,1:4) = [Type (Nd.xmax-Nd.xmin)/2       (Nd.xmax-Nd.xmin)/2
-(Nd.xmin+Nd.xmax); ... (Nd.xmax+Nd.xmin)/2       ; ...
                          0    (Nd.ymax(1)-Nd.ymin(1))/2 -(Nd.ymax(1)-Nd.ymin(1))/2 0
];% (Nd.ymax+Nd.ymin)/2];
                        x = (Nd.xmax+Nd.xmin)/2;
                      end
                      pnts(1,5:end) = x;
                      pnts(2,5:end) = (Nd.ymax+Nd.ymin)/2;
                      % Rotate
                      if ~AxisAligned; pnts(:,2:end) = Rot*pnts(:,2:end); end
                      pnts(:,5:end) = pnts(:,5:end) + Trans;
                    else
                      Type = 3; % Stretching is very probable
                      pnts = zeros(4,2+length(Nd.ymax));
                      if Nd.xmin == 0
                        pnts(:,1:2) = [Type 2*Nd.xmax; ...
                          0    0        ; ...
                          0    0        ; ...
```

```
              0    0        ];
            x = -Nd.xmax;
          else
            pnts(:,1:2) = [Type Nd.xmax-Nd.xmin   ; ...
              0    0                ; ...
              0    -(Nd.xmax+Nd.xmin); ...
              0    0                ];
            x = Nd.xmin;
          end
          pnts(1,3:end) = x;
          pnts(2,3:end) = Nd.ymin;
          pnts(3,3:end) = 0;
          pnts(4,3:end) = (Nd.ymax-Nd.ymin);
          % Rotate
          if ~AxisAligned
            pnts(1:2,2:end) = Rot*pnts(1:2,2:end);
            pnts(3:4,2:end) = Rot*pnts(3:4,2:end);
          end
          % Translate
          pnts(1:2,3:end) = pnts(1:2,3:end) + Trans;
        end
      end
    end
    cpnts{Nd.index} = pnts;
  end
end

% Calculate Face Locations and directions
if isfield(ME.Results.Data,'U') && ME.showPressureDropAnimation
    if isfield(ME.Results.Data,'U')
        fpnts = cell(1,size(ME.Results.Data.U,1));
    end
    % Define X,Y,Nx,Ny
    maxIndex = length(ME.Simulations.Fc_U);
    if ~isempty(ME.Faces)
      if isa(ME.Faces(1).Nodes(1).Body,'Body')
        iGroup = ME.Faces(1).Nodes(1).Body.Group;
      else
        iGroup = ME.Faces(1).Nodes(2).Body.Group;
      end
      Rot = RotMatrix(iGroup.Position.Rot - pi/2);
      Trans = [iGroup.Position.x; iGroup.Position.y];
      for Fc = ME.Faces
        if Fc.index <= maxIndex
            if isa(Fc.Nodes(1).Body,'Environment')
                Rot = RotMatrix(0);
                Trans = [0; 0];
            else
                if iGroup ~= Fc.Nodes(1).Body.Group
                    iGroup = Fc.Nodes(1).Body.Group;
                    Rot = RotMatrix(iGroup.Position.Rot - pi/2);
                    Trans = [iGroup.Position.x; iGroup.Position.y];
                end
            end
            i = Fc.index;
            if Fc.Nodes(1).Body == Fc.Nodes(2).Body
                if Fc.Nodes(1).xmax == Fc.Nodes(2).xmin
                    % Aligned horizontally
                    x = Fc.Nodes(1).xmax;
                    y = (Fc.Nodes(1).ymin + Fc.Nodes(1).ymax)/2;
                    Nx = 1;
                    Ny = 0;
                elseif Fc.Nodes(1).xmin == Fc.Nodes(2).xmax
                    % Aligned horizontally
                    x = Fc.Nodes(1).xmin;
                    y = (Fc.Nodes(1).ymin + Fc.Nodes(1).ymax)/2;
                    Nx = -1;
                    Ny = 0;
                elseif abs(Fc.Nodes(1).ymax(1) - Fc.Nodes(2).ymin(1)) < ...
                        abs(Fc.Nodes(1).ymin(1) - Fc.Nodes(2).ymax(1))
                    % Aligned Vertically
```

```
                    x = (Fc.Nodes(1).xmin + Fc.Nodes(1).xmax)/2;
                    y = Fc.Nodes.ymax;
                    Nx = 0;
                    Ny = 1;
                else
                    % Aligned Vertically
                    x = (Fc.Nodes(1).xmin + Fc.Nodes(1).xmax)/2;
                    y = Fc.Nodes.ymin;
                    Nx = 0;
                    Ny = -1;
                end
            else
                if Fc.Nodes(1).xmax == Fc.Nodes(2).xmin
                    % Aligned horizontally
                    x = Fc.Nodes(1).xmax; % Done
                    y = getCenterOfOverlapRegion(...
                        Fc.Nodes(1).ymin,...
                        Fc.Nodes(2).ymin,...
                        Fc.Nodes(1).ymax,...
                        Fc.Nodes(2).ymax);
                    Nx = 1; % Done
                    Ny = 0; % Done
                elseif Fc.Nodes(1).xmin == Fc.Nodes(2).xmax
                    % Aligned horizontally
                    x = Fc.Nodes(1).xmin; % Done
                    y = getCenterOfOverlapRegion(...
                        Fc.Nodes(1).ymin,...
                        Fc.Nodes(2).ymin,...
                        Fc.Nodes(1).ymax,...
                        Fc.Nodes(2).ymax);
                    Nx = -1; % Done
                    Ny = 0; % Done
                elseif abs(Fc.Nodes(1).ymax(1) - Fc.Nodes(2).ymin(1)) < ...
                        abs(Fc.Nodes(1).ymin(1) - Fc.Nodes(2).ymax(1))
                    % Aligned Vertically
                    x = getCenterOfOverlapRegion(...
                        Fc.Nodes(1).xmin,...
                        Fc.Nodes(2).xmin,...
                        Fc.Nodes(1).xmax,...
                        Fc.Nodes(2).xmax);
                    y = Fc.Nodes(1).ymax; % Done
                    Nx = 0; % Done
                    Ny = 1; % Done
                else
                    % Aligned Vertically
                    x = getCenterOfOverlapRegion(...
                        Fc.Nodes(1).xmin,...
                        Fc.Nodes(2).xmin,...
                        Fc.Nodes(1).xmax,...
                        Fc.Nodes(2).xmax);
                    y = Fc.Nodes(1).ymin; % Done
                    Nx = 0; % Done
                    Ny = -1; % Done
                end
            end
            if isscalar(y)
                fpnts{i} = Rot*[Nx x; Ny y] + [[0;0] Trans];
            else
                fpnts{i} = [Rot*[Nx; Ny] Rot*[x(ones(1,length(y))); y]+Trans];
            end
        end
      end
    end
end

% Calculate Solid Body Boundaries
n = 0;
for iGroup = ME.Groups
  for iBody = iGroup.Bodies
    if iBody.matl.Phase == enumMaterial.Solid
      n = n + 1;
```

```
      end
    end
  end
  bpnts = cell(1,n);
  n = 1;
  for iGroup = ME.Groups
    Rot = RotMatrix(iGroup.Position.Rot - pi/2);
    Trans = [iGroup.Position.x; iGroup.Position.y];
    for iBody = iGroup.Bodies
      if iBody.matl.Phase == enumMaterial.Solid
        [~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
        [y1,y2,~,~] = iBody.limits(enumOrient.Horizontal);
        if isscalar(y1) %&& isscalar(y2)
          if x1 == 0
            bpnts{n} = Rot*[-x2 x2 x2 -x2; y1 y1 y2 y2] + Trans;
          else
            bpnts{n} = Rot*[x1 x2 x2 x1; y1 y1 y2 y2] + Trans;
            n = n + 1;
            bpnts{n} = Rot*[-x1 -x2 -x2 -x1; y1 y1 y2 y2] + Trans;
          end
        else
          bpnts{n} = zeros(2,4,length(y1));
          if x1 == 0
            for i = 1:length(y1)
              bpnts{n}(:,:,i) = ...
                Rot*[-x2 x2 x2 -x2; y1(i) y1(i) y2(i) y2(i)] + Trans;
            end
          else
            for i = 1:length(y1)
              bpnts{n}(:,:,i) = ...
                Rot*[x1 x2 x2 x1; y1(i) y1(i) y2(i) y2(i)] + Trans;
            end
            n = n + 1;
            bpnts{n} = zeros(2,4,length(y1));
            for i = 1:length(y1)
              bpnts{n}(:,:,i) = ...
                Rot*[-x1 -x2 -x2 -x1; y1(i) y1(i) y2(i) y2(i)] + Trans;
            end
          end
        end
        n = n + 1;
      end
    end
  end

  % Animate
  frate = ME.animationFrameTime;
  if isfield(ME.Results.Data,'P') && ME.showPressureAnimation
  ME.Results.animateNode('P',cpnts,bpnts,frate,[],[],crun.title);
end
if isfield(ME.Results.Data,'T') && ME.showTemperatureAnimation
  ME.Results.animateNode('T',cpnts,bpnts,frate,[],[],crun.title);
end
if isfield(ME.Results.Data,'U') && ME.showVelocityAnimation
  ME.Results.animateFace('U',fpnts,bpnts,frate,[],[],crun.title);
end
if isfield(ME.Results.Data,'turb') && ME.showTurbulenceAnimation
  ME.Results.animateNode('turb',cpnts,bpnts,frate,[],[],crun.title);
end
if isfield(ME.Results.Data,'cond') && ME.showConductionAnimation
  ME.Results.animateNode('cond',cpnts,bpnts,frate,[],[],crun.title);
end
if isfield(ME.Results.Data,'dP') && ME.showPressureDropAnimation
  ME.Results.animateNode('dP',cpnts,bpnts,frate,[],[],crun.title);
end
end

% Ask if the user would like to save a snapshot
if nargin > 1
    if ~ME.Simulations(1).stop
      % Remove the snapshot as it will be replaced now
```

```
            for i = 1:length(ME.SnapShots)
              if strcmp(ME.SnapShots{i}.Name, crun.title)
                ME.SnapShots(i) = [];
                break;
              end
            end
            ME.Results.getSnapShot(ME,crun.title);
            saveME(ME);
          end
        else
          response = questdlg('Would you like to save a SnapShot?', ...
            'Save SnapShot','Yes','No','Yes');
          if strcmp(response,'Yes')
            ME.Results.getSnapShot(ME,getProperName('SnapShot'));
          end
        end
      end

      %% Undo Geometry Modifications
      % Uniform Scale Modification
      if nargin > 1
        if isfield(crun,'Uniform_Scale')
          % Scale the connections
          for iGroup = ME.Groups
            for iCon = iGroup.Connections
              iCon.x = iCon.x/crun.Uniform_Scale;
            end
            % Scale the positions
            iGroup.Position.x = iGroup.Position.x/crun.Uniform_Scale;
            iGroup.Position.y = iGroup.Position.y/crun.Uniform_Scale;
          end

          % Scale the bridge offsets
          for iBridge = ME.Bridges
            iBridge.x = iBridge.x/crun.Uniform_Scale;
          end

          % Scale the mechanisms
          for iLRM = ME.Converters
            iLRM.Uniform_Scale(1/crun.Uniform_Scale);
          end

          % Scale the view window
          set(ME.AxisReference, ...
            'XLim',get(ME.AxisReference, 'XLim')/crun.Uniform_Scale);
          set(ME.AxisReference, ...
            'YLim',get(ME.AxisReference, 'YLim')/crun.Uniform_Scale);
        end

        % To save the modified geometry
        saveME(ME);
      end
    end
  end
  ME.outputPath = backup_path;
  ME.CurrentSim(:) = [];
  ME.Results(:) = [];
  ME.resetDiscretization();
end

function assignSnapShot(ME, SS)
  Sim = ME.Simulations;
  for iGroup = ME.Groups
    for iBody = iGroup.Bodies
      for BData = SS.Data
        if iBody.ID == BData.ID
          if applyBody(BData,iBody)
            if iBody.matl.Phase == enumMaterial.Solid
              for Nd = iBody.Nodes
                i = Nd.index;
                if isnan(Nd.data.T)
```

```
                fprintf('err detected');
              else
                Sim.T(i) = Nd.data.T;
              end
            end
          else
            for Nd = iBody.Nodes
              i = Nd.index;
              if isfield(Nd.data,'matl')
                matl = Material(Nd.data.matl.name);
              else
                matl = Material(Nd.Body.matl.name);
              end
              if i <= length(Sim.P)
                if isfield(Nd.data,'P') && ~isnan(Nd.data.P)
                  P = Nd.data.P;
                else
                  P = ME.enginePressure;
                  for j = 1:length(Sim.Regions)
                    if any(Sim.Regions{j} == i)
                      if Sim.isEnvironmentRegion(j)
                        P = Sim.P(end);
                      end
                      break;
                    end
                  end
                end
                if isfield(Nd.data,'T')
                  if isnan(Nd.data.T)
                    fprintf('err detected');
                  else
                    Sim.T(i) = Nd.data.T;
                  end
                end
                if isfield(Nd.data,'Turb')
                  if isnan(Nd.data.Turb)
                    fprintf('err detected');
                  else
                    Sim.turb(i) = Nd.data.Turb;
                  end
                end
                if ~isnan(P)
                  vol = Nd.vol();
                  % Need to figure out what gas constant to
                  % ... use
                  Rgas = matl.R;
                  Sim.m(i) = P*vol(1)/(Rgas*Sim.T(i));
                end
              else
                if isnan(Nd.data.T)
                  fprintf('err detected');
                else
                  Sim.T(i) = Nd.data.T;
                end
              end
              if matl.Phase == enumMaterial.Gas
                  Sim.u(i) = matl.initialInternalEnergy(Sim.T(i));
              end
            end
          end
        end
        break;
      end
    end
  end
end

function saveME(Model)
    Model.Faces(:) = [];
    Model.Nodes(:) = [];
```

```
    Model.Simulations(:) = [];
    Model.CurrentSim(:) = [];
    Model.Results(:) = [];
    Model.PressureContacts(:) = [];
    Model.ShearContacts(:) = [];
    for iPV = Model.PVoutputs
      iPV.reset();
    end
    for iSense = Model.Sensors
        if ~isempty(iSense)
          iSense.reset();
          iSense.GUIObjects(:) = [];
        end
    end
    backupAxis = Model.AxisReference;
    Model.AxisReference(:) = [];
    for iGroup = Model.Groups
        for iBody = iGroup.Bodies
            iBody.GUIObjects(:) = [];
            iBody.Nodes(:) = [];
            iBody.Faces(:) = [];
            if ~isempty(iBody.Matrix)
                iBody.Matrix.Nodes(:) = [];
                iBody.Matrix.Faces(:) = [];
            end
        end
        for iCon = iGroup.Connections
            iCon.GUIObjects(:) = [];
            iCon.Faces(:) = [];
            iCon.NodeContacts(:) = [];
        end
        iGroup.GUIObjects(:) = [];
    end
    for iBridge = Model.Bridges
       iBridge.GUIObjects(:) = [];
       iBridge.Faces(:) = [];
    end
    save(['Saved Files\' Model.name '.mat'],'Model');
    Model.AxisReference = backupAxis;
    fprintf('Model Saved.\n');
end

%% Interface / Find stuff
function FindGroup(this,Pos)
  TheGroup = this.findNearestGroup(Pos,inf);
  this.HighLight(TheGroup);
end
function distributeGroup(this, GroupSpacing)
  % Take existing horizontal order and distribute
  for i = 1:length(this.Groups)
    for j = i+1:length(this.Groups)
      if this.Groups(j).Position.x < this.Groups(i).Position.x
        tempGroup = this.Groups(i);
        this.Groups(i) = this.Groups(j);
        this.Groups(j) = tempGroup;
      end
    end
  end
  x = 0;
  for iGroup = this.Groups
    iGroup.Position.x = x;
    dim1 = RotMatrix(iGroup.Position.Rot-pi/2)*[iGroup.Width*2; iGroup.Height];
    dim2 = RotMatrix(iGroup.Position.Rot-pi/2)*[iGroup.Width*2; -iGroup.Height];
    x = x + max([dim1(1) dim2(1)])+GroupSpacing;
  end
end
function [names, objects] = findNearest(this,Pnt,Tolerance)
  objects = cell(0);
  names = cell(0);
  % Find, within a radius of confidence, the nearest...
  %   Body, Group, Connection, Bridge and Leak Connection
```

```
Tolerance = Tolerance^2;
index = 1;
%% Group
if isempty(this.ActiveGroup)
  obj = this.findNearestGroup(Pnt,Tolerance);
  if ~isempty(obj)
    objects{index} = obj;
    names{index} = obj.name;
    index = index + 1;
  end
  TheGroup = obj;
else
  TheGroup = this.ActiveGroup;
  objects{index} = TheGroup;
  names{index} = TheGroup.name;
  index = index + 1;
end

%% Body
mindist = Tolerance;
Pntmod = (RotMatrix(pi/2 - TheGroup.Position.Rot)*Pnt') - ...
  [TheGroup.Position.x; TheGroup.Position.y];
for iBody = TheGroup.Bodies
  % Establish Rectangle of iBody
  [~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
  [~,~,y1,y2] = iBody.limits(enumOrient.Horizontal);

  R.Width = x2-x1;
  R.Height = y2-y1;
  R.Cx = (x1+x2)/2;
  R.Cy = (y1+y2)/2;
  dist = Dist2Rect(Pntmod(1),Pntmod(2),R.Cx,R.Cy,R.Width,R.Height);
  if dist < mindist
    mindist = dist;
    TheBody = iBody;
  else
    R.Cx = -R.Cx;
    dist = Dist2Rect(...
      Pntmod(1),Pntmod(2),R.Cx,R.Cy,R.Width,R.Height);
    if dist < mindist
      mindist = dist;
      TheBody = iBody;
    end
  end
end
if mindist < Tolerance
  objects{index} = TheBody;
  names{index} = TheBody.name;
  index = index + 1;
end

%% Connection
mindist = Tolerance;
Pntmod = (RotMatrix(pi/2 - TheGroup.Position.Rot)*Pnt') - ...
  [TheGroup.Position.x; TheGroup.Position.y];
for iConnection = TheGroup.Connections
  % Find nearest Connection
  switch iConnection.Orient
    case enumOrient.Vertical
      % Two lines to test
      if abs(Pntmod(1) - iConnection.x) < mindist
        mindist = abs(Pntmod(1) - iConnection.x);
        TheConnection = iConnection;
      end
      if abs(Pntmod(1) + iConnection.x) < mindist
        mindist = abs(Pntmod(1) + iConnection.x);
        TheConnection = iConnection;
      end
    case enumOrient.Horizontal
      % One line to test
      if abs(Pntmod(2) - iConnection.x) < mindist
```

```
          mindist = abs(Pntmod(2)-iConnection.x);
          TheConnection = iConnection;
        end
    end
  end
  if mindist < Tolerance
    objects{index} = TheConnection;
    names{index} = TheConnection.name;
    index = index + 1;
  end

  %% Bridge
  mindist = Tolerance;
  for iBridge = this.Bridges

  end

  %% Leak Connection
  mindist = Tolerance;
  for iLeakCon = this.LeakConnections

  end
end
function [TheGroup] = findNearestGroup(this,Pos,Tolerance)
  try Pnt = Pos(1,1:2);
  catch
    try Pnt = Pos(1:2,1)';
    catch; msgbox('Group Not Found due to improper input coordinates');
    end
  end
  [iBody, mindist] = this.findNearestBody(Pnt,Tolerance);
  for iGroup = this.Groups
    if isempty(iGroup.Bodies)
      if mindist > Dist2Rect(Pnt(1),Pnt(2),iGroup.Position.x,iGroup.Position.y,0,0)
        TheGroup = iGroup;
        return;
      end
    end
  end
  if ~isempty(iBody)
    TheGroup = iBody.Group;
  else
    TheGroup = this.Groups(1);
  end
end
function [TheBody, mindist] = findNearestBody(this,Pnt,Tolerance)
  mindist = Tolerance;
  TheBody = Body.empty;
  for iGroup = this.Groups
    Pntmod = (RotMatrix(pi/2 - iGroup.Position.Rot)*Pnt') - ...
      [iGroup.Position.x; iGroup.Position.y];
    for iBody = iGroup.Bodies
      % Establish Rectangle of iBody
      [~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
      [~,~,y1,y2] = iBody.limits(enumOrient.Horizontal);

      R.Width = x2-x1;
      R.Height = y2-y1;
      R.Cx = (x1+x2)/2;
      R.Cy = (y1+y2)/2;
      dist = Dist2Rect(Pntmod(1),Pntmod(2),R.Cx,R.Cy,R.Width,R.Height);
      if dist < mindist
        mindist = dist;
        TheBody = iBody;
      else
        R.Cx = -R.Cx;
        dist = Dist2Rect(...
          Pntmod(1),Pntmod(2),R.Cx,R.Cy,R.Width,R.Height);
        if dist < mindist
          mindist = dist;
          TheBody = iBody;
```

```
        end
      end
    end
  end
end
function [names, objects] = findFrames(this)
  for i = length(this.RefFrames):-1:1
    names{i} = this.RefFrames(i).name;
    objects{i} = this.RefFrames(i);
  end
end

%% Graphics
% Tests
function isInWindow = inWindow(this,pnt1,pnt2)
  if nargin == 2
      if isempty(this.AxisReference)
          this.AxisReference = gca;
          axes = this.AxisReference;
      else
          axes = this.AxisReference;
      end
    xlim = axes.XLim;
    ylim = axes.YLim;
    isInWindow = pnt1.x < xlim(2) && pnt1.x > xlim(1) && ...
      pnt1.y < ylim(2) && pnt1.y > ylim(1);
  elseif nargin == 3
    xlim = this.AxisReference.XLim;
    ylim = this.AxisReference.YLim;
    isInWindow = pnt1.x < xlim(2) && pnt1.x > xlim(1) && ...
      pnt1.y < ylim(2) && pnt1.y > ylim(1) && ...
      pnt2.x < xlim(2) && pnt2.x > xlim(1) && ...
      pnt2.y < ylim(2) && pnt2.y > ylim(1);
  end
end
function showOptions = produceShowOptions(this,showOptions)
  if nargin > 1 && length(showOptions) == 9
    this.showGroups = showOptions(1); % Groups
    if ~showOptions(2) && showOptions(2) ~= this.showBodies
      for iGroup = this.Groups
        for iBody = iGroup.Bodies
          iBody.removeFromFigure(this.AxisReference);
        end
      end
    end
    this.showBodies = showOptions(2); % Bodies
    if ~showOptions(3) && showOptions(3) ~= this.showConnections
      for iGroup = this.Groups
        for iCon = iGroup.Connections
          iCon.removeFromFigure(this.AxisReference);
        end
      end
    end
    this.showConnections = showOptions(3); % Connections
    if ~showOptions(4) && showOptions(4) ~= this.showLeaks
      for iLeak = this.LeakConnections
        iLeak.removeFromFigure(this.AxisReference);
      end
    end
    this.showLeaks = showOptions(4); % Leaks
    if ~showOptions(5) && showOptions(5) ~= this.showBridges
      for iBridge = this.Bridges
        iBridge.removeFromFigure(this.AxisReference);
      end
    end
    this.showBridges = showOptions(5); % Bridges
    % Already deleted
    this.showInterConnections = showOptions(6); % Node Connections
    % Already deleted
    this.showEnvironmentConnections = showOptions(7); % Environment Surround
    % Already deleted
```

```
        this.showBodyGhosts = showOptions(8); % Motion Ghosts
        % ?????
        this.showNodes = showOptions(9); % Node Outlines
      elseif nargin > 1 && ~isempty(showOptions)
        fprintf('XXX showOptions in "Model.show" should be a vector of length 9 containing
logical show conditions XXX\n');
        return;
      else
        % Define showOptions;
        showOptions = zeros(8,1);
        showOptions(1) = this.showGroups;
        showOptions(2) = this.showBodies;
        showOptions(3) = this.showConnections;
        showOptions(4) = this.showLeaks;
        showOptions(5) = this.showBridges;
        showOptions(6) = this.showInterConnections;
        showOptions(7) = this.showEnvironmentConnections;
        showOptions(8) = this.showBodyGhosts;
        showOptions(9) = this.showNodes;
      end
    end

    % Highlighting and Selecting
    function ActiveGroup = get.ActiveGroup(this)
      ActiveGroup = [];
      for obj = this.Selection
        if isa(obj{1},'Group')
          ActiveGroup = obj{1};
          return;
        end
      end
    end
    function switchHighLightedGroup(this,otherGroup)
      update(this);
      if ~isempty(otherGroup) && isvalid(otherGroup)
        for i = 1:length(this.Selection)
          if isa(this.Selection{i},'Group')
            this.Selection{i}.isActive = false;
            this.Selection{i} = otherGroup;
            otherGroup.isActive = true;
          end
        end
      end
    end
    function switchHighLighting(this,NewHighlightedObjects)
      update(this);
      this.clearHighLighting();
      for iObj = NewHighlightedObjects
        iObj.isActive = true;
        this.Selection{end+1} = iObj;
      end
    end
    function HighLight(this,HighlightedObjects)
      update(this);
      for iObj = HighlightedObjects
          iObj.isActive = true;
          this.Selection{end+1} = iObj;
      end
    end
    function clearHighLighting(this)
      update(this);
      i = 1; j = 0;
      for iObj = this.Selection
        if ~isa(iObj,'Group')
          iObj{1}.isActive = false; %#ok<FXSET>
        else; j = i;
        end
        i = i + 1;
      end
      if j > 0; this.Selection = {this.Selection{j}};
      else; this.Selection = cell(0);
```

```
  end
end

% Bulk Display
function XLim = getXLim(this)
  XLim = [inf -inf];
  for iGroup = this.Groups
    w = iGroup.Width;
    h = iGroup.Height;
    dx = w/2*sin(iGroup.Position.Rot);
    dy = h*cos(iGroup.Position.Rot);
    lim = iGroup.Position.x + [dx dx+dy -dx -dx+dy];
    limmx = max(lim);
    limmn = min(lim);
    if limmx > XLim(2); XLim(2) = limmx; end
    if limmn < XLim(1); XLim(1) = limmn; end
  end
end
function YLim = getYLim(this)
  YLim = [inf -inf];
  for iGroup = this.Groups
    w = iGroup.Width;
    h = iGroup.Height;
    dx = w/2*cos(iGroup.Position.Rot);
    dy = h*sin(iGroup.Position.Rot);
    lim = iGroup.Position.y + [dx dx+dy -dx -dx+dy];
    limmx = max(lim);
    limmn = min(lim);
    if limmx > YLim(2); YLim(2) = limmx; end
    if limmn < YLim(1); YLim(1) = limmn; end
  end
end
function removeStaticFromFigure(this)
  if ~isempty(this.StaticGUIObjects)
    children = get(this.AxisReference,'Children');
    for j = 1:length(this.StaticGUIObjects)
      if isgraphics(this.StaticGUIObjects(j))
        for i = length(children):-1:1
          if isgraphics(children(i)) && children(i) == this.StaticGUIObjects(j)
            children(i).delete;
            break;
          end
        end
      end
    end
    this.StaticGUIObjects = [];
  end
end
function removeDynamicFromFigure(this)
  if ~isempty(this.DynamicGUIObjects)
    children = get(this.AxisReference,'Children');
    for j = 1:length(this.DynamicGUIObjects)
      if isgraphics(this.DynamicGUIObjects(j))
        for i = length(children):-1:1
          if isgraphics(children(i)) && children(i) == this.DynamicGUIObjects(j)
            children(i).delete;
            break;
          end
        end
      end
    end
    this.DynamicGUIObjects = [];
  end
end
function removeGhostFromFigure(this)
  if ~isempty(this.GhostGUIObjects)
    children = get(this.AxisReference,'Children');
    for obj = this.GhostGUIObjects
      if isgraphics(obj)
        for i = length(children):-1:1
          if isgraphics(children(i)) && children(i) == obj
```

```
                children(i).delete;
                break;
              end
            end
          end
        end
        this.DynamicGUIObjects = [];
      end
    end
    function bringGhostToFront(this)
      if ~isempty(this.GhostGUIObjects)
        children = get(this.AxisReference,'Children');
        END = length(children);
        for obj = this.GhostGUIObjects
          if isgraphics(obj)
            for i = END:-1:1
              if isgraphics(children(i)) && children(i) == obj
                uistack(obj,'top');
                break;
              end
            end
          end
        end
      end
    end
    function show(this,showOptions)
      if this.isChanged; this.update(); end
      this.removeStaticFromFigure();
      this.removeGhostFromFigure();
      if nargin > 1
        showOptions = this.produceShowOptions(showOptions);
      else
        showOptions = this.produceShowOptions();
      end
      %showOptions =
[inputshowGroup,inputshowBodies,inputshowConnections,ishowLeaks,ishowBridges,ishowIntCon,ishowEnv
irCon)]
      % Fig = get(this.AxisReference,'parent');
      % hP = pan(Fig);
      % Go down through the hierarchy
      for iGroup = this.Groups
        %
show(this,CODE,AxisReference,Inc,showGroups,showBodies,showConnections,showLeaks,showInterConnect
ions,showEnvironmentConnections)
        iGroup.show('all',this.AxisReference,0,showOptions);
        % showGroups showBodies showConnections showLeaks showBridges showInterConnections
showEnvironmentConnections]
      end
      if this.showInterConnections || this.showNodes
        if ~this.isDiscretized()
          crun = struct('Model',this.name,...
            'title',[this.name ' test: ' date],...
            'rpm',this.engineSpeed,...
            'NodeFactor',this.deRefinementFactorInput);
          this.discretize(crun);
          if ~this.isDiscretized()
            fprintf('XXX No Nodes generated. XXX\n');
          end
        end
        n = length(this.Nodes);
        if n ~= 0
          nodeCenter(n) = Pnt2D(0,0);
          for iNode = this.Nodes
            nodeCenter(iNode.index) = iNode.minCenterCoords;
            isVis(iNode.index) = this.inWindow(nodeCenter(iNode.index));
          end
        end
      end

      if this.showInterConnections % Show Inter-Node Connections
        if this.isDiscretized()
```

```
          % Make array of Node Centers
          % Count nodes, stored in Groups
          n = length(this.Nodes);
          if n ~= 0
            % Make array of face coords
            % Count faces, stored in Model
            n = length(this.Faces);
            faceCoord = zeros(4,n);
            n = 1;
            % Take each face, assess whether it is active, then record
            for iFace = this.Faces
              if ~(iFace.Nodes(1).Type == enumNType.EN || ...
                  iFace.Nodes(2).Type == enumNType.EN)
                if iFace.Nodes(2).index < 1
                  fprintf('XXX error XXX');
                end
                if isVis(iFace.Nodes(1).index) && ...
                    isVis(iFace.Nodes(2).index)
                  c1 = nodeCenter(iFace.Nodes(1).index);
                  c2 = nodeCenter(iFace.Nodes(2).index);
                  faceCoord(:,n) = [c1.x,c2.x,c1.y,c2.y];
                  n = n + 1;
                end
              end
            end
            n = n - 1;

            % Plot
            nT = 3*n;
            xData = NaN(nT,1);
            yData = NaN(nT,1);
            ind = 1;
            for i = 1:3:nT-2
              xData(i:i+1) = faceCoord(1:2,ind);
              yData(i:i+1) = faceCoord(3:4,ind);
              ind = ind + 1;
            end
            if isempty(this.StaticGUIObjects)
              this.StaticGUIObjects = line(xData,yData,'Color',[0 1 0]);
            else
              this.StaticGUIObjects(end+1:end+length(this.Faces)) = line(xData,yData,'Color',[0 1
0]);
            end
          end
        end
      end
      if this.showNodes
        if this.isDiscretized()
          % Make array of Node Centers
          % Count nodes, stored in Groups
          n = length(this.Nodes);
          if n ~= 0
            % Plot
            xData = NaN(n,1);
            yData = NaN(n,1);
            j = 1;
            for nd = this.Nodes
              if isVis(nd.index)
                c1 = nodeCenter(nd.index);
                xData(j) = c1.x;
                yData(j) = c1.y;
                j = j + 1;
              end
            end
            if isempty(this.StaticGUIObjects)
              this.StaticGUIObjects = plot(xData,yData,'o',...
                'MarkerSize',2,...
                'MarkerEdgeColor',[0 0 1]);
            else
              this.StaticGUIObjects(end+1) = ...
                plot(xData,yData,'o',...
```

```
                'MarkerSize',2,...
                'MarkerEdgeColor',[0 0 1]);
            end
          end
        end
      end
      if this.showBridges
        for iBridge = this.Bridges
          iBridge.show(this.AxisReference);
        end
      else
        for iBridge = this.Bridges
          iBridge.removeFromFigure(this.AxisReference);
        end
      end
      if this.showLeaks
        for iLeak = this.LeakConnections
          iLeak.show(this.AxisReference);
        end
      else
        for iLeak = this.LeakConnections
          iLeak.removeFromFigure(this.AxisReference);
        end
      end
      if this.showSensors
        if ~isempty(this.Sensors)
          for iSensor = this.Sensors
            iSensor.show(this.AxisReference);
          end
        end
      else
        if ~isempty(this.Sensors)
          for iSensor = this.Sensors
            iSensor.removeFromFigure(this.AxisReference);
          end
        end
      end
      if this.showBodyGhosts
        this.bringGhostToFront();
      end
    end
    function Animate(this,showOptions)
      if this.isChanged; this.update(); end
      this.removeStaticFromFigure();
      this.removeGhostFromFigure();
      %showOptions =
[inputshowGroup,inputshowBodies,inputshowConnections,ishowLeaks,ishowBridges,ishowIntCon,ishowEnv
irCon)]
      if nargin > 1
        showOptions = this.produceShowOptions(showOptions);
      else
        showOptions = this.produceShowOptions();
      end

      % Don't show connections in annimation
      showOptions(3) = false;

      cla;
      % Set Screen to be constant dimensions
      ReferenceAxis = gca;
      mode = get(ReferenceAxis,'XLimMode');
      set(ReferenceAxis,'XLimMode','manual');
      set(ReferenceAxis,'YLimMode','manual');
      set(ReferenceAxis,'ZLimMode','manual');

      % Initialize
      t = cputime;
      FrameTime = ((2*pi)/(this.AnimationSpeed_rads*Frame.NTheta));
      figure(gcf);
      axes(this.AxisReference);
      Inc = 1;
```

```
% Make all static Bodies visible
for iGroup = this.Groups
  iGroup.show('Static',this.AxisReference,0,showOptions);
end

k = 1;
while this.isAnimating && cputime-t < this.AnimationLength_s
  nexttime = cputime + FrameTime;


  % Go down through the hierarchy
  for iGroup = this.Groups
    iGroup.show('Dynamic',this.AxisReference,Inc,showOptions);
  end
  if showOptions(4) % Leak Connections
    for iLeak = this.LeakConnections
      if iLeak.isDynamic
        iLeak.show(this.AxisReference);
      end
    end
  end
  if showOptions(5) % Bridge Connections
    for iBridge = this.Bridges
      iBridge.show(this.AxisReference);
    end
  end
  if showOptions(6) % Inter Node Connections, dynamic
    if this.isDiscretized()
      this.removeDynamicFromFigure();
      % Make array of Node Centers
      % Count nodes, stored in Groups
      n = length(this.Nodes);
      if n ~= 0
        % Calculate the node center, at bottom dead center for all
        for iNode = this.Nodes
          nodeCenter(iNode.index) = iNode.CenterCoords(Inc);
        end

        % Make array of face coords
        % Count faces, stored in Model
        n = 1;
        xData = NaN(3*length(this.Faces),1);
        yData = NaN(3*length(this.Faces),1);

        % Take each face, assess whether it is active, then record
        for iFace = this.Faces
          %if iFace.isDynamic && ...
          if ~(iFace.Nodes(1).Type == enumNType.EN || ...
              iFace.Nodes(2).Type == enumNType.EN) && ...
              iFace.isActive(Inc)
            c1 = nodeCenter(iFace.Nodes(1).index);
            c2 = nodeCenter(iFace.Nodes(2).index);
            if this.inWindow(c1,c2)
              xData(n) = c1.x;
              xData(n+1) = c2.x;
              yData(n) = c1.y;
              yData(n+1) = c2.y;
              n = n + 3;
            end
          end
        end
        n = n-1;
        xData = xData(1:n);
        yData = yData(1:n);

        if isempty(this.StaticGUIObjects)
          this.DynamicGUIObjects = line(xData,yData,'Color',[0 1 0]);
        else
          this.DynamicGUIObjects(end+1) = line(xData,yData,'Color',[0 1 0]);
        end
      end
```

```
          end
        end
        % Iterate the counter
        Inc = Inc + 1;
        if Inc > Frame.NTheta
          Inc = 1;
        end
        % Wait
        pause(10*max([0 nexttime-cputime]));
      end

      % Reset Screen to previous settings
      set(ReferenceAxis,'XLimMode',mode);
      set(ReferenceAxis,'YLimMode',mode);
      set(ReferenceAxis,'ZLimMode',mode);
    end

  end

end

function [Closed_Edge] = TrimFaces(this, region, Closed_Edge)
LEN = length(Closed_Edge);
for Nd = this.Nodes
  if Nd.index <= length(region)
    from = Nd;
    c = 1;
    while c == 1
      c = 0;
      % Determine the number of access points for the node
      for Fc = from.Faces
        if Fc.index <= LEN && ~Closed_Edge(Fc.index) && ...
            region(Fc.Nodes(1).index) == region(Fc.Nodes(2).index)
          c = c + 1; if c > 1; break; end; edge = Fc;
        end
      end
      if c == 1
        % This Node has only one access point (withing a region),
        % ... therefore it cannot be a part of a loop.
        % Any nodes that are chain to this node with only two total
        % ... access points must also not be part of a loop.
        Closed_Edge(edge.index) = true;
        if from == edge.Nodes(1)
          from = edge.Nodes(2);
        else
          from = edge.Nodes(1);
        end
      end
    end
  end
end
end

function [A,B,C,D] = populate_Fc_ABCD(Sim, Fc)
  fcb = Face.empty;
  fcf = Face.empty;
  count = 0;
  for fc = Fc.Nodes(1).Faces
    if fc.Type == enumFType.Gas && fc ~= Fc
      if count == 0
        fcb = fc;
        count = 1;
      else
        % pick the larger face
        if mean(fcb.data.Area) < mean(fc.data.Area)
          fcb = fc;
        end
      end
    end
  end
  if count == 1
```

```
  % Reference that backwards face
  if fcb.Nodes(2) == Fc.Nodes(1)
    Sim.Fc_Nd03(Fc.index,1) = fcb.Nodes(1).index;
  else
    Sim.Fc_Nd03(Fc.index,1) = fcb.Nodes(2).index;
  end
else
  % Reference itself
  Sim.Fc_Nd03(Fc.index,1) = Fc.Nodes(1).index;
  fcb = Fc;
end
count = 0;
for fc = Fc.Nodes(2).Faces
  if fc.Type == enumFType.Gas && ...
      fc ~= Fc
    if count == 0
      fcf = fc;
      count = 1;
    else
      % pick the larger face
      if mean(fcf.data.Area) < mean(fc.data.Area)
        fcf = fc;
      end
    end
  end
end
if count == 1
  % Reference that backwards face
  if fcb.Nodes(1) == Fc.Nodes(2)
    Sim.Fc_Nd03(Fc.index,2) = fcb.Nodes(2).index;
  else
    Sim.Fc_Nd03(Fc.index,2) = fcb.Nodes(1).index;
  end
else
  % Reference itself
  Sim.Fc_Nd03(Fc.index,2) = Fc.Nodes(2).index;
  fcf = Fc;
end

x1 = -0.5*Fc.data.Dist;
x0 = x1 - fcb.data.Dist;
x2 = -x1;
x3 = x2 + fcf.data.Dist;
if fcb ~= Fc && all(fcb.data.Area > 0) % Fc i - 1 exists
  if fcf ~= Fc && all(fcf.data.Area > 0) % Fc i + 1 exists
    % can fill xi, xi-1, xi+1 and xi+2, as well as A, B, C and D
    A = -((x1.*x2.*x3)./(x0-x1)./(x0-x2)./(x0-x3));
    B = -((x0.*x2.*x3)./(x1-x0)./(x1-x2)./(x1-x3));
    C = -((x0.*x1.*x3)./(x2-x0)./(x2-x1)./(x2-x3));
    D = -((x0.*x1.*x2)./(x3-x0)./(x3-x1)./(x3-x2));
  else
    A = -((x1.*x2)./(x0-x1)./(x0-x2));
    B = -((x0.*x2)./(x1-x0)./(x1-x2));
    C = -((x0.*x1)./(x2-x0)./(x2-x1));
    D = 0;
  end
else
  if fcf ~= Fc && all(fcf.data.Area > 0) % Fc i + 1 exists
    A = 0;
    B = -((x2.*x3)./(x1-x2)./(x1-x3));
    C = -((x1.*x3)./(x2-x1)./(x2-x3));
    D = -((x1.*x2)./(x3-x1)./(x3-x2));
  else
    A = 0.0;
    B = 0.5;
    C = 0.5;
    D = 0.0;
  end
end
sum = A+B+C+D;
for i = 1:length(sum)
```

```
    roundsum = round(sum);
    if roundsum == 1
      % No change
    elseif roundsum == -1
      A(min(i,length(A))) = -A(min(i,length(A)));
      B(min(i,length(B))) = -B(min(i,length(B)));
      C(min(i,length(C))) = -C(min(i,length(C)));
      D(min(i,length(D))) = -D(min(i,length(D)));
    else
      A(min(i,length(A))) = 0;
      B(min(i,length(B))) = 0.5;
      C(min(i,length(C))) = 0.5;
      D(min(i,length(D))) = 0;
    end
  end
  A = CollapseVector(A);
  B = CollapseVector(B);
  C = CollapseVector(C);
  D = CollapseVector(D);
end
```

G.3. Minor Elements

Custom Minor Loss

The minor loss is a class that includes the following functionality:

A constructor.

A validity test.

```
classdef CustomMinorLoss < handle
    %UNTITLED Summary of this class goes here
    %   Detailed explanation goes here

    properties
        name string;
        Body1 Body;
        Body2 Body;
        K12 double;
        K21 double;
    end

    methods
        function this = CustomMinorLoss(B1,B2)
            answers = {'untitled', '1','1'};
            firstround = true;
            while firstround || ~isStrNumeric(answers{2}) || ~isStrNumeric(answers{3})
                if firstround; firstround = false;
                else; msgbox('Numeric Values only'); end
                answers = inputdlg( ...
                  {'Descriptive Name', ...
                  'Loss Coefficient 1 - 2', ...
                  'Loss Coefficient 2 - 1'}, ...
                  ['Define a minor loss from: ' B1.name ...
                  ' to ' B2.name '.'],[1 35], ...
                  answers);
              if isempty(answers)
                  this.K12 = 0;
                  this.K21 = 0;
                 return;
              end
            end
            this.Body1 = B1;
            this.Body2 = B2;
            this.name = answers{1};
            this.K12 = str2double(answers{2});
            this.K21 = str2double(answers{3});
        end

        function isit = isValid(this)
           isit = ~isempty(this.Body1) && ...
               ~isempty(this.Body2) && ...
               isa(this.Body1,'Body') && ...
               isa(this.Body2,'Body') && (this.K12 > 0 || this.K21 > 0);
        end
    end
end
```

Face

The face is a class that includes the following functionality:

A constructor that assigns a variety of properties based on the nodes involved.

A name calculator.

An function for defining generic properties for faces defined inside of bodies.

A function for checking if the face is a pressure contact.

A function for checking which of the nodes is the largest, in the event this face is decimated and the remaining faces moved onto the larger.

Functions for calculating the total area, and setting the area of the face. Used in area weighted functions or for determining the minor loss coefficient.

```
classdef CustomMinorLoss < handle
    %UNTITLED Summary of this class goes here
    %   Detailed explanation goes here

    properties
        name string;
        Body1 Body;
        Body2 Body;
        K12 double;
        K21 double;
    end

    methods
        function this = CustomMinorLoss(B1,B2)
            answers = {'untitled', '1','1'};
            firstround = true;
            while firstround || ~isStrNumeric(answers{2}) || ~isStrNumeric(answers{3})
                if firstround; firstround = false;
                else; msgbox('Numeric Values only'); end
                answers = inputdlg( ...
                  {'Descriptive Name', ...
                  'Loss Coefficient 1 - 2', ...
                  'Loss Coefficient 2 - 1'}, ...
                  ['Define a minor loss from: ' B1.name ...
                  ' to ' B2.name '.'],[1 35], ...
                  answers);
              if isempty(answers)
                  this.K12 = 0;
                  this.K21 = 0;
                 return;
              end
            end
            this.Body1 = B1;
            this.Body2 = B2;
            this.name = answers{1};
            this.K12 = str2double(answers{2});
            this.K21 = str2double(answers{3});
        end

        function isit = isValid(this)
```

```
            isit = ~isempty(this.Body1) && ...
                ~isempty(this.Body2) && ...
                isa(this.Body1,'Body') && ...
                isa(this.Body2,'Body') && (this.K12 > 0 || this.K21 > 0);
        end
    end
end
```

Material

The material is a class containing hardcoded properties of various materials. It contains the following functions:

A creation functions that takes a material name and calls configure.

A modify function that opens a user form and calls configure.

Functions for calculating the thermal diffusivity and internal energy from the temperature.

```
classdef Material < handle
  %MATERIAL Summary of this class goes here
  %   Detailed explanation goes here

  properties (Constant)
    Source = {...
      'Carbon Steel';
      'Forged Carbon Steel (Medium Carbon Steel)';
      '304 Stainless Steel';
      '6061 Aluminum';
      'Pure Copper';
      'Plastic, ABS';
      'Plastic, Acrylic';
      'Plastic, Polycarbonate (High Viscosity)';
      'Plastic, Poly-Ethylene (High Density)';
      'Rubber, Polychloroprene (Neoprene)';
      'Rubber, Acrylonitrile-Butadiene (Nitrile)';
      'Rubber, Silicone';
      'Foam, Expanded Polystyrene';
      'Foam, Extruded Polystyrene';
      'Foam, Rigid Polyurethane';
      'AIR';
      'N2 Gas';
      'H2 Gas';
      'Helium Gas';
      'Perfect Insulator';
      'Constant Temperature'};
  end

  properties
    % General Properties
    name;
    Color double;
    Phase enumMaterial;
    ThermalConductivity double;
    dT_du double;
    dh_dT double;
    u2T function_handle;
    Density double;

    % Gas Properties
    R double;
    dT_duFunc function_handle;
    dh_dTFunc function_handle;
    kFunc function_handle;
    muFunc function_handle;
    gammaFunc function_handle;

  end

  methods
    function this = Material(MaterialName)
```

```
      if nargin == 0
        return;
      end
      this.Configure(MaterialName)
    end
    function Modify(this)
      for index = 1:length(this.Source)
        if strcmp(this.Source{index},this.name)
          break;
        end
      end
      index = listdlg('ListString',this.Source,...
        'SelectionMode','single',...
        'InitialValue',index);
      this.Configure(this.Source{index});
    end
    function Configure(this,MaterialName)
      this.name = MaterialName;
      % Thermal Conductivity
      % https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html
      switch MaterialName
        case 'Carbon Steel' % Carbon Steel
          this.Color = [0.400 0.384 0.384];% [102 98 98];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 43; % W/(m*K)
          this.dT_du = 1/502.416; % J/(kg*K)
          this.Density = 7850; % kg/(m^3)
        case 'Forged Carbon Steel (Medium Carbon Steel)'
          % See Medium Carbon Steel - MatWeb.pdf
          this.Color = [0.380 0.365 0.365];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 47.7; % W/(m*K)
          this.dT_du = 1/477; % J/(kg*K)
          this.Density = 7850; % kg/(m^3)
        case '304 Stainless Steel' % 304 Stainless Steel
          this.Color = [0.510 0.526 0.537];% [130 134 137];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 14.4; % W/(m*K)
          this.dT_du = 1/500; % J/(kg*K)
          this.Density = 8000; % kg/(m^3)
        case '6061 Aluminum' % 6061 Aluminum
          this.Color = [0.628 0.628 0.628];% [160 160 160];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 176.5; % 151-202 W/(m*K)
          this.dT_du = 1/897; % J/(kg*K)
          this.Density = 2700; % kg/(m^3)
        case 'Pure Copper' % Pure Copper
          this.Color = [0.628 0.416 0.259];% [160 106 66];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 401; % W/(m*K) % At 0 C
          this.dT_du = 1/385; % kg*K/J
          this.Density = 8960; % kg/(m^3)
        case 'Plastic, ABS' % Acrylonitrile Butadiene Styrene
          % http://www.substech.com/dokuwiki/doku.php?id=thermoplastic_acrylonitrile-butadiene-
styrene_abs
          % https://www.sciencedirect.com/topics/materials-science/acrylonitrile-butadiene-
styrene
          this.Color = [0.1 0.1 0.8]; % Blue
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 0.25; % W/(m*K)
          this.dT_du = 1/1690; % Specific heat capacity     1,390   –      1,920   J/kg·K
          this.Density = 1050;
        case 'Plastic, Acrylic'
          % http://www.matweb.com/search/datasheet.aspx?bassnum=O1303&ckck=1
          this.Color = [0.909 0.941 1]; %
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 0.198; % W/(m*K)
          this.dT_du = 1/1810; % Specific heat capacity     1,460   –      2,160   J/kg·K
          this.Density = 1185; % kg/(m^3)
        case 'Plastic, Polycarbonate (High Viscosity)'
          % MatWeb
```

```
  this.Color = [0.909 0.941 1]; %
  this.Phase = enumMaterial.Solid;
  this.ThermalConductivity = 0.198; % W/(m*K)
  this.dT_du = 1/1810; % Specific heat capacity     1,460   -       2,160   J/kg·K
  this.Density = 1200; % kg/(m^3)
case 'Plastic, Poly-Ethylene (High Density)'
  % MatWeb
  this.Color = [0.909 0.941 1]; %
  this.Phase = enumMaterial.Solid;
  this.ThermalConductivity = 0.196; % W/(m*K)
  this.dT_du = 1/1540; % Specific heat capacity     1,460   -       2,160   J/kg·K
  this.Density = 946; % kg/(m^3)
case 'Rubber, Polychloroprene (Neoprene)'
  % https://thermtest.com/materials-database#NEOPRENE
  this.Color = [0.1 0.1 0.1];
  this.Phase = enumMaterial.Solid;
  this.ThermalConductivity = 0.192; % W/(m*K)
  this.dT_du = 1/1029; % Specific heat capacity     1,460   -       2,160   J/kg·K
  this.Density = 1250; % kg/(m^3)
case 'Rubber, Acrylonitrile-Butadiene (Nitrile)'
  % https://thermtest.com/materials-database#NITRILE
  this.Color = [33/255 16/255 0];
  this.Phase = enumMaterial.Solid;
  this.ThermalConductivity = 0.243; % W/(m*K)
  this.dT_du = 1/1966; % Specific heat capacity     1,460   -       2,160   J/kg·K
  this.Density = 1000; % kg/(m^3)
case 'Rubber, Silicone'
  % https://thermtest.com/materials-database#SILICONE-RUBBER-(MEDIU
  this.Color = [22/255 25/255 37/255];
  this.Phase = enumMaterial.Solid;
  this.ThermalConductivity = 0.335; % W/(m*K)
  this.dT_du = 1/1255; % Specific heat capacity     1,460   -       2,160   J/kg·K
  this.Density = 1300; % kg/(m^3)
case 'Foam, Expanded Polystyrene'
  % http://www.eyoungindustry.com/uploadfile/file/20160612/20160612155656_94768.pdf
  % Implement subtype interface
  index = 0;
  while index == 0
    index = 1;
    index = listdlg('ListString',{...
      'L - 11 kg/m3','SL - 13.5 kg/m3',...
      'S - 16 kg/m3','M - 19 kg/m3',...
      'H - 24 kg/m3','VH - 28 kg/m3',...
      'Custom Density'},...
      'SelectionMode','single',...
      'InitialValue',index);
  end
  if index < 7
    Temp = [11 13.5 16 19 24 28];
    this.Density = Temp(index);
  else
    this.Density = str2double(inputdlg('Enter EPS density',...
      'Custom Expanded Polystyrene',[1 35],{'16'}));
  end
  this.Color = [1 0.83 0.83];
  this.Phase = enumMaterial.Solid;
  this.ThermalConductivity = 0.1142*(this.Density)^(-0.371); % W/(m*K)
  % https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html
  this.dT_du = 1/(1400); % Specific heat capacity   1,300   -       1,500   J/kg·K
case 'Foam, Extruded Polystyrene'
  % http://www.eyoungindustry.com/uploadfile/file/20160612/20160612155656_94768.pdf
  % Implement subtype interface
  index = 0;
  while index == 0
    index = 1;
    index = listdlg('ListString',{...
      'Custom Density'},...
      'SelectionMode','single',...
      'InitialValue',index);
  end
  if index < 1
```

```
            Temp = [];
            this.Density = Temp(index);
          else
            this.Density = str2double(inputdlg('Enter XPS density',...
              'Custom Expanded Polystyrene',[1 35],{'30'}));
          end
          this.Color = [1 0.83 0.83];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 0.036; % W/(m*K)
          % https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html
          this.dT_du = 1/(1400); % Specific heat capacity   1,300   -      1,500   J/kg·K
        case 'Foam, Rigid Polyurethane'
          % http://www.react-ite.eu/uploads/tx_mddownloadbox/PP02_Thermal_insulation_materials_-
_PP02_20130715.pdf
          % Implement subtype interface
          index = 0;
          while index == 0
            index = 1;
            index = listdlg('ListString',{...
              '30 kg/m3',...
              '40 kg/m3',...
              '80 kg/m3',...
              'Custom Density'},...
              'SelectionMode','single',...
              'InitialValue',index);
          end
          if index < 4
            Temp = [30 40 80];
            this.Density = Temp(index);
          else
            this.Density = str2double(inputdlg('Enter PUR density',...
              'Custom Rigid Polyurethane',[1 35],{'16'}));
          end
          this.Color = [0.957 0.937 0.745];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 0.0371*(this.Density)^(-0.098); % W/(m*K)
          this.dT_du = 1/1500; % Specific heat capacity     1,300   -      1,500   J/kg·K
        case 'AIR' % Standard Air
          this.Color = [0.906 0.906 0.906];% [231 231 231];
          this.Phase = enumMaterial.Gas;
          this.ThermalConductivity = 0.0262; % W/(m*K)
          this.R = 287;
          this.dT_duFunc = @(u) (-2.88367e-10)*u + (1.42462651e-3); % Verified
          this.dT_du = this.dT_duFunc(298);
          this.dh_dTFunc = @(T) 1013.5 - 0.15709*T + 0.00049079*T.^2 - 0.00000020552*T.^3;
          this.dh_dT = this.dh_dTFunc(298);
          this.u2T = @(u) (-1.44183718e-10)*u.^2 + (1.42462651e-3)*u; % Verified
          this.kFunc = @(T) (-1.3974e-11)*T.^3 + (-4.5769e-8)*T.^2 + ...
            (9.8961e-5)*T + 3.4920e-4; % Verified / Updated
          this.muFunc = @(T) (1.6834E-14)*T.^3 - (4.7591E-11)*T.^2 + ...
            7.1598E-08*T + 7.5908E-07; % Verified / Updated
        case 'N2 Gas' % Nitrogen
          fprintf('XXX Need cv and u2T for nitrogen XXX\n');
          this.Color = [0.906 0.906 0.906];
          this.Phase = enumMaterial.Gas;
          this.R = 296.8;
          this.dT_duFunc = @(u) -3.7744e-10*u + 1.447e-3; % Verified
          this.dT_du = this.dT_duFunc(298);
          % http://www.colby.edu/chemistry/PChem/notes/Ch7Tables.pdf
          this.dh_dTFunc = @(T) (28.882 - 0.00157*T + 0.00000808*T.^2 -
0.000000002871*T.^3)/0.0280134;
          this.dh_dT = this.dh_dTFunc(298);
          this.u2T = @(u) -1.8872e-10*(u.^2) + 1.447e-3*u - 1.2188e1; % Verified
          this.kFunc = @(T) 3.3552E-11*(T.^3) - 7.3741E-08*(T.^2) + 1.0792E-04*T - 6.5862E-04; %
Verified / Update
          this.muFunc = @(T) 1.9072E-14*(T.^3) - 4.9344E-11*(T.^2) + 7.1568E-08*T + 3.4160E-07; %
Verified / Updated
        case 'H2 Gas' % Hydrogen
          this.Color = [0.906 0.906 0.906];% [231 231 231];
          this.Phase = enumMaterial.Gas;
          this.R = 4124.2;
```

```
          this.dT_duFunc = @(u) -8.0404e-13*(T) + 1.0068E-04; % Verified
          this.dT_du = this.dT_duFunc(298);
          % http://www.colby.edu/chemistry/PChem/notes/Ch7Tables.pdf
          this.dh_dTFunc = @(T) (29.088 - 0.00192*T + 0.00000400*T.^2 -
0.000000000870*T.^3)/0.002016;
          this.dh_dT = this.dh_dTFunc(298);
          this.u2T = @(u) - 4.0202E-13*(T.^2) + 1.0068E-04*T + 1.8779E+00; % Verified
          this.kFunc = @(T) 9.0864E-10*(T.^3) - 1.0269E-06*(T.^2) + 8.7129E-04*T - 7.4747E-03; %
Verified
          this.muFunc = @(T) 8.4578E-13*(T.^3) - 1.8183E-09*(T.^2) + 2.8432E-06*T+ 1.8282E-04; %
Verified
        case 'Helium Gas' % Helium
          this.Color = [0.906 0.906 0.906];% [231 231 231];
          this.Phase = enumMaterial.Gas;
          this.R = 2077.1;
          this.dT_duFunc = @(u) 0.00032096; % Verified
          this.dT_du = this.dT_duFunc(298);
          this.dh_dTFunc = @(T) 20.786/0.004002602;
          this.dh_dT = this.dh_dTFunc(298);
          this.u2T = @(u) 0.00032096*u; % Verified
          this.kFunc = @(T) 1.7109E-10*(T.^3) - 3.3300E-07*(T.^2) + 4.5124E-04*(T) + 3.9533E-02;
% Verified
          this.muFunc = @(T) 2.8183E-14*(T.^3) - 5.6714E-11*(T.^2) + 7.0661E-08*(T) + 3.4685E-06;
% Verified
        case 'Perfect Insulator'
          this.Color = [0.15 0.15 0.15];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 0; % W/(m*K)
          this.dT_du = -1; % J/(kg*K)
          this.Density = 0.01; % kg/(m^3)
        case 'Constant Temperature'
          this.Color = [1 1 1];
          this.Phase = enumMaterial.Solid;
          this.ThermalConductivity = 1e30; %W/(m*K)
          this.dT_du = -1; % J/(kg*K)
          this.Density = 0.01;
        otherwise
          fprintf(['XXX MISSING PROPERTIES FOR MATERIAL: ' ...
            MaterialName '.\n']);
      end
    end
    function a = thermaldiffusivity(this)
      a = this.ThermalConductivity*this.dT_du/(this.Density);
    end
    function u = initialInternalEnergy(this,T)
      switch this.Phase
        case enumMaterial.Gas
          % Use u2T function
          uold = 298;
          r = this.u2T(uold) - T;
          while true
            uguess = uold - r/this.dT_duFunc(uold);
            r = this.u2T(uguess) - T;
            if abs(r) < 1e-8; break; end
            uold = uguess;
          end
          u = uguess;
        case enumMaterial.Solid
          if this.dT_du ~= 0
            u = T/this.dT_du;
          else
            u = 0;
          end
      end
    end
  end

end
```

Node

A node is a class that includes the following functionality:

A constructor.

A function use to merge two nodes into one.

A group of functions designed to calculate specific properties.

```
classdef Node < handle
  %NODE Summary of this class goes here
  %   Detailed explanation goes here

  properties
    isDynamic logical;
    Type enumNType;
    data;
    iPressure double;
    iTemperature double;
    xmin double;
    xmax double;
    ymin double;
    ymax double;
    Faces Face;
    Nodes Node;
    Body;

    isEnd logical; % Allows for the required distance calculation

    index int32; % For translation to array for solving
  end

  properties (Hidden)
    stateLocation Pnt2D;
    isminCenterCoordsCalcd logical = false;
    stateminCenterCoords Pnt2D;
    useStoredVolume logical;
    StoredVolume double;
  end

  properties (Dependent)
    minCenterCoords Pnt2D;
  end

  methods
    function this = Node(Type,xmin,xmax,ymin,ymax,Faces,Nodes,theBody,index)
      if nargin == 0; return; end
      % Node(Type, data, iPressure, iTemperature, xmin, xmax, ymin, ymax, Faces, Nodes, matl)
      this.Type = Type;

      this.xmin = xmin;
      this.xmax = xmax;
      this.ymin = ymin;
      this.ymax = ymax;
      if nargin == 5; return; end
      this.Faces = Faces;
      this.Nodes = Nodes;

      if this.vol() < 0
        fprintf('err');
      end

      this.index = index;
```

```
  this.Body = theBody;
  if isempty(this.data); this.calcData(); end

  this.updateisDynamic();
end
function [success, nd2del, fc2del] = combineSolid(this,other,refinementfactor)
  % Set outputs to default values
  nd2del = Node.empty;
  fc2del = Face.empty;
  success = false;

  % It must be a Face between two solid nodes
  if this.Type == enumNType.SN && other.Type == enumNType.SN

    % Find the face between the two nodes
    for fc = this.Faces
      if (fc.Nodes(1) == this && fc.Nodes(2) == other) || (...
          fc.Nodes(2) == this && fc.Nodes(1) == other)

        % Get the two materials
        if isfield(this.data,'matl'); matl1 = this.data.matl;
        else; matl1 = this.Body.matl;
        end
        if isfield(other.data,'matl'); matl2 = other.data.matl;
        else; matl2 = other.Body.matl;
        end

        % Calculate the timestep based on a Fourier Number of 0.25
        if matl1.dT_du == -1
          dT_du1 = 1e-30; else; dT_du1 = matl1.dT_du; end
        if matl2.dT_du == -1
          dT_du2 = 1e-30; else; dT_du2 = matl2.dT_du; end

        timestep1 = (0.25*matl1.Density/dT_du1)*this.vol()./fc.data.U;
        timestep2 = (0.25*matl2.Density/dT_du2)*other.vol()./fc.data.U;

        % If the timestep for this interaction would be too small
        if all(timestep1 < 1e-3) || all(timestep2 < 1e-3)
          %
          if sum(timestep1 < timestep2) > length(timestep1)/2
            collector = other;
            nd2del = this;
          else
            collector = this;
            nd2del = other;
          end
          fc2del = fc;
          success = true;
          break;
        end

        % Exit because only one face will be between these nodes
        break;
      end
    end

    if success
      % Calculate the updated properties
      collector.StoredVolume = this.vol() + other.vol();
      vol1 = this.vol();
      vol2 = other.vol();
      collector.useStoredVolume = true;
      if matl1.dT_du == -1
        collector.data.matl = matl1;
      elseif matl2.dT_du == -1
        collector.data.matl = matl2;
      elseif matl1 ~= matl2
        if isfield(collector.data,'matl'); matl = collector.data.matl;
        else; matl = collector.Body.matl;
        end
        mass = vol1*matl1.Density + vol2*matl2.Density;
```

```
        collector.data.matl = Material();
        collector.data.matl.Color = matl1.Color;
        collector.data.matl.Phase = enumMaterial.Solid;
        collector.data.matl.ThermalConductivity = ...
          (vol1*matl1.Density*matl1.ThermalConductivity + ...
          vol2*matl2.Density*matl2.ThermalConductivity)/...
          (vol1*matl1.Density + vol2*matl2.Density);
        collector.data.matl.Density = (vol1*matl1.Density + ...
          vol2*matl.Density)/collector.StoredVolume;
        collector.data.matl.dT_du = (vol1*matl1.Density*dT_du1 + ...
          vol2*matl2.Density*dT_du2)/mass;
      end

      % Modify the faces in the weaker node so that they reference the
      % ... collector instead.
      keep = true(size(nd2del.Faces));
      i = 1;
      for fc = nd2del.Faces
        if fc ~= fc2del
          if fc.Nodes(1) == nd2del
            fc.Nodes(1) = collector;
          elseif fc.Nodes(2) == nd2del
            fc.Nodes(2) = collector;
          end
        else
          keep(i) = false;
        end
        i = i + 1;
      end
      nd2del.Faces = nd2del.Faces(keep);

      % Remove the face that goes between the two nodes
      keep = true(size(collector.Faces));
      for i = 1:length(collector.Faces)
        if collector.Faces(i) == fc2del
          keep(i) = false;
        end
      end
      collector.Faces = collector.Faces(keep);
      collector.Faces(end+1:end+length(nd2del.Faces)) = nd2del.Faces;
    end
  end
end

function calcData(this)
  if this.Type ~= enumNType.EN
    matl = this.Body.matl;
    switch matl.Phase
      case enumMaterial.Solid
        %% Solids
        this.data.T = this.Body.Temperature();
        this.data.dT_dU = matl.dT_du;

      case {enumMaterial.Gas, enumMaterial.Liquid}
        %% Fluids
        this.data.P = this.Body.Pressure();
        this.data.T = this.Body.Temperature();
        if ~isempty(this.Body.Matrix) && ~isempty(this.Body.Matrix.Dh)
          %% Not an empty Volume
          % Scale the volume
          this.data.vol = this.vol()*this.Body.Matrix.data.Porosity;
          this.data.Dh = this.Body.Matrix.Dh;
          % Assign the Nusselt number function (Re,Pr)
          this.data.NuFunc_l = this.Body.Matrix.NuFunc_l;
          if ~this.Body.Matrix.isFullyLaminar
            this.data.NuFunc_t = this.Body.Matrix.NuFunc_t;
          else
            this.data.NuFunc_t = this.data.NuFunc_l;
          end
          dir = getBodyDirection(this.Body);
          if dir == 1
```

```
            % Horizontal
            this.data.Area = (this.ymax-this.ymin)*pi*(this.xmax + this.xmin)*...
              this.Body.Matrix.data.Porosity;
          else
            % Vertical
            this.data.Area = pi*(this.xmax^2 - this.xmin^2)*...
              this.Body.Matrix.data.Porosity;
          end
        else
          %% An empty channel
          this.data.vol = this.vol();
          dir = getBodyDirection(this.Body);
          if dir == 1
            % Horizontal
            this.data.Orient = enumOrient.Horizontal;
            this.data.Dh = 2.*(this.ymax-this.ymin);
            this.data.Area = (this.ymax-this.ymin)*pi*(this.xmax + this.xmin);
            % Assign default Nusselt Number Correlation
            this.data.NuFunc_l = @(Re) 3.66; % Fully Developed, Uniform Surface Temperature
          else
            this.data.Orient = enumOrient.Vertical;
            this.data.Dh = 2.*(this.xmax-this.xmin);
            this.data.Area = pi*(this.xmax^2 - this.xmin^2);
            % Assign default Nusselt Number Correlation
            ri_ro = this.xmin/this.xmax;
            if ri_ro == 0
              Nuo = 3.66;
              Nui = 0;
            else
              Nuo = 4.6961*(ri_ro)^(0.0548);
              Nui = 4.4438*(ri_ro)^(-0.43);
            end
            this.data.NuiFunc_l = @(Re) Nui;
            this.data.NuoFunc_l = @(Re) Nuo;
          end
          this.data.NuFunc_t = @(Re,Pr) 0.035*(Re.^0.75).*(Pr.^0.33);
        end
        if ~isscalar(this.data.Dh); this.data.Dh = CollapseVector(this.data.Dh); end
        if ~isscalar(this.data.Area); this.data.Area = CollapseVector(this.data.Area); end
      end
    else
      % Body is actually an environment
      this.data.T = this.Body.Temperature;
      this.data.P = this.Body.Pressure;
      this.data.h = this.Body.h;
      if isempty(this.Body.matl)
        this.Body.matl = Material('AIR');
      end
      this.data.rho = this.data.P/(this.data.T*this.Body.matl.R);
    end
  end
  function addFace(this,Face)
    this.Faces(end+length(Face):-1:end+1) = Face;
  end
  function updateisDynamic(this)
    if length(this.xmin) > 1 || length(this.xmax) > 1 || length(this.ymin) > 1 ||
length(this.ymax) > 1 % this.Type ~= enumNType.SN
      this.isDynamic = true;
    else
      for Face = this.Faces
        if Face.isDynamic
          this.isDynamic = true;
          return;
        end
      end
      this.isDynamic = false;
    end
  end
  function var = total_vol(this)
    var = (pi*(this.xmax^2 - this.xmin^2)).*(this.ymax - this.ymin);
  end
```

```
    function var = vol(this)
      if this.Type == enumNType.SN
        if this.useStoredVolume
          var = this.StoredVolume;
        else
          var = pi.*(this.xmax.^2-this.xmin.^2)*...
            (this.ymax(1)-this.ymin(1));
        end
      else
        if ~isa(this.Body,'Body')
          P = 1;
        elseif isempty(this.Body.Matrix)
          P = 1;
        else
          if isfield(this.Body.Matrix.data,'Porosity')
            P = this.Body.Matrix.data.Porosity;
          else
            P = 1;
          end
        end
        var = P*pi.*(this.xmax.^2-this.xmin.^2)*...
          (this.ymax-this.ymin);
        var = CollapseVector(var);
      end
    end
    function recalc_Dh(this)
      if this.Type ~= enumNType.SN && this.Type ~= enumNType.EN
        % Dh = 4 * Volume / Surface Area

        V = this.vol();
%         for fc = this.Faces
%           if fc.Type == enumFType.Mix
%             S_total = S_total + fc.data.Area;
%           end
%         end
%         S_total = 2*pi*(this.xmax^2 - this.xmin^2) + ... Top & Bottom
%           2*pi*(this.xmax + this.xmin)*(this.ymax - this.ymin); % Sides
        S_total = 2*pi*(this.xmin + this.xmax)*(this.ymax-this.ymin) + ...
          2*pi*(this.xmax^2-this.xmin^2);
        if isempty(this.Body.Matrix) || ...
            strcmp(this.Body.Matrix.name,'Undefined Matrix') == 1
          for fc = this.Faces
            if fc.Type == enumFType.Gas
              S_total = S_total - fc.data.Area;
            end
          end
        else
          if isfield(this.Body.Matrix.data,'ignore_canister') && ...
                  this.Body.Matrix.data.ignore_canister
             S_total = 0;
             includeGas = false;
          else
             includeGas = true;
          end
          for fc = this.Faces
            if fc.Type == enumFType.Mix
              % Include only matrix faces when it is a matrix, as the heat
              % ... exchange equations assume that it is just the heat
              % ... exchanger geometry.
              if fc.Nodes(1).Body == fc.Nodes(2).Body
                S_total = S_total + fc.data.Area;
              end
            end
            if includeGas
                if fc.Type == enumFType.Gas
                  S_total = S_total - fc.data.Area;
                end
            end
          end
        end
```

```
    Dh = 4*V./S_total; % 4*A*L/(P*L)
    this.data.Dh = CollapseVector(Dh);
  end
end
function center = get.minCenterCoords(this)
  if ~this.isminCenterCoordsCalcd || isempty(this.stateminCenterCoords)
    if this.isDynamic
      this.stateminCenterCoords = ...
        Pnt2D(0.5*(this.xmin+this.xmax),...
        0.5*(min(this.ymin)+min(this.ymax)));
    else
      this.stateminCenterCoords = ...
        Pnt2D(0.5*(this.xmin+this.xmax),...
        0.5*(this.ymin+this.ymax));
    end
  end
  if isa(this.Body,'Body')
    center = this.Body.Group.TranslatePnt2D(this.stateminCenterCoords);
  else
    center = this.stateminCenterCoords;
  end
end
function center = CenterCoords(this,Inc)
  if this.isDynamic
    if isscalar(this.ymin)
      if isscalar(this.ymax)
        center = this.minCenterCoords;
      else
        center = ...
          Pnt2D(0.5*(this.xmin+this.xmax), ...
          0.5*(this.ymin+this.ymax(Inc)));
      end
    else
      if isscalar(this.ymax)
        center = ...
          Pnt2D(0.5*(this.xmin+this.xmax), ...
          0.5*(this.ymin(Inc)+this.ymax));
      else
        center = ...
          Pnt2D(0.5*(this.xmin+this.xmax), ...
          0.5*(this.ymin(Inc)+this.ymax(Inc)));
      end
    end
  else
    center = this.stateminCenterCoords;
  end
  if isa(this.Body,'Body')
    center = this.Body.Group.TranslatePnt2D(center);
  else
    center = this.stateminCenterCoords;
  end
end
function Struct = getGrouping(this,Struct,n,sourceFace)
  % if this node is a transition, stop this recursion
  if nargin == 4
    for Fc = this.Faces
      if isfield(Fc.data,'K12') || ...
          (isfield(Fc.data,'dx') &&  ...
          abs(Fc.data.dx - sourceFace.data.dx)/sourceFace.data.dx > 0.1)
        return;
      end
    end
    this.data.Group = n;
    Struct.Nds = [Struct.Nds this];
  elseif nargin == 3
    val = 0;
    for Fc = this.Faces
      if isfield(Fc.data,'dx')

        if isscalar(val)
          if isscalar(Fc.data.dx)
```

```
            if Fc.data.dx > val
              val = Fc.data.dx;
            end
          else
            val = max([val(ones(size(Fc.data.dx))); Fc.data.dx]);
          end
        else
          if isscalar(Fc.data.dx)
            val(val<Fc.data.dx) = Fc.data.dx;
          else
            val = max([val; Fc.data.dx]);
          end
        end

      end
    end
    if isscalar(val) && val == 0
      return;
    end
    for Fc = this.Faces
      if isfield(Fc.data,'K12') || ...
          (isfield(Fc.data,'dx') && ...
          any(abs(Fc.data.dx - val)./val > 0.1))
        return;
      end
    end
  end
  for Fc = this.Faces
    if ~isfield(Fc.data,'Group') && isfield(Fc.data,'dx')
      Struct.Fcs = [Struct.Fcs Fc];
    end
  end
  for i = 1:length(this.Nodes)
    if isfield(this.Nodes(i).data,'P') && isfield(this.Faces(i).data,'dx')
      Struct = getGrouping(this.Nodes(i),Struct,n,this.Faces(i));
    end
  end
end
function value = getArea(this,ind,Connection)
  if ~isa(this.Body,'Body')
    value = 1e8;
    return;
  end
  if this.Body.divides(1) ~= this.Body.divides(2) || nargin < 3
    if isfield(this.data,'Area')
      if isscalar(this.data.Area)
        value = this.data.Area;
      else
        if ind == 0
          value = this.data.Area(end);
        else
          value = this.data.Area(ind);
        end
      end
    else
      value = 0;
    end
  else
   switch Connection.Orient
     case enumOrient.Vertical
       if ind == 0
         imin = 1;
         imax = 1;
       else
         imin = min(length(this.ymin),ind);
         imax = min(length(this.ymax),ind);
       end
       value = 2*pi*Connection.x*(this.ymax(imax)-this.ymin(imin));
     case enumOrient.Horizontal
       value = pi*(this.xmax^2-this.xmin^2);
   end
```

```
      end
    end
    function istouching = isTouching(this,other)
      istouching = ~(this.xmin > other.xmax || this.xmax < other.xmin) && ...
        ~(this.ymin(1) > other.ymax(1) || this.ymax(1) < other.ymin(1));
    end
    function totalGasSurfaceArea = getTotalGasSurfaceArea(this,Orientation)
      if isempty(this.data.WSNG) || length(this.data.WSNG.members) ~= 1
        for fc = this.Faces
          if fc.Type == enumFType.Mix && fc.Orient == Orientation
            totalGasSurfaceArea = totalGasSurfaceArea + fc.data.Area;
          end
        end
      else
        % Consider the total area, because this is a corner
        for fc = this.Faces
          if fc.Type == enumFType.Mix
            totalGasSurfaceArea = totalGasSurfaceArea + fc.data.Area;
          end
        end
      end
    end
  end
end
```

Node Contact

The node contact is a class that includes the following functionality:

A constructor.

A function used for calculating the periods of time where the two included nodes are touching.

A set of functions of calculating the face properties.

A set of functions that allow for masking or subtracting of two node contacts.

```
classdef NodeContact < handle
  %NODECONTACT Summary of this class goes here
  %   Detailed explanation goes here

  properties
    Node Node;
    Start double = 0;
    End double = 0;
    Type enumFType;
    Connection Connection;
    data struct;
  end

  methods
    function this = NodeContact(Node,Start,End,Type,Connection)
      if nargin == 0; return; end
      %NODECONTACT Construct an instance of this class
      %   Detailed explanation goes here
      this.Node = Node;
      this.Start = Start;
      this.End = End;
      this.Type = Type;
      this.Connection = Connection;
    end
    function ActiveTimes = activeTimes(NC1,NC2)
      ActiveTimes = ~((NC1.Start >= NC2.End) + (NC2.Start >= NC1.End));
      if ~any(ActiveTimes)
        ActiveTimes = logical([]);
        return;
      end
      if all(ActiveTimes)
        ActiveTimes = true;
        return;
      end
    end
    function [Area] = getArea(NC1,NC2,ActiveTimes)
      if nargin < 3
        ActiveTimes = NC1.activeTimes(NC2);
      end
      ActiveTimes = logical(ActiveTimes);
      if isscalar(ActiveTimes)
        % scalar: s1,e1,s2,e2
        if NC1.Connection.Orient == enumOrient.Vertical
          if isscalar(NC1.Start)
            if isscalar(NC2.Start)
              TheStart = max([NC1.Start NC2.Start]);
            else
              TheStart = NC2.Start;
              TheStart(TheStart<NC1.Start) = NC1.Start;
            end
          else
```

```
      if isscalar(NC2.Start)
        TheStart = NC1.Start;
        TheStart(TheStart<NC2.Start) = NC2.Start;
      else
        TheStart = max([NC1.Start; NC2.Start]);
      end
    end
    if isscalar(NC1.End)
      if isscalar(NC2.End)
        TheEnd = min([NC1.End NC2.End]);
      else
        TheEnd = NC2.End;
        TheEnd(TheEnd>NC1.End) = NC1.End;
      end
    else
      if isscalar(NC2.End)
        TheEnd = NC1.End;
        TheEnd(TheEnd>NC2.End) = NC2.End;
      else
        TheEnd = min([NC1.End; NC2.End]);
      end
    end
    Area = 2*pi*NC1.Connection.x*(TheEnd-TheStart);
  else
    Area = pi*(min([NC1.End NC2.End])^2-max([NC1.Start NC2.Start])^2);
  end
else % This case will only include Vertical because Horizontal never changes activation
  % Vertical
  if isscalar(NC1.Start)
    if isscalar(NC2.Start)
      TheStart = max([NC1.Start NC2.Start]);
    else
      TheStart = NC2.Start;
      TheStart(TheStart<NC1.Start) = NC1.Start;
    end
  else
    if isscalar(NC2.Start)
      TheStart = NC1.Start;
      TheStart(TheStart<NC2.Start) = NC2.Start;
    else
      TheStart = max([NC1.Start; NC2.Start]);
    end
  end
  if isscalar(NC1.End)
    if isscalar(NC2.End)
      TheEnd = min([NC1.End NC2.End]);
    else
      TheEnd = NC2.End;
      TheEnd(TheEnd>NC1.End) = NC1.End;
    end
  else
    if isscalar(NC2.End)
      TheEnd = NC1.End;
      TheEnd(TheEnd>NC2.End) = NC2.End;
    else
      TheEnd = min([NC1.End; NC2.End]);
    end
  end
  Area = 2*pi*NC1.Connection.x*(TheEnd-TheStart);
  Area(~ActiveTimes) = 0;
end
if NC1.Node.Type ~= enumNType.SN && NC2.Node.Type ~= enumNType.SN
    P = 1;
    for NC = [NC1 NC2]
      if isa(NC.Node.Body,'Body')
        if ~isempty(NC.Node.Body.Matrix)
          Mat = NC.Node.Body.Matrix;
          if ~strcmp(Mat.name,'Undefined Matrix') && ...
              isfield(Mat.data,'Porosity')
            P = min(P,Mat.data.Porosity);
          end
```

```
        end
      end
    end
    if P ~= 1
      Area = Area*P;
    end
  end
end
function [U] = getConductance(NC1,NC2,ActiveTimes)
  U = 0;
  ActiveTimes = logical(ActiveTimes);
  if isfield(NC1.Node.data,'matl'); matl1 = NC1.Node.data.matl;
  else; matl1 = NC1.Node.Body.matl;
  end
  if isfield(NC2.Node.data,'matl'); matl2 = NC2.Node.data.matl;
  else; matl2 = NC2.Node.Body.matl;
  end
  if isscalar(ActiveTimes)
    % Static
    % scalar: s1,e1,s2,e2
    L = abs(min([NC1.End NC2.End])-max([NC1.Start NC2.Start]));
    if NC1.Connection.Orient == enumOrient.Vertical
      if NC1.Node.Type == enumNType.SN % Solid Node
        U = AnnularConduction(...
          NC1.Node,  NC1.Connection.x,...
          L,         matl1);
        if U == 0
          return;
        end
      elseif NC1.Node.Type == enumNType.EN
        U = 2*pi*NC1.Connection.x*L*NC1.Node.Body.h;
      end
      if NC2.Node.Type == enumNType.SN % Solid Node
        if U ~= 0
          U = 1/(1/U + 1/...
            AnnularConduction(...
            NC2.Node, NC2.Connection.x,...
            L,        matl2));
        else
          U = AnnularConduction(...
            NC2.Node, NC2.Connection.x,...
            L,        matl2);
        end
      elseif NC2.Node.Type == enumNType.EN
        if U ~= 0
          U = 1/(1/U + 1/(2*pi*NC2.Connection.x*L*NC2.Node.Body.h));
        else
          U = 2*pi*NC2.Connection.x*L*NC2.Node.Body.h;
        end
      end
    else
      r1 = max([NC1.Start NC2.Start]);
      r2 = r1 + L;
      if NC1.Node.Type == enumNType.SN % Solid Node
        U = LinearConduction(NC1.Node, r1, r2, matl1);
        if U == 0; return; end
      elseif NC1.Node.Type == enumNType.EN
        U = 2*pi*(r2^2-r1^2)*NC1.Node.Body.h;
      end
      if NC2.Node.Type == enumNType.SN % Solid Node
        if U ~= 0
          U = 1/(1/U + 1/LinearConduction(NC2.Node, r1, r2, matl2));
        else
          U = LinearConduction(NC2.Node, r1, r2, matl2);
        end
      elseif NC2.Node.Type == enumNType.EN
          if U ~= 0
            U = 1/(1/U + 1/(2*pi*(r2^2-r1^2)*NC2.Node.Body.h));
          else
            U = 2*pi*(r2^2-r1^2)*NC2.Node.Body.h;
          end
```

```
        end
      end
      return;
    else
      % Dynamic - Vertical Only
      TheStart = zeros(1,Frame.NTheta);
      TheEnd = zeros(1,Frame.NTheta);
      if isscalar(NC1.Start)
        if isscalar(NC2.Start)
          TheStart = max([NC1.Start NC2.Start]);
        else
          TheStart = NC2.Start;
          TheStart(ActiveTimes & TheStart<NC1.Start) = NC1.Start;
        end
      else
        if isscalar(NC2.Start)
          TheStart = NC1.Start;
          TheStart(ActiveTimes & TheStart<NC2.Start) = NC2.Start;
        else
          TheStart(ActiveTimes) = max([NC1.Start(ActiveTimes); NC2.Start(ActiveTimes)]);
        end
      end
      if isscalar(NC1.End)
        if isscalar(NC2.End)
          TheEnd = min([NC1.End NC2.End]);
        else
          TheEnd = NC2.End;
          TheEnd(ActiveTimes & TheEnd>NC1.End) = NC1.End;
        end
      else
        if isscalar(NC2.End)
          TheEnd = NC1.End;
          TheEnd(ActiveTimes & TheEnd>NC2.End) = NC2.End;
        else
          TheEnd(ActiveTimes) = min([NC1.End(ActiveTimes); NC2.End(ActiveTimes)]);
        end
      end
      U = 2*pi*NC1.Connection.x*(TheEnd-TheStart);
      U(~ActiveTimes) = 0;
      % Actual Conduction Modifier
      r = NC1.Connection.x;
      L = U./(2*pi*r);
      if NC1.Node.Type == enumNType.SN
        if NC2.Node.Type == enumNType.SN
          % Both are solid
          U = 1./(1./AnnularConduction(NC1.Node,r,L,matl1) + ...
            1./AnnularConduction(NC2.Node,r,L,matl2));
        else
          % NC1 is the solid
          U = AnnularConduction(NC1.Node,r,L,matl1);
        end
      else
        % NC2 must be solid
        U = AnnularConduction(NC2.Node,r,L,matl2);
      end
    end
  end
  function [Dist] = getDistance(NC1,NC2,ActiveTimes)
%     Get distance to center of face
    c = getCenterOfOverlapRegion(NC1.Start,NC2.Start,NC1.End,NC2.End);
    switch NC1.Connection.Orient
      case enumOrient.Vertical
        Dist = 0;
        for NC = [NC1 NC2]
            if NC.Node.Type ~= enumNType.EN
                cx = (NC.Node.xmin + NC.Node.xmax)./2;
                cy = (NC.Node.ymin + NC.Node.ymax)./2;
                Dist = Dist + sqrt(...
                  (cx - NC.Connection.x).^2 + ...
                  (cy - c).^2);
            end
```

```
      end
    case enumOrient.Horizontal
      Dist = 0.0;
      for NC = [NC1 NC2]
        if NC.Node.Type ~= enumNType.EN
          cx = (NC.Node.xmin + NC.Node.xmax)./2;
          cy = (NC.Node.ymin + NC.Node.ymax)./2;
          if ~isempty(NC.Connection.RefFrame)
            Dist = Dist + sqrt(...
              (cx - c).^2 + ...
              (cy - NC.Connection.x - ...
              NC.Connection.RefFrame.Positions).^2);
          else
            Dist = Dist + sqrt(...
              (cx - c).^2 + ...
              (cy - NC.Connection.x).^2);
          end
        end
      end
  end
  Dist(~ActiveTimes) = 1e8;
  Dist = CollapseVector(Dist);
end
function [Dist] = getStabilityDistance(NC1,NC2,ActiveTimes)
    Dist = getDistance(NC1,NC2,ActiveTimes);
end
function [Dh] = getDh(NC1,NC2,ActiveTimes)
  % Determine if it is a transition or not (if not, define Dh)
  if NC1.Connection.Orient == NC2.Connection.Orient
    if isscalar(ActiveTimes)
      switch NC1.Connection.Orient
        case enumOrient.Vertical
          if all(NC1.Node.ymin == NC2.Node.ymin) && ...
              all(NC1.Node.ymax == NC2.Node.ymax)
            Dh = 2*(NC1.End - NC1.Start);
          else
            if isscalar(NC1.End)
              if isscalar(NC2.End)
                D2 = min([NC1.End NC2.End]);
              else
                D2 = NC2.End;
                D2(D2 > NC1.End) = NC1.End;
              end
            else
              if isscalar(NC2.End)
                D2 = NC1.End;
                D2(D2 > NC2.End) = NC2.End;
              else
                D2 = min([NC1.End; NC2.End]);
              end
            end
            if isscalar(NC1.Start)
              if isscalar(NC2.Start)
                D1 = max([NC1.Start NC2.Start]);
              else
                D1 = NC2.Start;
                D1(D1 < NC1.Start) = NC1.Start;
              end
            else
              if isscalar(NC2.Start)
                D1 = NC1.Start;
                D1(D1 < NC2.Start) = NC2.Start;
              else
                D1 = max([NC1.Start; NC2.Start]);
              end
            end
            Dh = 2*(D2 - D1);
          end
        case enumOrient.Horizontal
          if all(NC1.Node.xmin == NC2.Node.xmin) && ...
              all(NC1.Node.xmax == NC2.Node.xmax)
```

```
        Dh = 2*(NC1.End - NC2.Start);
      else
        if isscalar(NC1.End)
          if isscalar(NC2.End)
            D2 = min([NC1.End NC2.End]);
          else
            D2 = NC2.End;
            D2(D2 > NC1.End) = NC1.End;
          end
        else
          if isscalar(NC2.End)
            D2 = NC1.End;
            D2(D2 > NC2.End) = NC2.End;
          else
            D2 = min([NC1.End; NC2.End]);
          end
        end
        if isscalar(NC1.Start)
          if isscalar(NC2.Start)
            D1 = max([NC1.Start NC2.Start]);
          else
            D1 = NC2.Start;
            D1(D1 < NC1.Start) = NC1.Start;
          end
        else
          if isscalar(NC2.Start)
            D1 = NC1.Start;
            D1(D1 < NC2.Start) = NC2.Start;
          else
            D1 = max([NC1.Start; NC2.Start]);
          end
        end
        Dh = 2*(D2 - D1);
      end
  end
else
  switch NC1.Connection.Orient
    case enumOrient.Vertical
      if isscalar(NC1.End)
        if isscalar(NC2.End)
          D2 = min([NC1.End NC2.End]);
        else
          D2 = NC2.End;
          D2(D2 > NC1.End) = NC1.End;
        end
      else
        if isscalar(NC2.End)
          D2 = NC1.End;
          D2(D2 > NC2.End) = NC2.End;
        else
          D2 = min([NC1.End; NC2.End]);
        end
      end
      if isscalar(NC1.Start)
        if isscalar(NC2.Start)
          D1 = max([NC1.Start NC2.Start]);
        else
          D1 = NC2.Start;
          D1(D1 < NC1.Start) = NC1.Start;
        end
      else
        if isscalar(NC2.Start)
          D1 = NC1.Start;
          D1(D1 < NC2.Start) = NC2.Start;
        else
          D1 = max([NC1.Start; NC2.Start]);
        end
      end
      Dh = 2*(D2 - D1);
      Dh(Dh<0) = 0;
    case enumOrient.Horizontal
```

```
          if isscalar(NC1.End)
            if isscalar(NC2.End)
              D2 = min([NC1.End NC2.End]);
            else
              D2 = NC2.End;
              D2(D2 > NC1.End) = NC1.End;
            end
          else
            if isscalar(NC2.End)
              D2 = NC1.End;
              D2(D2 > NC2.End) = NC2.End;
            else
              D2 = min([NC1.End; NC2.End]);
            end
          end
          if isscalar(NC1.Start)
            if isscalar(NC2.Start)
              D1 = max([NC1.Start NC2.Start]);
            else
              D1 = NC2.Start;
              D1(D1 < NC1.Start) = NC1.Start;
            end
          else
            if isscalar(NC2.Start)
              D1 = NC1.Start;
              D1(D1 < NC2.Start) = NC2.Start;
            else
              D1 = max([NC1.Start; NC2.Start]);
            end
          end
          Dh = 2*(D2 - D1);
          Dh(Dh<0) = 0;
      end
    end
  else
    % This should never happen
    fprintf('XXX Perpendicular NodeContacts in Hydraulic Diameter Calc XXX\n');
  end
end
function [keep] = AlignedMask(M,T,b1,b2)
  Ms = M.Start;
  Me = M.End;
  N = max([length(Ms) length(Me) length(b1) length(b2)]);
  if nargin > 2
    % Test lower bounds of Mask
    for i = 1:N
      msi = min(length(Ms),i);
      mei = min(length(Me),i);
      b1i = min(length(b1),i);
      b2i = min(length(b2),i);
      if Ms(msi) >= b2(b2i)
        Ms(msi) = inf;
        Me(mei) = inf;
      else
        if Ms(msi) < b1(b1i)
          Ms(msi) = b1(b1i);
        end
      end
    end
    % Test upper bounds of Mask
    for i = 1:N
      msi = min(length(Ms),i);
      mei = min(length(Me),i);
      b1i = min(length(b1),i);
      b2i = min(length(b2),i);
      if Me(mei) ~= inf
        if Me(mei) <= b1(b1i)
          Me(mei) = -inf;
          Ms(msi) = -inf;
        else
          if Me(mei) > b2(b2i)
```

```
            Me(mei) = b2(b2i);
          end
        end
      end
    end

    keep = true;
    ActiveTimes = ~((Ms >= T.End) + (T.Start >= Me));
    if any(ActiveTimes)
      if isscalar(ActiveTimes)
        if Ms <= T.Start
          T.Start = Me;
        elseif Me >= T.End
          T.End = Ms;
        else
          temp = T.End;
          T.End = Ms;
          NewNC = NodeContact(...
            T.Node, Me, temp, T.Type, T.Connection);
          if NewNC.Start < NewNC.End
            T.Connection.addNodeContacts(NewNC);
          end
        end
        if T.Start >= T.End
          keep = false;
          return;
        end
      else
        for i = 1:length(ActiveTimes)
          ms = min(length(Ms),i);
          me = min(length(Me),i);
          ts = min(length(T.Start),i);
          te = min(length(T.End),i);
          if Ms(ms) <= T.Start(ts)
            T.Start(ts) = Me(me);
          elseif Me(me) >= T.End(te)
            T.End(te) = Ms(ms);
          else
            temp = T.End(te);
            T.End(te) = Ms(ms);
            NewNC = NodeContact(...
              T.Node, Me(me), temp, T.Type, T.Connection);
            if NewNC.Start < NewNC.End
              T.Connection.addNodeContacts(NewNC);
            end
          end
          if T.Start(ts) >= T.End(te)
            T.Start(ts) = T.End(te);
          end
        end
        if all(T.Start == T.End)
          keep = false;
          return;
        end
      end
    end
  end
  function [keep1, keep2] = MutualMask(M1,M2)
    Mask1 = CopyClass(M1);
    Mask2 = CopyClass(M2);
    keep1 = Mask1.AlignedMask(M2,-inf,inf);
    keep2 = Mask2.AlignedMask(M1,-inf,inf);
  end
 end
end
```

NonConnection

The non-connection is a class that includes a constructor and a name generation function.

```
classdef NonConnection
  %NONCONNECTION Summary of this class goes here
  %   Detailed explanation goes here

  properties
    Body1;
    Body2;
  end

  properties (Dependent)
    name;
  end

  methods
    function this = NonConnection(B1,B2)
      if nargin == 0
        return;
      end
      this.Body1 = B1;
      this.Body2 = B2;
    end

    function name = get.name(this)
      name = [this.Body1.name ' XXX ' this.Body2.name];
    end
  end

end
```

Position

The position is class that contains a constructor, plus operator and get/set interface.

```
classdef Position < handle
   %POSITION Summary of this class goes here
   %   Detailed explanation goes here

   properties
      x double = 0;
      y double = 0;
      Rot double = pi/2;
   end

   properties (Dependent)
     name;
   end

   methods
      function this = Position(x,y,Rot)
         switch nargin
            case 1
               this.x = x;
            case 2
               this.x = x;
               this.y = y;
            case 3
               this.x = x;
               this.y = y;
               this.Rot = Rot;
         end
      end
      function newPosition = plus(base,offset)
         newPosition.x = base.x + offset.x;
         newPosition.y = base.y + offset.y;
         newPosition.Rot = base.Rot;
         newPosition.Model = base.Model;
      end
      function name = get.name(this)
        name = sprintf('x: %f.0 y: %f.0 Rot: %f.00',this.x,this.y,this.Rot);
      end
      function Item = get(this,PropertyName)
        switch PropertyName
          case 'x'
            Item = this.x;
          case 'y'
            Item = this.y;
          case 'Theta'
            Item = this.Rot;
          otherwise
            fprintf(['XXX Position GET Inteface for ' PropertyName ' is not found XXX\n']);
        end
      end
      function set(this,PropertyName,Item)
        switch PropertyName
          case 'x'
            this.x = Item;
          case 'y'
            this.y = Item;
          case 'Theta'
            this.Rot = Item;
          otherwise
            fprintf(['XXX Position SET Inteface for ' PropertyName ' is not found XXX\n']);
        end
      end
   end
```

```
end
```

Pressure Contact

The pressure contact is a class that contains a constructor and a equals operator.

```
classdef PressureContact
  %FORCECONTACT Summary of this class goes here
  %   Detailed explanation goes here

  properties
    ConverterIndex;
    MechanismIndex;
    Area;
    GasNode;
  end

  methods
    function this = PressureContact(ConverterIndex,MechanismIndex,Area,Node)
      %FORCECONTACT Construct an instance of this class
      %   Detailed explanation goes here
      this.ConverterIndex = ConverterIndex;
      this.MechanismIndex = MechanismIndex;
      this.Area = Area;
      this.GasNode = Node;
    end

    function iseq = equal(this,other)
      if this.MechanismIndex == other.MechanismIndex && ...
          this.Area == other.Area && this.GasNode == other.GasNode
        iseq = true;
      else
        iseq = false;
      end
    end
  end
end
```

PVoutput

The PVoutput is a class that contains the following functionality:

A constructor.

A get / set interface.

A set of property update functions called during discretization.

A function called during destruction.

A set of functions for getting data during recording.

A plotting function for output.

```
classdef PVoutput < handle
  %UNTITLED Summary of this class goes here
  %   Detailed explanation goes here

  properties
    Body Body;
    name;
    % A series of node indexes over
    % ... which the pressure and volume is calculated
    Nodes cell;
    RegionNodes;
    Region;
    Model Model;
    P double;
    V double;
    Power double;
    Fig = [];
  end

  methods
    function this = PVoutput(Body)
      if nargin == 1
        Body.addPVoutput(this);
        this.Body = Body;
        this.Model = Body.Group.Model;
        this.Nodes = [];
        this.P = zeros(1,Frame.NTheta-1);
        this.V = this.P;
        % Define the name
        this.name = getProperName( 'PV output' );
      end
    end

    function Item = get(this,PropertyName)
      switch PropertyName
        case 'name'
          Item = this.name;
        case 'Source Body/Region'
          Item = this.Body;
        otherwise
          fprintf(['XXX PVoutput GET Inteface for ' PropertyName ' is not found XXX\n']);
      end
    end
    function set(this,PropertyName,Item)
```

```
  switch PropertyName
    case 'name'
      this.name = Item;
    case 'Source Body/Nodes'
      if ~isempty(Item)
        this.Body = Item;
        this.Body.change();
      end
    otherwise
      fprintf(['XXX Connection SET Inteface for ' PropertyName ' is not found XXX\n']);
      return;
  end
end

function update(this,Region)
  % Grab a node from the body
  this.RegionNodes = [];
  this.Nodes = cell(0);
  if this.Body.isDiscretized()
    i = 1;
    this.Region = Region(this.Body.Nodes(1).index);
    consideredbodies = Body.empty;
    for iGroup = this.Model.Groups
      for iBody = iGroup.Bodies
        if ~any(consideredbodies == iBody) && ...
            iBody.matl.Phase == enumMaterial.Gas && ...
            iBody.isDiscretized() && ...
            Region(iBody.Nodes(1).index) == this.Region
          % get this.Nodes{i}(j)
          j = 1;
          otherbodies = iBody;
          k = 1;
          while k <= length(otherbodies)
            for nd = otherbodies(k).Nodes % Search this body & any other bodies
              if nd.Type ~= enumNType.SN && ~isscalar(nd.vol())
                this.Nodes{i}(j) = nd.index; j = j + 1;
                for fc = nd.Faces
                  if fc.Type == enumFType.Gas && ...
                      fc.Nodes(1).Body ~= fc.Nodes(2).Body
                    if fc.Nodes(1) == nd
                      if ~isscalar(fc.Nodes(2).vol()) && ...
                          ~any(otherbodies == fc.Nodes(2).Body)
                        otherbodies(end+1) = fc.Nodes(2).Body;
                      end
                    else
                      if ~isscalar(fc.Nodes(1).vol()) && ...
                          ~any(otherbodies == fc.Nodes(1).Body)
                        otherbodies(end+1) = fc.Nodes(1).Body;
                      end
                    end
                  end
                end
              end
            end
            k = k + 1;
          end
          consideredbodies(end+1:end+length(otherbodies)) = otherbodies(:);
          % get this.RegionNodes(this.Nodes{i}(:));
          if j > 1
            i = i + 1;
          end
        end
      end
    end
    indexes = 1:length(Region);

    this.RegionNodes = indexes(Region(end) ~= this.Region);
  else
    this.Nodes = cell(0);
    return;
  end
```

```
end

function reset(this)
  this.P = [];
  this.V = [];
end

function deReference(this)
  iModel = this.Model;
  for i = length(iModel.PVoutputs):-1:1
    if iModel.PVoutputs(i) == this
      iModel.PVoutputs(i) = [];
      break;
    end
  end
  if ~isempty(this.Body) && isvalid(this.Body)
    for i = length(this.Body.PVoutputs):-1:1
      if this.Body.PVoutputs(i) == this
        this.Body.PVoutputs(i) = [];
        break;
      end
    end
    this.Body.change();
  end
  this.delete();
end

function isequal = equal(this,other)
  isequal = (this.Body == other.Body);
end

function getData(this,Sim)
  if isempty(this.P)
    this.P = zeros(Frame.NTheta-1,length(this.Nodes));
  end
  index = Sim.Inc;
  for i = 1:length(this.Nodes)
    indV = (Sim.vol(this.Nodes{i})' + Sim.old_vol(this.Nodes{i})')/2;
    sumV = sum(sum(indV));
    this.P(index,i) = sum(indV.*Sim.P(this.Nodes{i})')/sumV;
    this.V(index,i) = sumV;
  end
end

function updatePlot(this)
  if isempty(this.Fig) || ~isvalid(this.Fig) || this.Fig < 1
    this.Fig = figure();
  end
  figure(this.Fig);
  title('Pressure vs Volume Diagram');
  xlabel('Volume (m^3)');
  ylabel('Pressure (Pa)');
  set(gcf,'color','w');
  a = this.Fig.CurrentAxes;
  WTotal = 0;
  Text = '';
  for i = 1:length(this.Nodes)
    pV = zeros(size(this.V,1)+1,1); pP = pV;
    pV(1:end-1) = this.V(:,i); pV(end) = this.V(1,i);
    pP(1:end-1) = this.P(:,i); pP(end) = this.P(1,i);
    W = PowerFromPV(pP,pV);
    WTotal = WTotal + W;
    if W > 0; Color = 'b'; % Color is Blue
    else; Color = 'r'; % Color is Red
    end
    plot(pV,pP,'Color',Color,'LineStyle','-');
    hold on;
    plot(pV(1),pP(1),'Color','k','Marker','o');
  end
  this.Power = WTotal;
  Text = [Text 'Total = ' num2str(WTotal,4) 'Joules/Cycle'];
```

```
      %fprintf([num2str(WTotal) '\n']);
      text(a.XLim(1)+0.01*(a.XLim(2)-a.XLim(1)),...
        a.YLim(2)-0.05*(a.YLim(2)-a.YLim(1)), Text);
      drawnow;
      hold off;
    end

    function plotData(this,is_saved,ModelName)
      if ~(isempty(this.Fig) || ~isvalid(this.Fig) || this.Fig < 1)
        close(this.Fig);
      end
      oldfigure = gcf;
      oldaxes = gca;
      a = gca;
      updatePlot(this);
      h = gcf;
      xlabel('Volume (m^3)');
      ylabel('Pressure (Pa)');

      if is_saved
        frame = getframe(h);
        im = frame2im(frame);
        [imind,cm] = rgb2ind(im,256);
        data = struct(...
          'Name',this.name,...
          'IndependentVariable',this.V,...
          'DependentVariable',this.P);
        if isempty(this.Body.Group.Model.outputPath)
          str = [this.name '_' ModelName];
        else
          str = [this.Body.Group.Model.outputPath '\' ...
            this.name '_' ModelName];
        end
        str = replace(str,':',' -');
        save([str '.mat'],'data');
        imwrite(imind,cm,[str '.jpg']);
      end

      close(h);
      figure(oldfigure);
      axes(oldaxes);
    end
  end
end
```

Sensor

A sensor is a class that contains the following functionality:

A constructor.

A dereference function (called prior to deletion).

A get / set interface.

An update function called during discretization.

A set of functions for getting data during recording.

A plotting function for output.

A display function for displaying on the GUI.

```
classdef Sensor < handle
  %UNTITLED Summary of this class goes here
  %   Detailed explanation goes here

  properties
    name;
    Body;
    Model;
    LocationStyle;
    averaging; % 1 for phase based, 2 for time based
    IndependentVariable; % May be time or angle
    DataType; % Cell Array
    Data; % Cell Array
    dimensions; % 1 for point, 2 for line
    PntCount; % Number of elements along a line
    Nodes; % Vector
    Interp; % Matrix

    % Derived Components
    PlotCoordinates; % Vector 1xN
    LocalCoordinates;

    index = 0; % adding to the data set
    GUIObjects;
  end

  methods
    function this = Sensor(Modelobj,Body)
      if nargin == 2
        this.Body = Body;
        this.Model = Modelobj;
        this.index = 0;

        % Define the name
        this.name = getProperName( 'Sensor' );

        % Define the location
        notdone = true;
        source = {...
          'Body Center','Body xmax',...
          'Body xmin','Body ymax',...
```

```
      'Body ymin','Body xaxis',...
      'Body yaxis'};
    while notdone
      index = listdlg('PromptString','What is the position of this Senso?',...
        'SelectionMode','single',...
        'ListString',source);
      if index ~= 0
        notdone = false;
      end
    end
    this.LocationStyle = source{index};

    % Define the independent variable
    notdone = true;
    source = {'Phase','Time'};
    while notdone
      index = listdlg('PromptString','What is the independent variable?',...
        'SelectionMode','single',...
        'ListString',source);
      if index ~= 0
        notdone = false;
      end
    end
    this.averaging = index;

    % Define the dependent variable
    notdone = true;
    source = {'T','P','turb'};
    while notdone
      index = listdlg('PromptString','What is the dependent variable?',...
        'SelectionMode','single',...
        'ListString',source);
      if index ~= 0
        notdone = false;
      end
    end
    this.DataType = source{index};

    % Define the point count
    switch this.LocationStyle
      case {'Body xaxis','Body yaxis'}
        notdone = true;
        while notdone
          answer = inputdlg('How many sample points along the line?',...
            'Integer only',[1 50]);
          test = str2double(answer);
          if ~isnan(test)
            if floor(test) == test
              this.PntCount = test-1;
              notdone = false;
            end
          end
        end
    end
    Body.addSensor(this);
    this.update();
  end
end
function deReference(this)
  if ~isempty(this.Model) && isvalid(this.Model)
    for i = length(this.Model.Sensors):-1:1
      if this.Model.Sensors(i) == this
        this.Model.Sensors(i) = [];
        break;
      end
    end
  end
  if ~isempty(this.Body) && isvalid(this.Body)
    for i = length(this.Body.Sensors):-1:1
      if this.Body.Sensors(i) == this
        this.Body.Sensors(i) = [];
```

```
        break;
      end
    end
    this.Body.change();
  end
  this.removeFromFigure(gca);
  this.delete();
end
function isit = isValid(this)
  isit = isvalid(this) && ~isempty(this.Body) && ...
    ~isempty(this.Model) && isvalid(this.Body) && isvalid(this.Model);
end
function item = get(this,PropertyName)
  switch PropertyName
    case 'Name'
      item = this.name;
    case 'Samples'
      item = this.PntCount + 1;
    otherwise
      fprintf(['XXX Sensor GET Inteface for ' PropertyName ...
        ' is not found XXX\n']);
  end
end
function set(this,PropertyName,Item)
  switch PropertyName
    case 'Name'
      this.name = Item;
    case 'Samples'
      this.PntCount = Item - 1;
      this.update();
    otherwise
      fprintf(['XXX Sensor SET Inteface for ' PropertyName ...
        ' is not found XXX\n']);
  end
end
function update(this)
  if ~this.Body.isDiscretized()
    this.Body.discretize();
    if ~this.Body.isDiscretized()
      fprintf(['XXX Sensor: ' this.name ...
        ' Update failed XXX\n'])
      return;
    end
  end
  switch this.LocationStyle
    case 'Body Center'
      % place the point right in the middle of the body volume and use
      % the nodes as the interpolation points
      this.dimensions = 1; % Point
      [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
      [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
      x = (xmin+xmax)/2; y = (ymin+ymax)/2;
      this.LocalCoordinates = [x; y];
    case 'Body xmax'
      % place the point right at the middle of the xmax edge.
      this.dimensions = 1; % Point
      [~,~,~,xmax] = this.Body.limits(enumOrient.Vertical);
      [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
      x = xmax; y = (ymin+ymax)/2;
      this.LocalCoordinates = [x; y];
    case 'Body xmin'
      % place the point right at the middle of the xmin edge.
      this.dimensions = 1; % Point
      [~,~,xmin,~] = this.Body.limits(enumOrient.Vertical);
      [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
      x = xmin; y = (ymin+ymax)/2;
      this.LocalCoordinates = [x; y];
    case 'Body ymax'
      % place the point right at the middle of the ymax edge.
      this.dimensions = 1; % Point
      [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
```

```
    [~,~,~,ymax] = this.Body.limits(enumOrient.Horizontal);
    x = (xmin+xmax)/2; y = ymax;
    this.LocalCoordinates = [x; y];
  case 'Body ymin'
    % place the point right at the middle of the ymin edge.
    this.dimensions = 1; % Point
    [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
    [~,~,ymin,~] = this.Body.limits(enumOrient.Horizontal);
    x = (xmin+xmax)/2; y = ymin;
    this.LocalCoordinates = [x; y];
  case 'Body yaxis'
    % Place the point along the xaxis align volume center
    this.dimensions = 2; % Line
    [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
    [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
    x1 = (xmin+xmax)/2; y1 = ymin;
    x2 = (xmin+xmax)/2; y2 = ymax;
    this.PlotCoordinates = linspace(y1,y2,this.PntCount+1);
    this.LocalCoordinates = [x1 y1; x2 y2];
  case 'Body xaxis'
    % Place the point along the yaxis align volume center
    this.dimensions = 2; % Line
    [~,~,xmin,xmax] = this.Body.limits(enumOrient.Vertical);
    [~,~,ymin,ymax] = this.Body.limits(enumOrient.Horizontal);
    x1 = xmin; y1 = (ymin+ymax)/2;
    x2 = xmax; y2 = (ymin+ymax)/2;
    this.PlotCoordinates = linspace(x1,x2,this.PntCount+1);
    this.LocalCoordinates = [x1 y1; x2 y2];
end
if this.dimensions == 1
  % Point
  loc = Pnt2D(x,y);
  [nds,intrp] = findClosest4(loc,this.Body);
  this.Nodes = nds;
  this.Interp = intrp;
else
  % Line
  this.Nodes = zeros(this.PntCount+1,4);
  this.Interp = zeros(this.PntCount+1,4);
  loc(this.PntCount+1) = Pnt2D();
  for i = 1:this.PntCount+1
    loc(i) = Pnt2D(...
      x1*(this.PntCount-i+1)/(this.PntCount) + x2*(i-1)/this.PntCount,...
      y1*(this.PntCount-i+1)/(this.PntCount) + y2*(i-1)/this.PntCount);
    [nds, intrp] = findClosest4(loc(i),this.Body);
    this.Nodes(i,1:length(nds)) = nds;
    this.Interp(i,1:length(intrp)) = intrp;
  end
  % Simplify
  % Form the nodes array
  tempNodes = zeros(numel(this.Nodes),1);
  start = 1;
  len = 3;
  for i = 1:this.PntCount+1
    tempNodes(start:start+len) = this.Nodes(i,:)';
    start = start + len + 1;
  end
  tempNodes = unique(tempNodes(tempNodes>0));
  tempNodes = sort(tempNodes);
  tempInterp = zeros(length(tempNodes),this.PntCount+1);
  for i = 1:this.PntCount+1
    for j = 1:length(tempNodes)
      where = find(this.Nodes(i,:) == tempNodes(j));
      if isempty(where)
        tempInterp(j,i) = 0;
      else
        tempInterp(j,i) = this.Interp(i,where(1));
      end
    end
  end
  this.Interp = tempInterp;
```

```
    this.Nodes = tempNodes;
  end
  if this.Model.showSensors
    this.show(gca);
  end
end
function reset(this)
  this.IndependentVariable = [];
  this.index = 0;
  this.Data = [];
end

function getData(this,Simulation)
  property = this.DataType;
  switch property
    case 'T'
      SourceData = Simulation.T(this.Nodes);
    case 'P'
      SourceData = Simulation.P(this.Nodes);
    case 'Turb'
      SourceData = Simulation.turb(this.Nodes);
    otherwise
      fprintf(['XXX Property: ' property ...
        ' not supported in the Sensor Class XXX\n']);
      return;
  end
  % Get the data by interpolating the cells
  switch this.averaging
    case 1 % Angular Recording with overwrite
      this.index = Simulation.Inc;
      if isempty(this.IndependentVariable)
          LEN = Frame.NTheta-1;
          AInc = 2*pi/(Frame.NTheta-1);
          this.IndependentVariable = linspace(0,AInc*LEN,LEN);
      end
    case 2 % Temporal Recording
      this.index = this.index + 1;
      this.IndependentVariable(this.index) = Simulation.curTime;
  end
  switch this.dimensions
    case 1
      % Grab a single point
      this.Data(this.index) = sum(this.Interp(:).*SourceData(:));
    case 2
      % Grab a vector of points
      if isempty(this.Data)
        this.Data(this.PntCount+1,1) = 0;
      end
      for j = 1:this.PntCount+1
        this.Data(j,this.index) = sum(this.Interp(:,j).*SourceData(:));
      end
  end
end

function plotData(this,is_saving,ModelName)
  oldfigure = gcf;
  oldaxes = gca;
  h = figure();
  set(h,'color','w');
  a = gca;
  switch this.DataType
    case 'T'
      titleStr = [this.name ': Temperature vs '];
      label2 = 'Temperature (K)';
      switch this.dimensions
        case 1
          a.YAxis.TickLabelFormat = '%.1f';
        case 2
          a.YAxis.TickLabelFormat = '%.2f';
      end
    case 'P'
```

```
      titleStr = [this.name ': Pressure vs '];
      label2 = 'Pressure (Pa)';
      switch this.dimensions
        case 1
          a.YAxis.TickLabelFormat = '%.0f';
        case 2
          a.YAxis.TickLabelFormat = '%.2f';
      end
    case 'turb'
      titleStr = [this.name ': Turbulent Weight vs '];
      label2 = 'Turbulence Weight (0-1)';
      switch this.dimensions
        case 1
          a.YAxis.TickLabelFormat = '%.2f';
        case 2
          a.YAxis.TickLabelFormat = '%.2f';
      end
  end
  switch this.dimensions
    case 1
      % Make a line plot
      if length(this.Data) == length(this.IndependentVariable)
        plot(this.IndependentVariable,this.Data);
      else
        plot(this.Data);
        fprintf('XXX Sensor could not plot due to unequal lengthed vectors. XXX\n');
      end
      switch this.averaging
        case 1
          % Make a plot in relation to angle
          titleStr = [titleStr 'angle'];
          title(titleStr);
          xlabel('angle (rad)');
          ylabel(label2);
          a.XAxis.TickLabelFormat = '%.2f';
        case 2
          % Make a plot in relation to time
          titleStr = [titleStr 'time'];
          title(titleStr);
          xlabel('time (s)');
          ylabel(label2);
          a.XAxis.TickLabelFormat = '%.0f';
      end
    case 2
      % Make a surface plot
      [X,Y] = meshgrid(this.IndependentVariable,this.PlotCoordinates);
      Z = this.Data;
      s = surf(X,Y,Z);
      s.EdgeColor = 'none';
      view(0,90);
      xlim([0, max(this.IndependentVariable)]);
      ylim([min(this.PlotCoordinates), max(this.PlotCoordinates)]);
      colormap jet;
      hcb = colorbar;
      switch this.DataType
        case 'T'
          yt=get(hcb,'Ticks');
          set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.1f'))));
        case 'P'
          yt=get(hcb,'Ticks');
          set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.2e'))));
        case 'turb'
          yt=get(hcb,'Ticks');
          set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.2f'))));
      end
      switch this.averaging
        case 1
          % Make a plot in relation to angle
          titleStr = [titleStr 'angle'];
%           t = title(titleStr);
          xlabel('angle (rad)');
```

```
            ylabel('position (m)');
            zlabel(label2);
          case 2
            % Make a plot in relation to time
            titleStr = [titleStr 'time'];
%             t = title(titleStr);
            xlabel('time (s)');
            ylabel('position (m)');
            zlabel(label2);
        end
        ylabel(hcb, titleStr);
    end

    if is_saving
      frame = getframe(h);
      im = frame2im(frame);
      [imind,cm] = rgb2ind(im,256);
      data = struct(...
        'Name',this.name,...
        'IndependentVariable',this.IndependentVariable,...
        'DependentVariable',this.Data);
      if isempty(this.Body.Group.Model.outputPath)
        str = [ModelName '_' titleStr];
      else
        str = [this.Body.Group.Model.outputPath '\' ...
          ModelName '_' titleStr];
      end
      str = replace(str,':',' -');
      save([str '.mat'],'data');
      imwrite(imind,cm,[str '.jpg']);
    end

    close(h);
    figure(oldfigure);
    axes(oldaxes);
  end
  function removeFromFigure(this,AxisReference)
    if ~isempty(this.GUIObjects)
      children = get(AxisReference,'Children');
      for obj = this.GUIObjects
        if isgraphics(obj)
          for i = length(children):-1:1
            if isgraphics(children(i)) && children(i) == obj
              children(i).delete;
              break;
            end
          end
        end
      end
      this.GUIObjects = [];
    end
  end
  function show(this,AxisReference)
    this.removeFromFigure(AxisReference);
    color = [1 0 1]; % magenta
    % Plot a yellow symbol where the sensor is
    if size(this.LocalCoordinates,2) == 2
      % It is a line
      pos1 = RotMatrix(this.Body.Group.Position.Rot-pi/2)*this.LocalCoordinates(1,:)';
      pos2 = RotMatrix(this.Body.Group.Position.Rot-pi/2)*this.LocalCoordinates(2,:)';
      this.GUIObjects = line([pos1(1) pos2(1)],[pos1(2) pos2(2)],...
        'Color',color,'Marker','o','MarkerSize',8);
    else
      % It is a point
      pos = RotMatrix(this.Body.Group.Position.Rot-pi/2)*this.LocalCoordinates(:);
      this.GUIObjects = line(pos(1),pos(2),...
        'Color',color,'Marker','o','MarkerSize',8);
    end
  end
end
```

```
end
```

Shear Contact

A shear contact is a class that includes a constructor and an equals operator.

```
classdef ShearContact
  %FORCECONTACT Summary of this class goes here
  %   Detailed explanation goes here

  properties
    ConverterIndex;
    MechanismIndex;
    Area;
    LowerNode;
    UpperNode;
    ActiveTimes;
  end

  methods
    function this = ShearContact(...
        ConverterIndex,MechanismIndex,Area,Node1,Node2,ActiveTimes)
      if nargin == 6
        %FORCECONTACT Construct an instance of this class
        %   Detailed explanation goes here
        this.ConverterIndex = ConverterIndex;
        this.MechanismIndex = MechanismIndex;
        this.Area = Area;
        this.LowerNode = Node1;
        this.UpperNode = Node2;
        this.ActiveTimes = ActiveTimes;
      end
    end
    function iseq = equal(this,other)
      if this.ConverterIndex == other.ConverterIndex && ...
          this.MechanismIndex == other.MechanismIndex && ...
          this.LowerNode == other.LowerNode && ...
          this.UpperNode == other.UpperNode
        iseq = true;
      else
        iseq = false;
      end
    end
  end
end
```

G.4. Mechanical

Linear to Rotational Mechanism

The linear to rotational mechanism is a class that includes the following functionality:

A static function that assembles the property table.

A constructor and destruction function.

A function that takes the user inputted properties and turns them into coefficients for load calculations.

A function that opens up the mechanism interface.

A set of functions that may be referenced in the form of anonymous functions during simulation. As they apply to different mechanism types.

```
classdef LinRotMechanism < handle
  %MECHANISM Summary of this class goes here
  %   Detailed explanation goes here

  properties (Constant)
    g = 9.81;
    Source = {...
      'Ideal Sinusoid';
      'Custom Profile Mechanism';
      'Slider Crank'};
    %       'Scotch Yoke';
    %       'Ross Yoke';
    %       'Rhombic Drive'};
    StrokeText = 'Stroke (m)';
    PhaseText = 'Phase (rad)';
    PistonMassText = 'Piston Mass (kg)';
    TiltAngleText = 'Tilt from Hor. (rad)';
    OrientationText = 'Orientation: "u" aligned with positive y, "d" opposite';
    EfficiencyText = 'Mechanical Efficiency (0.##)';
    %     isPropertyEditable ...
    %       = {'Stroke (m)', 'Phase (rad)', 'Weight (kg)', 'Tilt from Hor. (rad)', 'Aspect
Ratio', 'Custom Profile Fcn';
    %          true        , true         , true         , true                  , false
, true               ;
    %          true        , true         , true         , true                  , true
, false              ;
    %          true        , true         , true         , true                  , false
, false              };

  end

  properties
    ID;
    Model Model;

    isValid logical = true;
    Type char;
    Stroke double = [];
    Phase double = [];
    Frames Frame;

    STilt double;
    CTilt double;
```

```
  %     lengths double = [];
  %     masses double = [];
  %     descriptions char = [];

  originalInput = [];

  outputFcn function_handle;

  Data;

  dont_propegate logical = false;

end

properties (Dependent)
  name;
end

methods (Static)
  function [Source, Instructions, Widths] = GetPropertyTableSource(Type,originalSource)
    switch Type
      case 'Ideal Sinusoid'
        Source = {...
          LinRotMechanism.StrokeText, ...
          LinRotMechanism.PhaseText, ...
          LinRotMechanism.PistonMassText, ...
          'Other Mass (kg)', ...
          LinRotMechanism.TiltAngleText, ...
          LinRotMechanism.OrientationText, ...
          LinRotMechanism.EfficiencyText};
        Source = AddRow(Source,1);
        Instructions = [...
          'The ideal Sinusoid produces N frictionless osscilating ' ...
          'mass mechanism that follows a perfect sinusoidal motion. ' ...
          'This is best used when the mechanism is unknown or seal ' ...
          'and pumping losses are much greater than mechanism friction.'];
      case 'Custom Profile Mechanism'
        Source = {...
          LinRotMechanism.StrokeText, ...
          LinRotMechanism.PhaseText, ...
          LinRotMechanism.PistonMassText, ...
          'Other Mass (kg)', ...
          'Mech. Mom. Inert. (kg m^2)', ...
          LinRotMechanism.TiltAngleText, ...
          'Custom Profile Fcn', ...
          LinRotMechanism.OrientationText, ...
          LinRotMechanism.EfficiencyText};
        Source = AddRow(Source,1);
        Instructions = [...
          'The Custom Profile Mechanism produces N simulated osscilating ' ...
          'mass mechanism that follow a custom motion profile. ' ...
          'Piston Mass includes the mass of any attached components. ' ...
          'The user has the option to simulate the mass effects of ' ...
          'non-circular gear pairs or cam drives.'];
      case 'Slider Crank'
        Source = {...
          LinRotMechanism.StrokeText, ...
          LinRotMechanism.PhaseText, ...
          'Crank Mass (kg)', ...
          'Crank C.O.M Radius (m)', ...
          'Crank C.O.M Angle (rad)', ...
          'Crank Rot. Inertia (kgn^2)',...
          'Crank-Con Fric. Fcn', ...
          'Con Length (m)' , ...
          'Con. Mass (kg)', ...
          'Con. C.O.M Radius from CR-CN pin (m)', ...
          'Con. Rot. Inertia (kgn^2)',...
          'Con-Piston Fric. Fcn', ...
          LinRotMechanism.PistonMassText, ...
          'Piston Fric. Fcn', ...
          LinRotMechanism.TiltAngleText, ...
```

```
          'Slider-Offset (m)', ...
          LinRotMechanism.OrientationText};
        Source = AddRow(Source,1);
        Instructions = [...
          'The slider crank produces N psuedo sinusoidal motions. ' ...
          'It auto-defines mechanism lengths based on ' ...
          'Stroke and Aspect Ratio. Piston, Crank and Connecting Arm ' ...
          'Masses are by default placed in the center of their bars; ' ...
          'the user can modify this location or choose the ' ...
          'AutoBalance option. Friction Fcns take an input of a normal '...
          'force and provide back a opposing force.'];
        %         case 'Scotch Yoke'
        %           Source = {...
        %             LinRotMechanism.StrokeText, ...
        %             LinRotMechanism.PhaseText, ...
        %             LinRotMechanism.PistonMassText, ...
        %             'Crank Mass (kg)', ...
        %             'Crank Length (m)', ...
        %             'Crank C.O.M Radius (m)', ...
        %             'Crank C.O.M Angle (rad)', ...
        %             'Roller Fric. Fcn', ...
        %             'Linear Bearing Fric. Fcn', ...
        %             'Mech. Mom. Inter. (kg m^2)', ...
        %             LinRotMechanism.TiltAngleText
        %             LinRotMechanism.OrientationText};
        %           Source = AddRow(Source,1);
        %           Instructions = [...
        %             'The scotch yoke produces N perfect sinusoidal motions. ' ...
        %             'It auto-defines mechanism lengths based on ' ...
        %             'Stroke. Crank structural masses are placed in the center ' ...
        %             'of its bar, the user can modify this location or choose ' ...
        %             'the AutoBalance option. Piston Mass includes the mass of ' ...
        %             'attached components. Friction Fcns take an input of a ' ...
        %             'normal force and provide back an opposing force.'];
        %         case 'Rhombic Drive'
        %           Source = {...
        %             LinRotMechanism.StrokeText, ...
        %             LinRotMechanism.PhaseText, ...
        %             'Crank Mass (kg)', ...
        %             'Crank C.O.M Radius (m)', ...
        %             'Crank C.O.M Angle (rad)', ...
        %             'Crank Rot. Inertia (kgn^2)',...
        %             'Crank-Con Fric. Fcn', ...
        %             'Con Length (m)' , ...
        %             'Con. Mass (kg)', ...
        %             'Con. C.O.M Radius from CR-CN pin (m)', ...
        %             'Con. Rot. Inertia (kgn^2)',...
        %             'Con-Piston Fric. Fcn', ...
        %             LinRotMechanism.PistonMassText, ...
        %             'Piston Fric. Fcn', ...
        %             LinRotMechanism.TiltAngleText, ...
        %             'Slider-Offset (m)', ...
        %             LinRotMechanism.OrientationText};
        %           Source = AddRow(Source,1);
        %           Instructions = [...
        %             'The rhombic drive is a type of slider crank mechanism ' ...
        %             'that uses 2 sets of cranks that are mirrored in such a ' ...
        %             'way that they have 0 side loads. The Type of Rhombic ' ...
        %             'drive used in Beta Type Stirling engines contains two ' ...
        %             'sets one of which is phased at 180 degrees relative and ' ...
        %             'of opposite orientation.'];
      end
      if nargin > 1
        % Then try to prefill it as best as you can
        Source = MergeTables(Source,originalSource);
      end
      for col = size(Source,2):-1:1
        Widths{col} = length(Source{1,col})*6;
      end
    end
  end
```

```
methods
  function this = LinRotMechanism(Model,Type,PropertyTable)
    if nargin > 1
      this.Model = Model;
      this.ID = Model.getLRMID();
      this.Populate(Type,PropertyTable);
    end
  end
  function deReference(this)
    % Get index of this LinRotMechanism
    ind = 1;
    for iLinRotMech = this.Model.Converters
      if iLinRotMech == this; break;
      else; ind = ind + 1;
      end
    end

    for iGroup = this.Model.Groups
      for iCon = this.Model.Connections
        if ~isempty(iCon.RefFrame)
          if iCon.RefFrame.Mechanism == ind
            iCon.RefFrame = [];
            iCon.change();
          end
        end
      end
    end

    for i = length(this.Model.RefFrames):-1:1
      if this.Model.RefFrames(i).Mechanism == ind
        this.Model.RefFrames(i) = [];
      elseif this.Model.RefFrames(i).Mechanism > ind
        this.Model.RefFrames(i).Mechanism = ...
          this.Model.RefFrames(i).Mechanism - 1;
      end
    end

    this.Model.Converters(ind) = [];
    this.Model.change();
    this.delete();
  end
  function Populate(this,Type,PropertyTable)
    if isempty(this.ID)
      this.ID = this.Model.getLRMID();
    end
    this.Data = struct.empty;
    this.Type = Type;
    this.originalInput = PropertyTable;
    LEN = size(PropertyTable,1)-1;
    if isempty(this.Frames)
      this.Frames(LEN) = Frame();
    elseif length(this.Frames) < LEN
      % Chop off
      for i = length(this.Frames):-1:LEN+1
        this.Frames(i).deReference();
        this.Frames(i) = [];
      end
    elseif length(this.Frames) > LEN
      % Top up
      this.Frames(LEN) = Frame();
    end
    this.populateTilt();
    for i = 1:LEN
      newValue = str2double(FindInTable(this,this.StrokeText,i+1));
      if length(this.Stroke) >= i
        shift = newValue - this.Stroke(i);
        if shift ~= 0
          % Stroke
          if ~this.dont_propegate && this.Model.RelationOn
            for iGroup = this.Model.Groups
```

```
          for RMan = iGroup.RelationManagers
            if RMan.Orient == enumOrient.Horizontal
              maxconPiston = Connection.empty;
              maxconStroke = Connection.empty;
              maxxPiston = -inf;
              maxxStroke = -inf;
              for rel = RMan.Relations
                if ~isempty(rel.frame) && ...
                    rel.frame == this.Frames(i)
                  switch rel.mode
                    case enumRelation.Piston
                      if rel.con1.x > maxxPiston
                        maxxPiston = rel.con1.x;
                        maxconPiston = rel.con1;
                      end
                      if rel.con2.x > maxxPiston
                        maxxPiston = rel.con2.x;
                        maxconPiston = rel.con2;
                      end
                    case enumRelation.Stroke
                      if rel.con1.x > maxxStroke
                        maxxStroke = rel.con1.x;
                        maxconStroke = rel.con1;
                      end
                      if rel.con2.x > maxxStroke
                        maxxStroke = rel.con2.x;
                        maxconStroke = rel.con2;
                      end
                  end
                end
              end
              success = true;
              if ~isempty(maxconStroke)
                [success, ~] = ...
                  RMan.Edit(maxconStroke, shift);
              end
              if success && ...
                  isempty(maxconStroke) && ~isempty(maxconPiston)
                [success, ~] = ...
                  RMan.Edit(maxconPiston, -shift);
              end
              if ~success
                fprintf(['XXX Could not edit mechanism ' ...
                  'due to geometric conflict XXX\n']);
              end
            end
          end
        end
      end
    end
  end
  this.Stroke(i) = newValue;
end
this.dont_propegate = false;
switch Type
  case {'Ideal Sinusoid', 'Custom Profile Mechanism'}
    for i = 1:LEN
      Im1 = 0;
      % Find Properties
      % Phase
      this.Phase(i) = str2double(FindInTable(this,this.PhaseText,i+1));
      % Piston Mass
      mp = str2double(FindInTable(this,this.PistonMassText,i+1));
      % Other Mass
      m1 = str2double(FindInTable(this,'Other Mass (kg)',i+1));
      % Tilt is already covered
      % Orientation
      orientation = FindInTable(this,LinRotMechanism.OrientationText,i+1);
      switch orientation
        case 'u'; orient = 1;
        case 'd'; orient = -1;
```

```
            otherwise; orient = nan();
          end
          % Mechanical Efficiency
          eff = str2double(FindInTable(this,LinRotMechanism.EfficiencyText,i+1));

          if strcmp(Type,'Custom Profile Mechanism')
            CustomFcn = str2func(FindInTable(this,'Custom Profile Fcn',i+1));
            fh = functions(CustomFcn);
            isFcnValid = ~isempty(fh.file);
          else
            isFcnValid = true;
          end
          if isnan(this.Stroke(i)) || isnan(this.Phase(i)) || ...
              isnan(mp) || isnan(m1) || isnan(orient) ||...
              isnan(eff) || ~isFcnValid
            fprintf(...
              ['XXX ' Type ' is invalid, Frames not created. Trouble Components below.
XXX\n']);
            if isnan(this.Stroke(i))
              fprintf(...
                ['Stroke = ' FindInTable(this,this.StrokeText,i+1) '\n']);
            end
            if isnan(this.Phase(i))
              fprintf(...
                ['Phase = ' FindInTable(this,this.PhaseText,i+1) '\n']);
            end
            if isnan(mp)
              fprintf(...
                ['mp = ' FindInTable(this,this.PistonMassText,i+1) '\n']);
            end
            if isnan(m1)
              fprintf(...
                ['m1 = ' FindInTable(this,'Other Mass (kg)',i+1) '\n']);
            end
            if isnan(orient)
              fprintf(...
                ['Orient = ' orientation '\n']);
            end
            if isnan(eff)
              fprintf(...
                ['Eff. = ' FindInTable(this,this.EfficiencyText,i+1) '\n']);
            end
            if isFcnValid
              fprintf(...
                ['Fcn. = ' FindInTable(this,'Custom Profile Fcn',i+1) '\n']);
            end
            this.isValid = false;
            return;
          end
          %% Define motion of Frames
          if strcmp(Type,'Custom Profile Mechanism')
            CustomProfile = CustomFcn(Frame.NTheta,this.Phase(i));
          else
            Ang = (0:Frame.NTheta-1)/(Frame.NTheta-1)*2*pi + this.Phase(i);
            CustomProfile = this.Stroke(i)/2 + this.Stroke(i)*cos(Ang)/2;
          end
          if orient == 1
            xmin = min(CustomProfile);
            xmax = max(CustomProfile);
          else
            xmin = max(CustomProfile);
            xmax = min(CustomProfile);
          end
          this.Frames(i).Positions = (CustomProfile-xmin).*...
            (this.Stroke/(xmax-xmin));
          this.Frames(i).MechanismIndex = i;
          this.Frames(i).Mechanism = this;
          defineDataFromMotionProfile(Im1,mp,m1,eff,orient,this,i); % (Im1,mp,m1,eff,this,ind)
        end
      case 'Slider Crank'
        Ang = zeros(LEN,Frame.NTheta);
```

```
          for i = 1:LEN
            % Phase
            this.Phase(i) = str2double(FindInTable(this,this.PhaseText,i+1));
            Ang(i,:) = (0:Frame.NTheta-1)/(Frame.NTheta-1)*2*pi + this.Phase(i);
          end
          for i = 1:LEN
            d1 = this.Stroke(i);
            % Crank Mass (kg)
            m1 = str2double(FindInTable(this,'Crank Mass (kg)',i+1));
            % Crank C.O.M Radius (m)
            r1 = str2double(FindInTable(this,'Crank C.O.M Radius (m)',i+1));
            % Crank C.O.M Angle (rad)
            Ang_g1 = str2double(FindInTable(this,'Crank C.O.M Angle (rad)',i+1));
            % Crank Rot. Inertia (kgn^2)
            Im1 = str2double(FindInTable(this,'Crank Rot. Inertia (kgn^2)',i+1));
            % Crank-Con Fric. Fcn
            this.Data.F12{i} = str2func(FindInTable(this,'Crank-Con Fric. Fcn',i+1));
            fh = functions(this.Data.F12{i});
            isF12Valid = ~isempty(fh.file);
            % Con Length (m)
            d2 = str2double(FindInTable(this,'Con Length (m)',i+1));
            % Con. Mass (kg)
            m2 = str2double(FindInTable(this,'Con. Mass (kg)',i+1));
            % Con. C.O.M Radius from CR-CN pin (m)
            r2 = str2double(FindInTable(this,'Con. C.O.M Radius from CR-CN pin (m)',i+1));
            % Con. Rot. Inertia (kgn^2)
            Im2 = str2double(FindInTable(this,'Con. Rot. Inertia (kgn^2)',i+1));
            % Con-Piston Fric. Fcn
            this.Data.F23{i} = str2func(FindInTable(this,'Con-Piston Fric. Fcn',i+1));
            fh = functions(this.Data.F23{i});
            isF23Valid = ~isempty(fh.file);
            % Piston Mass (kg)
            m3 = str2double(FindInTable(this,'Piston Mass (kg)',i+1));
            % Piston Fric. Fcn
            this.Data.F3{i} = str2func(FindInTable(this,'Piston Fric. Fcn',i+1));
            fh = functions(this.Data.F3{i});
            isF3Valid = ~isempty(fh.file);
            % Tilt Angle
            Tilt = str2double(FindInTable(this,LinRotMechanism.TiltAngleText,i+1));
            % Slider-Offset (m)
            d3 = str2double(FindInTable(this,'Slider-Offset (m)',i+1));
            % Orientation: "u" aligned with positive y, "d" opposite
            orientation = str2double(FindInTable(this,'Orientation: "u" aligned with positive y,
"d" opposite',i+1));
            switch orientation
              case 'u'; orient = 1;
              case 'd'; orient = -1;
              otherwise; orient = nan();
            end

            if isnan(d1) || isnan(this.Phase(i)) || isnan(m1) || ...
                isnan(r1) || isnan(Ang_g1) || isnan(Im1) || ...
                ~isF12Valid || isnan(d2) || isnan(m2) || ...
                isnan(r2) || isnan(Im2) || ~isF23Valid || ...
                isnan(m3) || ~isF3Valid || isnan(Tilt) || ...
                isnan(d3) || isnan(orient)
              fprintf(...
                ['XXX ' Type ' is invalid, Frames not created. Trouble Components below.
XXX\n']);
              if isnan(d1)
                fprintf(...
                  ['Stroke = ' FindInTable(this,this.StrokeText,i+1) '\n']);
              end
              if isnan(this.Phase(i))
                fprintf(...
                  ['Phase = ' FindInTable(this,this.PhaseText,i+1) '\n']);
              end
              if isnan(m1)
                fprintf(...
                  ['Crank Mass (kg) = ' FindInTable(this,'Crank Mass (kg)',i+1) '\n']);
              end
```

```
            if isnan(r1)
              fprintf(...
                ['Crank C.O.M Radius (m) = ' FindInTable(this,'Crank C.O.M Radius (m)',i+1)
'\n']);
            end
            if isnan(Ang_g1)
              fprintf(...
                ['Crank C.O.M Angle (rad) = ' FindInTable(this,'Crank C.O.M Angle
(rad)',i+1)]);
            end
            if isnan(Im1)
              fprintf(...
                ['Crank Rot. Inertia (kgn^2) = ' FindInTable(this,'Crank Rot. Inertia
(kgn^2)',i+1) '\n']);
            end
            if isF12Valid
              fprintf(...
                ['Crank-Con Fric. Fcn = ' FindInTable(this,'Crank-Con Fric. Fcn',i+1) '\n']);
            end
            if isnan(d2)
              fprintf(...
                ['Con Length (m) = ' FindInTable(this,'Con Length (m)',i+1) '\n']);
            end
            if isnan(m2)
              fprintf(...
                ['Con. Mass (kg) = ' FindInTable(this,'Con. Mass (kg)',i+1) '\n']);
            end
            if isnan(r2)
              fprintf(...
                ['Con. C.O.M Radius from CR-CN pin (m) = ' FindInTable(this,'Con. C.O.M Radius
from CR-CN pin (m)',i+1) '\n']);
            end
            if isnan(Im2)
              fprintf(...
                ['Con. Rot. Inertia (kgn^2) = ' FindInTable(this,'Con. Rot. Inertia
(kgn^2)',i+1) '\n']);
            end
            if isF23Valid
              fprintf(...
                ['Con-Piston Fric. Fcn = ' FindInTable(this,'Con-Piston Fric. Fcn',i+1) '\n']);
            end
            if isnan(m3)
              fprintf(...
                ['Piston Mass (kg) = ' FindInTable(this,'Piston Mass (kg)',i+1) '\n']);
            end
            if isF3Valid
              fprintf(...
                ['Piston Fric. Fcn = ' FindInTable(this,'Piston Fric. Fcn',i+1) '\n']);
            end
            if isnan(Tilt)
              fprintf(...
                [LinRotMechanism.TiltAngleText ' = '
FindInTable(this,LinRotMechanism.TiltAngleText,i+1) '\n']);
            end
            if isnan(d3)
              fprintf(...
                ['Slider-Offset (m) = ' FindInTable(this,'Slider-Offset (m)',i+1) '\n']);
            end
            if isnan(orient)
              fprintf(...
                ['Orientation: "u" aligned with positive y, "d" opposite = ' orientation
'\n']);
            end
            this.isValid = false;
            return;
          end

          % Theta_SC is defined as Ang(i,:)
          Ang_sc = Ang(i,:)';
          C1 = cos(Ang_sc);
          S1 = sin(Ang_sc);
```

```
            C2 = cos(Beta_sc);
            S2 = sin(Beta_sc);
            Beta_sc = asin((d3 - d1*S1)/d2);
            Beta_g = Beta_sc + Tilt;
            Ang_g = Ang_sc + Tilt + Ang_g1;
            this.Data.T2(:,i) = tan(Beta_sc);

            % Coefficients on Alpha_2
            C_Omega2 = (-d1/d2).*(C1./C2);
            this.Data.Omega2(:,i) = C_Omega2;
            B_Alpha2 = ((d1*S1+d2*S2.*C_Omega2.^2)./(d2*C2));

            % Coefficients on Acceleration 1 x
            B_a1x = -r1*cos(Ang_sc + Ang_g1);
            C_a1x = -r1*sin(Ang_sc + Ang_g1);

            % Coefficients on Acceleration 1 y
            B_a1y = -r1*sin(Ang_sc + Ang_g1);
            C_a1y = r1*cos(Ang_sc + Ang_g1);

            % Coefficients on Acceleration 2 x
            B_a2x = (-d1*C1 - r2*C2.*C_Omega2.^2 - r2*S2.*B_Alpha2);
            C_a2x = (-d1*S1 - r2*S2.*C_Omega2);

            % Coefficients on Acceleration 2 y
            B_a2y = (-d1*S1 - r2*S2.*C_Omega2.^2 + r2*C2.*B_Alpha2);
            C_a2y = (d1*C1 + r2*C2.*C_Omega2);

            % Coefficients on Acceleration 3 x
            B_a3x = (-d1*C1 - d2*C2.*C_Omega2.^2 - d2*S2.*B_Alpha2);
            C_a3x = (-d1*S1 - d2*S2.*C_Omega2);

            % Piston Position & Velocity Coefficient on Omega
            this.Data.x_p(:,i) = d1*C1 + d2*C2 - sqrt((d2-d1)^2 - d3^2);
            this.Data.v_p(:,i) = -d1*S1 - d2*S2*C_Omega2;

            this.Data.A1(:,i) = m3*C_a3x;
            this.Data.A2(:,i) = m2*C_a2x + this.Data.A1(:,i);
            this.Data.A3(:,i) = (-Im2*C_Omega2./(d2*C2) + this.Data.T2(:,i).*this.Data.A1(:,i));
            this.Data.A4(:,i) = m2*C_a2y + this.Data.A3(:,i);
            this.Data.A5(:,i) = m1*C_a1x + this.Data.A2(:,i);
            this.Data.A6(:,i) = m1*C_a1y + this.Data.A4(:,i);

            this.Data.B1(:,i) = m3*B_a3x;
            this.Data.B2(:,i) = m2*B_a2x + this.Data.B1(:,i);
            this.Data.B3(:,i) = (-Im2*B_Alpha2./(d2*C2) + this.Data.T2(:,i).*this.Data.B1(:,i));
            this.Data.B4(:,i) = m2*B_a2y + this.Data.B3(:,i);
            this.Data.B5(:,i) = m1*B_a1x + this.Data.B2(:,i);
            this.Data.B6(:,i) = m1*B_a1y + this.Data.B4(:,i);

            this.Data.G1(:,i) = this.g*m3*this.STilt(i);
            this.Data.G2(:,i) = this.g*m2*this.STilt(i) + this.Data.G1(:,i);
            this.Data.G3(:,i) = (-this.g*r2*cos(Beta_g)./(d2*C2) +
this.Data.T2(:,i).*this.Data.G1(:,i));
            this.Data.G4(:,i) = this.g*m2*cos(Beta_g) + this.Data.G3(:,i);
            this.Data.G5(:,i) = this.g_m1*this.STilt(i) + this.Data.G2(:,i);
            this.Data.G6(:,i) = this.g*m1*this.CTilt(i) + this.Data.G4(:,i);

            temp_5 = -this.CTilt(i)*this.Data.A5(:,i) + this.STilt(i)*this.Data.A6(:,i);
            this.Data.A6(:,i) = -this.STilt(i)*this.Data.A5(:,i) -
this.CTilt(i)*this.Data.A6(:,i);
            this.Data.A5(:,i) = temp_5;

            temp_5 = -this.CTilt(i)*this.Data.B5(:,i) + this.STilt(i)*this.Data.B6(:,i);
            this.Data.B6(:,i) = -this.STilt(i)*this.Data.B5(:,i) -
this.CTilt(i)*this.Data.B6(:,i);
            this.Data.B5(:,i) = temp_5;

            temp_5 = -this.CTilt(i)*this.Data.G5(:,i) + this.STilt(i)*this.Data.G6(:,i);
            this.Data.G6(:,i) = -this.STilt(i)*this.Data.G5(:,i) -
this.CTilt(i)*this.Data.G6(:,i);
```

```
        this.Data.G5(:,i) = temp_5;

        this.Data.E5(:,i) = orient*(-this.CTilt(i) + this.STilt(i)*this.Data.T2(Inc,i));
        this.Data.E6(:,i) = orient*(-this.STilt(i) - this.CTilt(i)*this.Data.T2(Inc,i));

        this.Data.AM(:,i) = -(Im1 - d1*S1.*this.Data.A2(:,i) + d1*C1.*this.Data.A4(:,i));
        this.Data.BM(:,i) = -(-d1*S1.*this.Data.B2(:,i) + d1*C1.*this.Data.B4(:,i));
        this.Data.GM(:,i) = -(this.g*m1*r1*cos(Ang_g) - ...
          d1*S1.*this.Data.A2(:,i) + d1*C1.*this.Data.A4(:,i));
        this.Data.EM(:,i) = orient*-1*(-d1*S1 + d1*C1*this.Data.T2(:,i));
        this.outputFcn = @this.SliderCrank;

        if strcmp(Type,'Custom Profile Mechanism')
          CustomProfile = CustomFcn(Frame.NTheta,this.Phase(i));
        else
          Ang = (0:Frame.NTheta-1)/(Frame.NTheta-1)*2*pi + this.Phase(i);
          CustomProfile = this.Stroke(i)/2 + this.Stroke(i)*cos(Ang)/2;
        end
        if orient == 1
          xmin = min(CustomProfile);
          xmax = max(CustomProfile);
        else
          xmin = max(CustomProfile);
          xmax = min(CustomProfile);
        end
        this.Frames(i).Positions = (CustomProfile-xmin).*...
          (this.Stroke/(xmax-xmin));
        this.Frames(i).MechanismIndex = i;
        this.Frames(i).Mechanism = this;
      end
      %         case 'Scotch Yoke'
      %           Ang = zeros(LEN,Frame.NTheta);
      %           for i = 1:LEN
      %             Ang(i,:) = (0:Frame.NTheta-1)/(Frame.NTheta-1)*2*pi + this.Phase(i);
      %           end
      %           for i = 1:LEN
      %
      %           end
      %         case 'Rhombic Drive'
      %
  end
end
function Modify(this)
  persistentData = Holder({this.Type,this.originalInput});
  h = CreateMechanismInterface(persistentData);
  uiwait(h);
  if isempty(persistentData.vars)
    this.deReference();
  else
    this.Populate(persistentData.vars{1},persistentData.vars{2});
  end

  % Find all Connections that have frames that reference this index
  for iGroup = this.Model.Groups
    for iCon = iGroup.Connections
      if ~isempty(iCon.RefFrame)
        if iCon.RefFrame.Mechanism == this
          iCon.change();
        end
      end
    end
  end
end

%% Get/Set Interface
function Item = get(this,PropertyName)
  switch PropertyName
    case 'Name'
      Item = this.name;
    case 'Stroke'
      if size(this.originalInput,1)-1 == 1
```

```
        for c = 1:size(this.originalInput,2)
          if contains(this.originalInput{1,c},'Stroke')
            if isStrNumeric(this.originalInput{2,c})
              Item = str2double(this.originalInput{2,c});
              return;
            end
          end
        end
      else
        fprintf(['XXX Gradient Descent does ' ...
          'not support mechanisms with ' ...
          'multiple strokes XXX\n']);
        return;
      end
    otherwise
      fprintf(['XXX Lin Rot Mechanism GET Inteface for ' PropertyName ...
        ' is not found XXX\n']);
  end
end
function set(this,PropertyName,Item)
  switch PropertyName
    case 'Stroke'
      if size(this.originalInput,1)-1 == 1
        for c = 1:size(this.originalInput,2)
          if contains(this.originalInput{1,c},'Stroke')
            if isStrNumeric(this.originalInput{2,c})
              this.originalInput{2,c} = num2str(Item);
              return;
            end
          end
        end
        this.Populate(this.Type,this.originalInput);
      else
        fprintf(['XXX Gradient Descent does ' ...
          'not support mechanisms with ' ...
          'multiple strokes XXX\n']);
        return;
      end
    otherwise
      fprintf(['XXX Lin Rot Mechanism SET Inteface for ' PropertyName ...
        ' is not found XXX\n']);
  end
end

function Uniform_Scale(this, Uniform_Scale)
  for c = 1:size(this.originalInput,2)
    if contains(this.originalInput{1,c},'(m)')
      factor = Uniform_Scale;
    elseif contains(this.originalInput{1,c},'(kg)')
      factor = Uniform_Scale ^ 3;
    elseif contains(this.originalInput{1,c},'(kg m^2)')
      factor = Uniform_Scale ^ 5;
    else
      continue;
    end
    for r = 2:size(this.originalInput,1)
      if isStrNumeric(this.originalInput{r,c})
        this.originalInput{r,c} = ...
          num2str(...
          factor * str2double(this.originalInput{r,c}));
      end
    end
  end
  this.dont_propegate = true;
  this.Populate(this.Type,this.originalInput);
end

%% Dependent
function var = get.name(this)
  var = this.Type;
  for i = 1:length(this.Stroke)
```

```
        var = [var ' ' num2str(i) ':(L=' num2str(this.Stroke(i)) ', P=' num2str(this.Phase(i))
')'];
      end
    end

    %% Internal Helpers
    function populateTilt(this)
      for i = 2:size(this.originalInput,1)
        Tilt = str2double(FindInTable(this,this.TiltAngleText,i));
        if isnan(Tilt)
          fprintf('XXX Invalid value for Tilt from Horizontal, perfectly horizontal assumed.
XXX\n');
          ReplaceInTable(this,'0',this.TiltAngleText,i)
          this.STilt(i-1) = 0;
          this.CTilt(i-1) = 1;
        else
          this.STilt(i-1) = sin(Tilt);
          this.CTilt(i-1) = cos(Tilt);
        end
      end
    end

    % Ideal Motions
    function defineDataFromMotionProfile(Im1,mp,m1,eff,~,this,ind)
      %% Define Loads
      dx_dtheta = getFirstDer(this.Frames(ind).Positions);
      d2x_dtheta2 = getSecondDer(this.Frames(ind).Positions);

      Ax = -this.CTilt(ind)*mp*dx_dtheta;
      Bx = -this.CTilt(ind)*mp*d2x_dtheta2;
      Gx = -this.g*(mp + m1)*this.STilt(ind);
      Ex = this.CTilt(ind); % * Fp

      Ay = -this.STilt(ind)*mp*dx_dtheta;
      By = -this.STilt(ind)*mp*d2x_dtheta2;
      Gy = -this.g*(mp + m1)*this.CTilt(ind);
      Ey = this.STilt(ind); % * Fp

      Am = -Im1 - mp*(dx_dtheta).^2;
      Bm = -mp*dx_dtheta.*d2x_dtheta2;
      Gm = -this.g*this.STilt(ind)*mp*dx_dtheta;
      Em = dx_dtheta; % * Fp

      if isfield(this.Data,'Ax')
        appendData(this,'Ax',Ax,ind);
        appendData(this,'Bx',Bx,ind);
        appendData(this,'Gx',Gx,ind);
        appendData(this,'Ex',Ex,ind);

        appendData(this,'Ay',Ay,ind);
        appendData(this,'By',By,ind);
        appendData(this,'Gy',Gy,ind);
        appendData(this,'Ey',Ey,ind);

        appendData(this,'Am',Am,ind);
        appendData(this,'Bm',Bm,ind);
        appendData(this,'Gm',Gm,ind);
        appendData(this,'Em',Em,ind);
        this.Data.Eff(ind) = eff;
      else
        this.Data = struct(...
          'Ax',Ax,'Bx',Bx,'Gx',Bx,'Ex',Ex,...
          'Ay',Ay,'By',By,'Gy',Gy,'Ey',Ey,...
          'Am',Am,'Bm',Bm,'Gm',Gm,'Em',Em,...
          'Eff',eff);
      end

      this.outputFcn = @this.MotionWithEfficiency;
    end

    function output = MotionWithEfficiency(this,input)
```

```
      % input = [dA, ddA, Fp, Inc, mechindex]
      % output = [Fx, Fy, M]
      output = zeros(3,1);
      inc = input(4);
      i = input(5);
      if inc > 1
        incp = inc - 1;
      else
        incp = size(this.Data.Ax,1) - 1;
      end

      % Horizontal Load, as felt by the drive shaft
      if size(this.Data.Gx,1) == 1
        output(1) = (this.Data.Ax(incp,i) + this.Data.Ax(inc,i))*input(2) + ...
          (this.Data.Bx(incp,i) + this.Data.Bx(inc,i))*input(1)^2 + ...
          2*this.Data.Gx(1,i) + ...
          2*this.Data.Ex(i)*input(3);
      else
        output(1) = (this.Data.Ax(incp,i) + this.Data.Ax(inc,i))*input(2) + ...
          (this.Data.Bx(incp,i) + this.Data.Bx(inc,i))*input(1)^2 + ...
          (this.Data.Gx(incp,i) + this.Data.Gx(inc,i)) + ...
          2*this.Data.Ex(i)*input(3);
      end

      % Vertical Load, as felt by the drive shaft\
      if size(this.Data.Gy,1) == 1
        output(2) = (this.Data.Ay(incp,i) + this.Data.Ay(inc,i))*input(2) + ...
          (this.Data.By(incp,i) + this.Data.By(inc,i))*input(1)^2 + ...
          2*this.Data.Gy(i) + ...
          2*this.Data.Ey(i)*input(3);
      else
        output(2) = (this.Data.Ay(incp,i) + this.Data.Ay(inc,i))*input(2) + ...
          (this.Data.By(incp,i) + this.Data.By(inc,i))*input(1)^2 + ...
          (this.Data.Gy(incp,i) + this.Data.Gy(inc,i)) + ...
          2*this.Data.Ey(i)*input(3);
      end

      % Moment as felt by shaft
      if (this.Data.Em(incp,i) + this.Data.Em(inc,i))*input(3) < 0
        % Power is leaving the flywheel
        output(3) =(this.Data.Am(incp,i) + this.Data.Am(inc,i))*input(2) + ...
          (this.Data.Bm(incp,i) + this.Data.Bm(inc,i))*input(1)^2 + ...
          (this.Data.Gm(incp,i) + this.Data.Gm(inc,i)) + ...
          (this.Data.Em(incp,i) + this.Data.Em(inc,i))*input(3)/double(this.Data.Eff(i));
      else
        % Power is entering the flywheel
        output(3) =(this.Data.Am(incp,i) + this.Data.Am(inc,i))*input(2) + ...
          (this.Data.Bm(incp,i) + this.Data.Bm(inc,i))*input(1)^2 + ...
          (this.Data.Gm(incp,i) + this.Data.Gm(inc,i)) + ...
          (this.Data.Em(incp,i) + this.Data.Em(inc,i))*input(3)*double(this.Data.Eff(i));
      end
      output = output / 2;
    end

    %{
    % Simplified Arbitrary Motions
function defineDataForComplexCustomProfile(L,Mp,Ip,Mr,Iconst,Eff,this,ind)
      dx_dtheta = getFirstDer(this.Frames(ind).Positions);
      d2x_dtheta2 = getSecondDer(this.Frames(ind).Positions);
      if Ip ~= 0
        % Gears
        A2 = asin_omni(this.Frames(ind).Positions/L - 1);
        dA2_dtheta = getFirstDer(A2);
        d2A2_dtheta2 = getSecondDer(A2);
        % Coefficient on omega1^2
        BddA2 = Ip.*d2A2_dtheta2;
        % Coefficient on alpha1
        AddA2 = -Ip.*dA2_dtheta;
      else
        % Cam Drive
        BddA2 = 0; % no pulsing rotational elements
```

```
        AddA2 = 0; % " " "
      end
      % C1 - Coeff on ddA for Fx as felt by drive shaft
      this.Data(1,:,ind) = -dx_dtheta;
      % C2 - Coeff on dA^2 for Fx as felt by drive shaft
      this.Data(2,:,ind) = -d2x_dtheta2;
      % C3 - Gravity contribution for Fx as felt by drive shaft
      this.Data(3,:,ind) = -this.STilt*this.g*(Mp + Mr);
      % C4 - Coeff on ddA for Fy
      this.Data(4,:,ind) = -this.CTilt*this.g*(Mr);
      % Maybe consider a pressure angle, but center distance also
      % required

      % C - Coeff on Fp for M
      this.Data(5,:,ind) = -dx_dtheta;
      % C - Coeff on ddA for M
      this.Data(6,:,ind) = (Mp.*(dx_dtheta.^2) - AddA2)*Eff;
      % C - Coeff on dA^2 for M
      this.Data(7,:,ind) = ...
        (-Mp.*(dx_dtheta).*(d2x_dtheta2) - BddA2)*Eff - Iconst;

      this.outputFcn = @this.CustomProfileMechanism;
    end

function output = CustomProfileMechanism(this,input)
      % input = [dA, ddA, Fp, Inc, mechindex]
      % output = [Fx, Fy, M]
      output = zeros(3,1);
      output(1) ...
        = input(3)... = Fp
        + this.Data(1,input(4))*input(2)... + C1*ddA
        + this.Data(2,input(4))*input(1)^2 ... + C2*dA^2
        + this.Data(3,input(4)); % + C3
      output(2) ... Vertical Load, as felt by the drive shaft
        = this.STilt*output(1);
      output(1) ... Horizontal Load, as felt by the drive shaft
        = this.CTilt*output(1);
      % M =
      output(3) ... Moment as felt by shaft
        = this.Data(4,input(4))*input(3)... % C4*Fp
        + this.Data(5,input(4))*input(2)... % C5*ddA
        + this.Data(6,input(4))*input(1)^2; % C6*dA^2
    end
    %}

    % Slider Crank
    function output = SliderCrank(this,input)
      % input = [dA, ddA, Fp, Inc, mechindex]
      % output = [Fx, Fy, M]
      dA = input(1);
      ddA = input(2);
      Fp = input(3);
      Inc = input(4);
      i = input(5);
      F12 = this.Data.F12{i}(sqrt((...
        this.Data.A2(Inc,i)*ddA + ...
        this.Data.B2(Inc,i)*dA^2 + ...
        this.Data.G2(Inc,i) + Fp)^2 + ...
        (this.Data.A4(Inc,i)*ddA + ...
        this.Data.B4(Inc,i)*dA^2 + ...
        this.Data.G4(Inc,i) - ...
        this.Data.T2(Inc,i)*Fp)^2));
      F3y = abs(this.Data.A3(Inc,i)*ddA + ...
        this.Data.B3(Inc,i)*dA^2 + ...
        this.Data.G3(Inc,i) - ...
        this.Data.T2(Inc,i)*Fp);
      F23 = this.Data.F23{i}(...
        sqrt((this.Data.A1(Inc,i)*ddA + ...
        this.Data.B1(Inc,i)*dA^2 + ...
        this.Data.G1(Inc,i) + Fp)^2 + (F3y)^2));
      F3y = this.Data.F3{i}(F3y);
```

```
  LostTorque = -dA*(...
    abs(F12*(this.Data.Omega2(Inc,i)-1)) + ...
    abs(F23*this.Data.Omega2(Inc,i)) + ...
    abs(F3y*this.Data.v_p(Inc,i)));

  output = zeros(3,1);
  output(1) = ... % Horizontal Load
    this.Data.A5(Inc,i)*ddA + this.Data.B5(Inc,i)*dA^2 + ...
    this.Data.G5(Inc,i) + ...
    this.Data.E5(Inc,i)*Fp;
  output(2) = ... % Vertical Load
    this.Data.A6(Inc,i)*ddA + this.Data.B6(Inc,i)*dA^2 + ...
    this.Data.G6(Inc,i) + ...
    this.Data.E6(Inc,i)*Fp;
  output(3) = ... % Moment as felt by shaft
    this.Data.AM(Inc,i)*ddA + this.Data.BM(Inc,i)*dA^2 + ...
    this.Data.GM(Inc,i) + this.Data.EM(Inc,i)*Fp + ...
    LostTorque;
end

function output = ScotchYoke(this,input)
  % input = [dA, ddA, Fp, Inc, mechindex]
  % output = [Fx, Fy, M]

end

function output = RhombicDrive(this,input)
  % input = [dA, ddA, Fp, Inc, mechindex]
  % output = [Fx, Fy, M]
  dA = input(1);
  ddA = input(2);
  Fp = input(3);
  Inc = input(4);
  i = input(5);
  F12 = this.Data.F12{i}(sqrt((...
    this.Data.A2(Inc,i)*ddA + ...
    this.Data.B2(Inc,i)*dA^2 + ...
    this.Data.G2(Inc,i) + Fp)^2 + ...
    (this.Data.A4(Inc,i)*ddA + ...
    this.Data.B4(Inc,i)*dA^2 + ...
    this.Data.G4(Inc,i) - ...
    this.Data.T2(Inc,i)*Fp)^2));
  F3y = abs(this.Data.A3(Inc,i)*ddA + ...
    this.Data.B3(Inc,i)*dA^2 + ...
    this.Data.G3(Inc,i) - ...
    this.Data.T2(Inc,i)*Fp);
  F23 = this.Data.F23{i}(...
    sqrt((this.Data.A1(Inc,i)*ddA + ...
    this.Data.B1(Inc,i)*dA^2 + ...
    this.Data.G1(Inc,i) + Fp)^2 + (F3y)^2));
  F3y = this.Data.F3{i}(F3y);

  % TANalpha_2L4 = tan(pressure angle)/(2*l4)

  output = zeros(3,1);
  output(3) = ... % Moment as felt by shaft
    this.Data.AM(Inc,i)*ddA + this.Data.BM(Inc,i)*dA^2 + ...
    this.Data.GM(Inc,i) + this.Data.EM(Inc,i)*Fp;
  output(1) = 0.5*(... % Horizontal Load
    this.Data.A5(Inc,i)*ddA + this.Data.B5(Inc,i)*dA^2 + ...
    this.Data.G5(Inc,i) + ...
    this.Data.E5(Inc,i)*Fp + ...
    output(3)*this.Data.TANalpha_2L4(i)*this.STilt(i));
  output(2) = 0.5*(... % Vertical Load
    this.Data.A6(Inc,i)*ddA + this.Data.B6(Inc,i)*dA^2 + ...
    this.Data.G6(Inc,i) + ...
    this.Data.E6(Inc,i)*Fp - ...
    output(3)*this.Data.TANalpha_2L4(i)*this.CTilt(i));

  LostTorque = -dA*(...
    abs(F12*(this.Data.Omega2(Inc,i)-1)) + ...
```

```
        abs(F23*this.Data.Omega2(Inc,i)) + ...
        abs(F3y*this.Data.v_p(Inc,i)) + ...
        abs(this.Data.Faux{i}(sqrt(output(1)^2+output(2)^2))));

      output(3) = output(3) + LostTorque;
    end
  end

end

function PropertyValue = FindInTable(LinRotMech,Item,row)
for col = 1:size(LinRotMech.originalInput,2)
  if strcmp(LinRotMech.originalInput{1,col},Item)
    PropertyValue = LinRotMech.originalInput{row,col};
    return;
  end
end
fprintf(['XXX no property called "' Item '" for LinRotMechanism/Type = "' ...
  LinRotMech.Type '". Value of "" applied. XXX\n']);
PropertyValue = '';
end

function ReplaceInTable(LinRotMech,PropertyValue,Item,row)
for col = 1:size(LinRotMech.originalInput,2)
  if strcmp(LinRotMech.originalInput{1,col},Item)
    LinRotMech.originalInput{row,rol} = PropertyValue;
    return;
  end
end
fprintf(['XXX no property called "' Item '" for LinRotMechanism/Type = "' ...
  LinRotMech.Type '". Value of "" applied. XXX\n']);
end

function Template = MergeTables(Template,Data)
for Dcol = 1:size(Data,2)
  % For each column of Data
  % Find the representative column in Template
  for Tcol = 1:size(Template,2)
    if strcmp(Data{1,Dcol},Template{1,Tcol})
      for row = 2:size(Data,1)
        Template{row,Tcol} = Data{row,Dcol};
      end
      break;
    end
  end
end
end

function appendData(ME,field,Data,ind)
if isfield(ME.Data,field)
  if size(ME.Data.(field),1) == size(Data,1)
    ME.Data.(field)(:,ind) = Data;
  elseif size(ME.Data.(field),1) == 1
    temp = repmat(ME.Data.(field),size(Data,1),1);
    ME.Data.(field) = temp;
    ME.Data.(field)(:,ind) = Data;
  elseif size(Data,1) == 1
    ME.Data.(field)(:,ind) = Data;
  else
    fprintf('XXX Frame divisions have changed, please implement a fix XXX\n');
  end
else
  ME.Data.(field)(:,ind) = Data;
end
end
```

Mechanical System

The mechanical system is a class that includes the following functionality:

A constructor.

A get / set interface.

Solve: Takes the motion state and piston force and translates it through the linear to rotational mechanisms to produce an acceleration.

A set of unused functions that were investigating approximating arbitrary mechanisms with N-dimensional interpolation.

```
classdef MechanicalSystem < handle
   %UNTITLED2 Summary of this class goes here
   %   Detailed explanation goes here

   properties (Constant)
      SteadyStateRMS = 0.1;
      NDimModelCalcRadius = [10 10 3];
   end

   properties (Dependent)
       isConverged;
   end

   properties
      Model Model; %

      Converters LinRotMechanism; % Array Containing Linear-Rotational Converters
      Inertia double = 1; % Real Flywheel Inertia
      DriveTrainWeight double = 1;
      DriveTrainFricCoef double = 0;
      LoadFunction function_handle; % Function that takes current motion and provides a counter
load

      InertiaMod double = 1; % Modifier Used to allow the engine to get up to speed faster, or
stabilize it during slow times.
      KE double = 0; % Kinetic Energy
      Alpha double = 0; % The rotational acceleration
      Omega double = 0; % The rotational speed
      Theta double = 0; % The physical Angle


      LastCycle double; % (Theta, Omega)
      ThisCycle double; % Continously recorded and checked for convergence

      % Set in SetInitialConditions
      Points double; % Array indicating the points at which the model is calculated for each
variable
      Inc double; % Vector indicating the increment that is used to discretize each variable
   end

   properties (Dependent)
     name;
   end

   methods
      %% Constructor
```

```
      function this = MechanicalSystem(Model,Converters,~,Inertia,LoadFunction)
         this.Model = Model;
         % Define other parameters
         this.Converters = Converters;
         this.Inertia = Inertia;
         this.LoadFunction = LoadFunction;
      end
      function iname = get.name(~)
        iname = 'Mechanical System';
      end
      function Item = get(this, PropertyName)
        switch PropertyName
          case 'name'
            Item = this.name();
          case 'Flywheel Inertia'
            Item = this.Inertia;
          case 'Drive Train Weight'
            Item = this.DriveTrainWeight;
          case 'Drive Train Normal Friction Coefficient'
            Item = this.DriveTrainFricCoef;
          case 'Load Function'
            Item = this.LoadFunction;
          otherwise
            fprintf(['XXX MechanicalSystem GET Inteface for ' PropertyName ' is not found
XXX\n']);
            return;
        end
      end
      function set(this,PropertyName,Item)
        switch PropertyName
          case 'name'
            % Do nothing
          case 'Flywheel Inertia'
            this.Inertia = Item;
          case 'Drive Train Weight'
            this.DriveTrainWeight = Item;
          case 'Drive Train Normal Friction Coefficient'
            this.DriveTrainFricCoef = Item;
          case 'Load Function'
            this.LoadFunction = Item;
          otherwise
            fprintf(['XXX MechanicalSystem SET Inteface for ' PropertyName ' is not found
XXX\n']);
            return;
        end
      end

      function Power = Solve(this,Inc,dA,ddA,Forces)
         M = 0;
         fric = abs(this.DriveTrainWeight*this.DriveTrainFricCoef);
         for i = 1:length(this.Converters)
           for j = 1:length(Forces{i})
             F = this.Converters(i).outputFcn([dA ddA Forces{i}(j) Inc j]);
             M = M + F(3);
             fric = fric + sqrt(F(1)^2 + F(2)^2)*this.DriveTrainFricCoef;
           end
%            if i == length(this.Converters)
%                fprintf([', ' num2str(M*dA) '\n']);
%            elseif i == 1
%               fprintf(num2str(M*dA));
%            else
%               fprintf([', ' num2str(M*dA)]);
%            end
         end
         Power = (M - fric)*dA;
      end

      function SetInitialConditions(this,iTheta,iOmega)
         this.Theta = iTheta;
         this.Omega = iOmega;
         this.Alpha = 0;
```

```
   end

   %% Analysis Function
   function RMS = compareCycles(this)
      % Calculate the RMS error between cycles
      Match = interp1(this.LastCycle(:).Theta,...
         this.LastCycle(:).Omega,...
         this.ThisCycle(:).Theta);
      RMS = rssq(Match - this.ThisCycle.Omega)/sqrt(length(Match));
   end
   function Converged = get.isConverged(this)
       Converged = this.compareCycles() < this.SteadyStateRMS;
   end

   %% Simulation Function
   function move(this,InputForces)
      %% Do something with the Input Forces
      % http://matlab.izmiran.ru/help/techdoc/matlab_prog/ch_dat41.html
      % If you use the colon to index multiple cells in conjunction
      %  with the curly brace notation, MATLAB treats the contents of
      %  each cell as a separate variable. For example, assume you have
      %  a cell array T where each cell contains a separate vector. The
      %  expression T{1:5} is equivalent to a comma-separated list of
      %  the vectors in the first five cells of T.
      if this.isKinematic
         % Collect the input parameters
         Parameters = cell(length(InputForces)+2,1);
         Parameters{1} = mod(this.Theta,2*pi);
         Parameters{2} = this.Omega*this.Omega;
         for r = 3:length(Parameters)
            Parameters{r} = InputForces(r-2);
         end
         % Interpolate the Mechanical System Results
         this.Alpha = interpn(Parameters{:},this.NDimModel,...
            this.Points{:},'linear',NaN);
         % ThetaInc,   this.sqOmegaInc,   this.ForceInc{:},...
         if isnan(this.Alpha)
            % Assess if the extrapolation array needs to be expanded to
            % the next parameter

            % Find the parameter that goes out
             % Points
             C = zeros(length(this.Points),1);
             for i = 1:length(this.Points)
                 if Parameters(i) > this.Points{i}(end)
                     C(i) = ceil((Parameters(i)-this.Points{i}(end))/this.Inc(i));
                 elseif Parameters(i) < this.Points{i}(1)
                     C(i) = -ceil(abs(Parameters(i)-this.Points{i}(end))/this.Inc(i));
                 end
             end

             this.UpdateMechanicalModel(C);

             this.Alpha = interpn(Parameters{:},this.NDimModel,...
                this.Points{:},'linear',NaN);
         end

         % Move Position ahead
         ChThetaeInVelocity = this.Model.dt*this.Alpha;
         this.Theta = this.Theta + this.Model.dt*(this.Omega+ChThetaeInVelocity/2);
         this.Omega = this.Omega + ChThetaeInVelocity;

         for iFrame = this.Model.RefFrames
            if iFrame.Mechanism == this
               iFrame.Position = getPosition(this.Theta);
            end
         end
      end
   end
end
```

```
end
```

G.5. Motion

Motions

Idealized Square Wave Motion

```
function [ pos ] = box_wave( Nang, Phase )
  if nargin == 0
    Nang = 200;
    Phase = 0;
  end
  Phase = Phase + pi/2;
  e = 0.8;
  n = 2;
  con_cr_ratio = 2;
  TransferPhase = pi/2;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
end
```

Idealized Saw Wave Motion

```
function [ pos ] = v_wave( Nang, Phase )
Phase = Phase + pi;
%r = 5;
%L = sqrt((1-2*r)^2+(Nang-1)^2);
%theta = r*sin(asin((Nang-1)/L)-asin(2*r/L));
%d = r*sin(theta);
%offset = r*cos(theta);
pos = zeros(1,Nang);
for i = 1:Nang
  x = mod(i-1 + (-Phase)/(2*pi)*(Nang-1),Nang-1);
  if x < 0.5*(Nang-1)
    % Within First Top Circle
    pos(i) = 1 - 2*x/(Nang-1);
  else
    pos(i) = 2*(x-(Nang-1))/(Nang-1) + 1;
  end
end
ends = zeros(1,4);
for i = 1:100
  ends(1:2) = pos(1:2);
  ends(3:4) = pos(end-1:end);
  pos(2:end-1) = (pos(1:end-2) + pos(3:end))/2;
  pos(1) = (ends(2) + ends(4))/2;
  pos(end) = (ends(1) + ends(3))/2;
end
pos = pos - min(pos);
pos = pos / max(pos);
end
```

Slider Crank Motion with connecting rod 2 times larger than crank rod

```
function [ pos ] = e0_n2_r2( Nang, Phase )
  Phase = Phase + pi;
  e = 0;
  n = 2;
  con_cr_ratio = 2;
  TransferPhase = 0;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
end
```

Slider Crank Motion with connecting rod 6 times larger than crank rod

```
function [ pos ] = e0_n2_r6( Nang, Phase )
  Phase = Phase + pi;
  e = 0;
  n = 2;
  con_cr_ratio = 6;
  TransferPhase = 0;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
end
```

Slider Crank Motion driven by 1/5 ellipical gears with connecting rod 2 tiems larger than crank rod, arranged to produce dwelling motion.

```
function [ pos ] = e15_n2_r2_Box( Nang, Phase )
  if nargin == 0
    Nang = 200;
    Phase = 0;
  end
  Phase = Phase + pi/2;
  e = 1/4;
  n = 2;
  con_cr_ratio = 2;
  TransferPhase = pi/2;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
end
```

Slider Crank Motion driven by 1/5 ellipical gears with connecting rod 2 tiems larger than crank rod, arranged to produce saw wave motion.

```
function [ pos ] = e15_n2_r2_Sharp( Nang, Phase )
  Phase = Phase + pi;
  e = 1/5;
  n = 2;
  con_cr_ratio = 2;
  TransferPhase = 0;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
end
```

Slider Crank Motion driven by 1/5 ellipical gears with connecting rod 6 tiems larger than crank rod, arranged to produce dwelling motion.

```
function [ pos ] = e15_n2_r6_Box( Nang, Phase )
  if nargin == 0
    Nang = 200;
    Phase = 0;
  end
  Phase = Phase + pi/2;
  e = 1/5;
  n = 2;
  con_cr_ratio = 6;
  TransferPhase = pi/2;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
```

```
end
```

Slider Crank Motion driven by 1/5 ellipical gears with connecting rod 6 tiems larger than crank rod, arranged to produce saw wave motion.

```
function [ pos ] = e15_n2_r6_Sharp( Nang, Phase )
  Phase = Phase + pi;
  e = 1/5;
  n = 2;
  con_cr_ratio = 6;
  TransferPhase = 0;
  pos = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase);
end
```

Basic Elliptical motion

```
function [pos] = Ellipsoidal(Nang,Phase,e,n,con_cr_ratio,TransferPhase)
  ang = mod(linspace(0,2*pi,Nang),2*pi);
  C = (sqrt(1+(n^2-1)*(1-e^2)) + e)/(n*(1-e));
  % Pass ang through the transfer function
  ang = atanSmooth(C*tan(ang)) + TransferPhase;
  l_cr = 0.5;
  l_con = l_cr*con_cr_ratio;
  ang2 = asin((-l_cr*sin(ang))/l_con);
  pos = l_con*(cos(ang2) - 1) + l_cr*(cos(ang) + 1);
  pos(1:end-1) = shiftVector(pos(1:end-1),Phase);
  pos(end) = pos(1);
end
```

G.6. Simulation

Simulation

Simulation is a class that performs all conduction and gas relations operations. It includes the following functionality:

A run function that sets up the simulation, performs warmup and during simulation it calls the time integration function (running over increments) and calls the mechanism solve function (between increments). This function also tracks steady-state, adjusts pressure, solves for steady-state temperatures and performs recording operations.

The time integration function.

The loop solving sub-function.

A function that calculates the cost, in relation to the Newton-Raphson algorithm.

A function that calculates the average of the dynamic properties.

A function that interpolates properties given an increment value.

A function that updates the engine pressure.

A set of functions for calculating turbulence weighting, flow loss coefficients and temperature related properties.

```
classdef Simulation < handle
  % Simulation objects contain all the arrays of each particular node, and
  % each particular interface type along with all supporting information
  % tables

  properties (Constant)
    U_Tolerance = 1e-6;
    turb_Tolerance = 0.05;
    RE_Tolerance = 1;
    InertiaMod = 0.1;
  end

  properties

    MaxCourant = 0.25;
    MaxFourier = 0.25;

    Model Model;
    %% Face Properties
    % Face Types
    Mix_Fc;

    % Dynamic Data
    Dynamic;
    Dyn = 1;

    % Node Property Pointers to Dynamic Data
```

```
isDynVol double;%
DynVol int16;
DynDh int16;
Fc_DynArea int16;
Fc_DynDh int16;
Fc_DynK12 int16;
Fc_DynK21 int16;
Fc_DynVel_Factor int16;
Fc_DynShear_Factor int16;
Fc_DynDist int16;
Fc_DynCond_Dist int16;
Fc_DynCond int16;
Fc_Dyndx int16;
Fc_DynWCond int16;
SC_Active int16;
%dL_dt double;
%dD_dt double;

%% Solid Conduction
Cond_Nds1;
Cond_Nds2;
Cond_Nds;
Cond_Fcs;
CondNet;
% Energy Transport
Trans_Fcs;
TransNet;
% Faces to Nodes

%% MEchanical System
Press_Contact;
Shear_Contact;
MechanicalSystem MechanicalSystem;
dA = 0;
dA_old = 0;

%% Max Courant
dt_max double;

%% General Gas
dT_duFunc cell;
dh_dTFunc cell; % Additions
kFunc cell;
muFunc cell;
R double; % Defined by Region
Rs; % All Nodes

NuFunc_l_el cell;
NuFunc_t_el cell;
Fc_NkFunc_l_el cell;
Fc_NkFunc_t_el cell;

%% Node Properties
CondFlux double;%
NuFunc_l cell;%
NuFunc_t cell;%
dT_dU double;%
dh_dT double;% Gas nodes only, Additions
dV_dt double;%
u double;%
T double;%
P double;%
dP double;%
rho double;%
m double;%
vol double;%
old_vol double;%
k double;%
mu double;%
Dh double;%
Nu double;%
```

```
RE double;%
f double;%
P_backup double;%
U double;%
dU double;

% Turbulence
turb double;
Area double;
Va double;
to double;

%% Face Properties
Fc_Nd int16;%
Fc_Dist double;%
Fc_Cond_Dist double;%
Fc_dx double;%
Fc_K12 double;%
Fc_K21 double;%
Fc_U double;%
Fc_RE double;%
Fc_f double;%
Fc_R double;%
Fc_fFunc_l cell;%
Fc_fFunc_t cell;%
Fc_NkFunc_l cell;%
Fc_NkFunc_t cell;%
Fc_Area double;%
Fc_Dh double;%
Fc_Cond double;%
Fc_T double;
Fc_u double;
Fc_k double;
Fc_mu double;
Fc_rho double;
Fc_Vel_Factor double;
Fc_Shear_Factor double;
Fc_W double;

% Prandtl Number
PR double;%
Fc_PR;

%% Parameter inspection made it here:

% Turbulence
Fc_turb double;
Fc_to double;
useTurbulenceFc logical;
useTurbulenceNd logical;
dturb double;
REcrit double;

stop logical;
curTime double;
Solid_t double;
MAXdt double;
A_Inc;
Inc;
MoveCondition int16;

% Solver
Regions cell;
isEnvironmentRegion logical;
RegionFcs cell;
ActiveRegionFcs cell;
RegionFcCount int16;
RegionLoops cell;
RegionLoops_Ind cell;
Faces cell;
Fc2Col double;
```

```
    ExplicitLeak double;
    ExplicitNorm double;
    KpU_2A double;
    Fc_V double;
    Fc_V_averager double;
    Fc_turb_averager double;
    Fc_dP double;
    Fc_V_backup double;
    A_Press cell;
    u2T cell;
%     extfc cell;
    Solid_dt_max;
    isLoopRegionFcs;
    Fc2Col_loop;

    Nd_Solid_dt;
    doScale;
    Acceleration_Coef = 1;
    SteadyState_Factor = 1;
    Acceleration_Factor = 1;

    % Statistics Collection
    ToEnvironmentSolid;
    ToEnvironmentGas;
    ToSource;
    ToSink;
    E_ToEnvironment;
    E_ToSource;
    E_ToSink;
    E_Flow_Loss;
    Sources;
    Sinks;
    VolMin;
    VolMax;
    ShuttleFaces;
    StaticFaces;
    ExergyLossShuttle;
    ExergyLossStatic;

    countFailed = 0.0;
    countSuccess = 0.0;

    ACond;
    bCond;
    BoundaryNodes;
    MixFcs;
    CondEff;
    CondTempEff;
    CycleTime;
    ss_condition;
    continuetoSS;

%     Fric_l_current;
%     Fric_t_current;
%     Fric_l_index;
%     Fric_t_index;
%     Fric_tbl;
%     Fric_tbt;


    % Engine Pressure Assignment
    PRegion = [];
    PRegionTime = [];
    CycledE = 0;

    Fc_Nd03 int16;
    Fc_A double;
    Fc_DynA;
    Fc_B double;
    Fc_DynB;
    Fc_C double;
```

```
  Fc_DynC;
  Fc_D double;
  Fc_DynD;


  EffRE double;

  FcApprox;
end

methods

  function [Results, success] = Run(ME, islast, do_warmup, ss_tolerance, options)
    success = true;
    ME.stop = false;

    if nargin > 4 && options.isManual == false
      simTime = options.simTime; % Maximum Simulation Time
      ME.ss_condition = options.SS; % True or False for steady state detection
      ME.continuetoSS = false;
      switch options.movement_option % C - Continuous, V - Variable
        case 'C'; ME.MoveCondition = 1;
        case 'V'; ME.MoveCondition = 2;
      end
      ME.dA = options.rpm*2*pi/60;
      ME.dA_old = ME.dA;
      ME.MAXdt = options.max_dt;
      ME.T(ME.Sources) = options.SourceTemp;
      ME.T(ME.Sinks) = options.SinkTemp;
      engine_Pressure = options.EnginePressure;
    else
      %% Get user input
      while isempty(ME.Model.name) && ~isempty(ME.Model.Sensors)
        answer = inputdlg(...
          ['Please name the model so that ' ...
          'the data can be saved properly'],'Name Model',[1 50],{''});
        if ~isempty(answer{1})
          ME.Model.name = answer{1};
        end
      end
      % inputdlg( prompt , dlg_title , num_lines , defAns );
      invalid = true;
      output = {'10','SS','C','60','0.1'};
      while invalid
        output = inputdlg({...
          'Maximum Simulation Time (seconds)',...
          'End Condition (SS - Steady State)',...
          'Motion Condition (C - Constant Velocity, V - Variable Velocity)',...
          'Initial Velocity (rpm)',...
          'maximum time step (s)'},...
          'Enter Simulation Parameters',...
          [1 20],...
          output);
        invalid = false;
        if isempty(output)
            Results = [];
            return;
        end
        if ~all(ismember(output{1}, '0123456789+-.eE')); invalid = true;
        elseif ~strcmp(output{2},'SS') && ~isempty(output{2}); invalid = true;
        elseif ~strcmp(output{3},'C') && ~strcmp(output{3},'V'); invalid = true;
        elseif ~all(ismember(output{4}, '0123456789+-.eE')); invalid = true;
        elseif ~all(ismember(output{5}, '0123456789+-.eE')); invalid = true;
        end
      end

      simTime = str2double(output{1});
      switch output{2}
        case 'SS'; ME.ss_condition = true;
        otherwise; ME.ss_condition = false;
      end
```

```
  ME.continuetoSS = false;
  switch output{3}
    case 'C'; ME.MoveCondition = 1;
    case 'V'; ME.MoveCondition = 2;
  end
  ME.dA = str2double(output{4})*2*pi/60;
  ME.dA_old = ME.dA;
  ME.MAXdt = str2double(output{5});
  engine_Pressure = ME.Model.enginePressure;
end

Load_Function_is_Not_Given = false;

if ME.Model.recordOnlyLastCycle
  ME.MaxCourant = ME.Model.MaxCourantConverging;
  ME.MaxFourier = ME.Model.MaxFourierConverging;
else
  ME.MaxCourant = ME.Model.MaxCourantFinal;
  ME.MaxFourier = ME.Model.MaxFourierFinal;
end

%% Early Initialize
ME.A_Inc = 2*pi/(Frame.NTheta-1);
ME.Inc = 1;
ME.curTime = 0;
Results = Result();
Results.Model = ME.Model;
Results.Data = struct();
Results.Data.QEnv = 0;
Results.Data.QSource = 0;
Results.Data.QSink = 0;
Results.Data.Flow_Loss = 0;
Results.Data.Power = 0;
Results.Data.CR = 0;

indf = 1:length(ME.Fc_V);
record_data = islast || ME.ss_condition == false;

%% Set up data acquisition
grab_Pressure = ME.Model.recordPressure;
grab_Temperature = ME.Model.recordTemperature;
grab_Velocity = ME.Model.recordVelocity;
grab_PressureDrop = ME.Model.recordPressureDrop;
grab_Turbulence = ME.Model.recordTurbulence;
grab_ConductionFlux = ME.Model.recordConductionFlux;
if ME.MoveCondition == 1 || ME.Model.recordOnlyLastCycle
  dt = ME.A_Inc/ME.dA;
  if ME.Model.recordOnlyLastCycle; LEN = Frame.NTheta-1;
  else; LEN = ceil((simTime*ME.dA/ME.A_Inc));
  end
  Results.Data.A = linspace(0,ME.A_Inc*LEN,LEN);
  Results.Data.dA = ME.dA(ones(1, LEN+2));
  Results.Data.t = linspace(0,LEN*dt,LEN+2);
  if grab_Pressure
    Results.Data.P = zeros(length(ME.P),LEN);
    Results.Data.P(:,1) = ME.P;
  end
  if grab_Temperature
    Results.Data.T = zeros(length(ME.T),LEN);
    Results.Data.T(:,1) = ME.T;
  end
  if grab_Velocity
    Results.Data.U = zeros(length(ME.Fc_dx),LEN);
    Results.Data.U(:,1) = ME.Fc_V./ME.Fc_Area(indf);
  end
  if grab_PressureDrop
    Results.Data.dP = zeros(length(ME.P),LEN);
    Results.Data.dP(:,1) = ME.dP;
  end
  if grab_Turbulence
    Results.Data.turb = zeros(length(ME.P),LEN);
```

```
    Results.Data.turb(:,1) = ME.turb;
  end
  if grab_ConductionFlux
    Results.Data.cond = zeros(length(ME.T),LEN);
    Results.Data.cond(:,1) = ME.CondFlux;
  end
else
  % Grab Pressure
  if grab_Pressure; Results.Data.P = ME.P; end
  % Grab Temperature
  if grab_Temperature; Results.Data.T = ME.T; end
  % Grab Velocity
  if grab_Velocity
    Results.Data.U = ME.Fc_V./ME.Fc_Area(indf);
  end
  if grab_PressureDrop
    Results.Data.dP = ME.dP;
  end
  % Grab Turbulence
  if grab_Turbulence; Results.Data.turb = ME.turb; end
  if grab_ConductionFlux; Results.Data.cond = ME.CondFlux; end
  Results.Data.A = 0;
  Results.Data.dA = ME.dA;
  Results.Data.t = 0;
end
if ~isempty(ME.Model.Sensors)
  for iSensor = ME.Model.Sensors; iSensor.reset(); end
end
if ~isempty(ME.Model.PVoutputs)
  for iPVoutput = ME.Model.PVoutputs; iPVoutput.reset(); end
end
n = 2;

AdjustTime = 0;
previousTime = 0;
ME.dt_max = 2*ME.A_Inc/(ME.dA_old + ME.dA);

%% Initialize All the sub functions
clear assignDynamic;
clear implicitSolve;
% clear dUFunc;
clear KValue;
clear solve_loops;
% dUFunc(ME);
% KValue(ME);
assignDynamic(ME, ME.Inc, false);
implicitSolve(ME, true);
sindn = length(ME.P)+1:length(ME.T);
ME.old_vol = ME.vol;

%% Warm Up Phase
if do_warmup
  progressbar('Warmup Phase');
  hmax = mean(ME.Solid_dt_max);
  t = 0;
  progressbar_update = 1;

  if ME.Model.warmUpPhaseLength > 0; assignAvgDynamic(ME); end

  % Record a backup of the gas properties, just so that we don't have
  % ... to bother.
  indn = 1:length(ME.P); indf = 1:length(ME.Fc_U); indmf = ME.Mix_Fc;
  Cfcs = ME.Cond_Fcs; Cnd1 = ME.Cond_Nds1; Cnd2 = ME.Cond_Nds2;
  Gm = ME.m(indn); Gu = ME.u(indn); GT = ME.T(indn);
  Sm = ME.m(sindn); ST = ME.T(sindn);
  Q = zeros(length(ME.T),1);
  ME.Fc_Cond(indmf) = ME.Fc_Area(indmf)./(ME.Fc_R(indmf)' + 15);
  ME.Fc_Cond(indf) = 0.5*ME.Fc_Area(indf)./ME.Fc_Cond_Dist(indf);
  while (t < ME.Model.warmUpPhaseLength)
    h = min(hmax, ME.Model.warmUpPhaseLength - t);
```

```
    Ti = [GT; ME.T(sindn)];

    Q(:) = 0;
    Qfc = ME.Fc_Cond(Cfcs).*(Ti(Cnd1) - Ti(Cnd2));
    for i = 1:3:length(ME.CondNet)-2
      Q(ME.CondNet{i+1}) = Q(ME.CondNet{i+1}) + ...
        ME.CondNet{i}.*Qfc(ME.CondNet{i+2});
    end

    % Internal Energy Change - Gas
    Gu = Gu + h*Q(indn)./Gm;

    % Temperature - Gas
    GT = ME.u2T(Gu);

    % Temperature - Solid
    ST = ME.dT_dU(sindn).*Q(sindn)./Sm;

    t = t + h;
    if progressbar_update > 1/h
      progressbar(t/ME.Model.warmUpPhaseLength);
      progressbar_update = 1;
    else
      progressbar_update = progressbar_update + 1;
    end
  end

  ME.T(sindn) = ST;
end

sindn = length(ME.P):length(ME.T);

progressbar('Main Dynamic Loop');
%% Set up Steady State Detection Code
if ME.ss_condition
  ss_cycles = 5;
  Precord = zeros(1,ss_cycles);
  Load_Function_is_Not_Given = isempty(ME.MechanicalSystem.LoadFunction);
  if Load_Function_is_Not_Given && ME.MoveCondition == 2
    ME.MaxCourant = ME.Model.MaxCourantFinal;
    ME.MaxFourier = ME.Model.MaxFourierFinal;
    % Turn off pressure, temperature adjustments.
    % Set timestep to final value.
    ME.continuetoSS = true;
    if nargin > 4 && ...
        isfield(options,'set_Load') && options.set_Load ~= 0
      temp = options.set_Load;
    else
      temp = 0;
    end
    LoadRecord = temp;
    SetSpeed = ME.dA;
  else
    ME.continuetoSS = false;
  end
end

%% Main Loop

ME.curTime = 0;
ME.CycledE = 0;
cycle_count = 0;
MechCycleEnergy = 0;
Plot_Powers = zeros(1000,1);
Plot_Learning_Rate = zeros(1000,1);
since_inflection = 0;
Plot_Number = 0;
power_factor = 1;
%Convergence_Plot = figure();
%Factor_Plot = figure();
if ME.ss_condition
```

```
        Tavg = zeros(size(ME.T));
        Tavg_count = 0;
      end
      while (ME.curTime < simTime)
        %% Main Solve
        ME.dt_max = 2*ME.A_Inc/(ME.dA_old + ME.dA);
        Forces = ME.Iteration_Solve();
        for i = length(Forces)
          for j = length(Forces{i})
            if isnan(Forces{i}(j)) || ~isreal(Forces{i}(j))
              ME.stop = true;
              success = false;
            end
          end
        end
        if ME.stop
%           fprintf('Simulation Finished Prematurely. (in Run)\n');
          clear assignDynamic;
          clear implicitSolve;
          % clear dUFunc;
          clear KValue;
          clear solve_loops;
          return;
        end
        ME.curTime = ME.curTime +  ME.dt_max;
        progressbar(ME.curTime/simTime);
        Power = ME.MechanicalSystem.Solve(ME.Inc,(ME.dA_old + ME.dA)/2,0,Forces);
        MechCycleEnergy = MechCycleEnergy + Power*ME.dt_max;
        if ~isempty(ME.MechanicalSystem.LoadFunction)
          Power = Power - ME.MechanicalSystem.LoadFunction((ME.dA_old + ME.dA)/2)*(ME.dA_old +
ME.dA)/2;
        end
        switch ME.MoveCondition
          case 1 % For Constant Motion Systems
            % Do nothing
          case 2 % For variable systems
            ME.dA_old = ME.dA;
            % fprintf([num2str(Power*ME.dt_max) '\n']);
            new_ke = Power*ME.dt_max + 0.5*ME.MechanicalSystem.Inertia*ME.dA^2;
            if new_ke < 0 && ME.ss_condition && ...
                  ME.Model.recordOnlyLastCycle && ...
                  Load_Function_is_Not_Given
                ME.dA = 0.1*2*pi; % Minimum speed of 0.1 Hz
            else
              if new_ke < 0
                ME.stop = true;
              else
                ME.dA = sqrt(2*new_ke/ME.MechanicalSystem.Inertia);
              end
            end
            if ME.ss_condition && ...
              ME.Model.recordOnlyLastCycle && ...
              Load_Function_is_Not_Given
              if ME.dA < 0.1*2*pi
                ME.dA = 0.1*2*pi;
              end
            end
            % fprintf([num2str(ME.dA) '\n']);
        end

        if ME.stop
          fprintf('Simulation Finished Prematurely. (in Run)\n');
          clear assignDynamic;
          clear implicitSolve;
          % clear dUFunc;
          clear KValue;
          clear solve_loops;
          return;
        end

        %% Obtain Results
```

```
if ME.Model.recordOnlyLastCycle
  Results.Data.dA(ME.Inc) = ME.dA;
  Results.Data.t(ME.Inc) = ME.curTime - AdjustTime;
  if grab_Pressure; Results.Data.P(:,ME.Inc) = ME.P; end
  if grab_Temperature; Results.Data.T(:,ME.Inc) = ME.T; end
  if grab_Velocity
    Results.Data.U(:,ME.Inc) = ME.Fc_V./ME.Fc_Area(indf);
  end
  if grab_PressureDrop
    Results.Data.dP(:,ME.Inc) = ME.dP;
  end
  if grab_Turbulence; Results.Data.turb(:,ME.Inc) = ME.turb; end
  if grab_ConductionFlux; Results.Data.cond(:,ME.Inc) = ME.CondFlux; end
  if ME.Model.recordStatistics
    Results.Data.QEnv(ME.Inc) = ME.E_ToEnvironment;
    Results.Data.QSource(ME.Inc) = ME.E_ToSource;
    Results.Data.QSink(ME.Inc) = ME.E_ToSink;
    Results.Data.Flow_Loss(ME.Inc) = ME.E_Flow_Loss;
    Results.Data.Power(ME.Inc) = Power;
    Results.Data.CR = ME.VolMax(:)./ME.VolMin(:);
    % Reset them
    ME.E_ToEnvironment = 0;
    ME.E_ToSource = 0;
    ME.E_ToSink = 0;
    ME.E_Flow_Loss = 0;
  end
else
  if ME.MoveCondition == 2
    Results.Data.A(n) = Results.Data.A(n-1) + ME.A_Inc;
    Results.Data.dA(n) = ME.dA;
    Results.Data.t(n) = ME.curTime;
    if length(Results.Data.t) == n
      LEN = abs(min([100 ceil(((simTime-ME.curTime)*ME.dA/ME.A_Inc))]));
      Results.Data.A(n:n+LEN) = linspace(Results.Data.A(n-1),Results.Data.A(n-1)+...
        LEN*ME.A_Inc,LEN+1);
      Results.Data.dA(n+LEN) = 0;
      Results.Data.t(n+LEN) = 0;
      if grab_Pressure; Results.Data.P(length(ME.P),n+LEN) = 0; end
      if grab_Temperature; Results.Data.T(length(ME.P),n+LEN) = 0; end
      if grab_Velocity
        Results.Data.U(length(ME.Fc_dx),n+LEN) = 0;
      end
      if grab_PressureDrop
        Results.Data.dP(length(ME.P),n+LEN) = 0;
      end
      if grab_Turbulence; Results.Data.turb(length(ME.turb),n+LEN) = 0; end
      if grab_ConductionFlux; Results.Data.cond(length(ME.CondFlux),n+LEN) = 0; end
      if ME.Model.recordStatistics
        Results.Data.QEnv(n+LEN) = 0;
        Results.Data.QSource(n+LEN) = 0;
        Results.Data.QSink(n+LEN) = 0;
        Results.Data.Power(n+LEN) = 0;
      end
    end
  end
  if grab_Pressure; Results.Data.P(:,n) = ME.P; end
  if grab_Temperature; Results.Data.T(:,n) = ME.T; end
  if grab_Velocity
    Results.Data.U(:,n) = ME.Fc_V./ME.Fc_Area(indf);
  end
  if grab_PressureDrop
    Results.Data.dP(:,n) = ME.dP;
  end
  if grab_Turbulence; Results.Data.turb(:,n) = ME.turb; end
  if grab_ConductionFlux; Results.Data.cond(:,n) = ME.CondFlux; end
  if ME.Model.recordStatistics
    Results.Data.QEnv(n) = ME.E_ToEnvironment;
    Results.Data.QSource(n) = ME.E_ToSource;
    Results.Data.QSink(n) = ME.E_ToSink;
    Results.Data.Flow_Loss(n) = ME.E_Flow_Loss;
    Results.Data.Power(n) = Power;
```

```
    Results.Data.CR = ME.VolMax(:)./ME.VolMin(:);
    % Reset them
    ME.E_ToEnvironment = 0;
    ME.E_ToSource = 0;
    ME.E_ToSink = 0;
    ME.E_Flow_Loss = 0;
  end
end
if ~isempty(ME.Model.Sensors)
  for iSensor = ME.Model.Sensors; iSensor.getData(ME); end
end
if ~isempty(ME.Model.PVoutputs)
  for iPVoutput = ME.Model.PVoutputs; iPVoutput.getData(ME); end
end
if ME.curTime > previousTime + ME.Model.animationFrameTime
  previousTime = ME.curTime;
end
ME.old_vol = ME.vol;
n = n + 1;

%% Test Conditions (Reverse, Steady State, etc...)
if ME.ss_condition && ME.Model.recordOnlyLastCycle
    if ME.MoveCondition == 2
      if Load_Function_is_Not_Given
        if ME.dA < 0
          ME.dA = 0.1*2*pi; % Minimum speed of 0.1 Hz
        end
      end
    end
end
if ME.dA < 0
  fprintf('XXX Engine Reversed Directions, solving exited XXX\n');
  return;
else
  if ME.ss_condition && ~ME.continuetoSS
    Tavg = Tavg + ME.T;
    Tavg_count = Tavg_count + 1;
    if Tavg_count == 1
      T_previous = Tavg;
    end
  end
  ME.Inc = ME.Inc + 1;
  if ME.Inc == Frame.NTheta
    cycle_count = cycle_count + 1;
    Plot_Number = Plot_Number + 1;
    Plot_Powers(Plot_Number) = MechCycleEnergy/(ME.curTime - AdjustTime);
    fprintf(['Speed: (rpm) ' num2str(60*ME.dA/(2*pi)) ...
      'Power: (W) ' num2str(Plot_Powers(Plot_Number)) '\n']);

    Results.Data.SnapShot_P = ME.Rs.*ME.T(1:length(ME.P)).*...
      ME.m(1:length(ME.P))./ME.vol(1:length(ME.P));

    if ME.Model.showLivePV
      for iPVoutput = ME.Model.PVoutputs; iPVoutput.updatePlot(); end
    end

    % Acquire an understanding of the solution plateauing
    Plot_Number = Plot_Number + 1;
    Plot_Powers(Plot_Number) = MechCycleEnergy/(ME.curTime - AdjustTime);
    MechCycleEnergy = 0;
    Plot_Learning_Rate(Plot_Number) = power_factor;
%     if isempty(Convergence_Plot) || ...
%         ~isvalid(Convergence_Plot) || ...
%         Convergence_Plot < 1
%       Convergence_Plot = figure();
%     end
%     figure(Convergence_Plot);
%     plot(1:Plot_Number,Plot_Powers(1:Plot_Number));

    %cycle_count = cycle_count + 1;
    ME.Inc = 1;
```

```
%             if isempty(Factor_Plot) || ...
%                 ~isvalid(Factor_Plot) || ...
%                 Factor_Plot < 1
%               Factor_Plot = figure();
%             end
            %figure(Factor_Plot);
            %plot(1:Plot_Number,Plot_Learning_Rate(1:Plot_Number));

            % Get Local curvature
            if Plot_Number > 2
              Power_curv_backup = power_curv;
              power_curv = (Plot_Powers(Plot_Number) - ...
                2*Plot_Powers(Plot_Number - 1) + ...
                Plot_Powers(Plot_Number - 2));
              if Plot_Number > 3
                % Detect if crossed inflection point
                if sign(power_curv) ~= sign(Power_curv_backup) && since_inflection > 3
                  power_factor = 0;
                  since_inflection = 0;
                else
                  power_factor = ...
                    min(1,max(0,...
                    power_factor + 0.25/(1 + 2*abs(power_factor - 0.5))));
                end
              end
            else
              power_curv = 1;
              power_factor = ...
                min(1,max(0,...
                power_factor + 0.25/(1 + 2*abs(power_factor - 0.5))));
            end
            since_inflection = since_inflection + 1;

            % Detect if it is steady state
            if ME.ss_condition
              if ~ME.continuetoSS
%                 fprintf(['Mixed Face Conduction: ' ...
%                   num2str(sum(ME.CondEff / ME.CycleTime)) '.\n']);
%                 fprintf(['Volume Averaged Reynolds Number: ' ...
%                   num2str(sum(ME.EffRE / ME.CycleTime)) '.\n']);
                ME.EffRE(:) = 0;
                % Calculate Average Temperatures and current shift
                Tavg = Tavg/Tavg_count;

                % Modify T_delta to prevent a constant change in
                % ... temperature being regarded as an oscillation.
                T_constant = ME.T - T_previous;
                Tavg = Tavg + T_constant/2;
                T_delta = ME.T - Tavg;

                A = ME.ACond;
                b = ME.bCond;
                ME.CondEff = ME.CondEff / ME.CycleTime;
                ME.CondTempEff = ME.CondTempEff / ME.CycleTime;
                for i = ME.BoundaryNodes
                  % Modify the diagonal from default values to include the
                  % ... average conductance to other nodes (gas nodes)
                  A(i,i) = A(i,i) + sum(ME.CondEff(ME.MixFcs{i}));
                  % Calculate the b values so that they are:
                  % ...  bi = sum of others( sum of other(delta * Cond * To))
                  % ...                     ( / sum of delta
                  b(i) = b(i) + sum(ME.CondTempEff(ME.MixFcs{i}));
                end

                if cycle_count == 1
                  for i = 1:size(A,1)
                    if all(A(i,:) == 0)
                      ME.ACond(i,i) = 1;
                      ME.bCond(i) = 298;
                      A(i,i) = 1;
```

```
            b(i) = 298;
          end
        end
      end

      ME.CondEff(:) = 0;
      ME.CondTempEff(:) = 0;
      ME.CycleTime = 0;

      A = sparse(A);
      var = A\b;

      % Calculate shifted values based on current transient
      ME.T(sindn) = var + T_delta(sindn);

      % Reset Tavg for the next cycle
      Tavg(:) = 0;
      Tavg_count = 0;

    end

    % Detect if it is steady state
    % Compare the average over 10 cycles to see if it appears to
    % be converged
    Precord(1:ss_cycles-1) = Precord(2:ss_cycles);
    Precord(ss_cycles) = Plot_Powers(Plot_Number);
    temp = ss_tolerance*max(Precord(end),1);
    % ContinuetoSS is the a flag for the last cycle which is run
    % ... at a finer timestep that the converging cycles.
    if ME.continuetoSS; break; end
    if CustomRSSQ(diff(Precord)) < temp
        ME.continuetoSS = true;
        ME.MaxCourant = ME.Model.MaxCourantFinal;
        ME.MaxFourier = ME.Model.MaxFourierFinal;
    end
  end

  % Modify Gas Mass so that the engine is at the engine pressure.
  if ME.Model.recordOnlyLastCycle
    %i = 1;
    for i = 1:length(ME.Regions)
      if ~ME.isEnvironmentRegion(i)
        nodes = ME.Regions{i};
        Pregion = ME.PRegion(i)/ME.PRegionTime;
        ME.m(nodes) = ...
          (power_factor*engine_Pressure/Pregion + ...
          (1-power_factor))*ME.m(nodes);
      end
    end
    ME.PRegion(:) = 0; ME.PRegionTime(:) = 0;
%     for iPVoutput = ME.Model.PVoutputs
%       Pregion = ME.PRegion(i)/ME.PRegionTime(i);
%       ME.PRegion(i) = 0; ME.PRegionTime(i) = 0;
%       ME.m(iPVoutput.RegionNodes) = ...
%         (power_factor*engine_Pressure/Pregion + ...
%         (1-power_factor))*ME.m(iPVoutput.RegionNodes);
%       i = i + 1;
%     end

  end

  % Assess cycle time and modify mechanism load accordingly
  if ME.ss_condition && ME.Model.recordOnlyLastCycle
    if ME.MoveCondition == 2
      if Load_Function_is_Not_Given
        % Modify Load to approach initial speed
        % Calculate Speed
        speed = 2*pi/(ME.curTime - AdjustTime);
        dspeed = min(0.01/(max(log(Plot_Number),1)), ...
            0.5*abs((SetSpeed - speed)/SetSpeed));
        if speed < SetSpeed
```

```
            LoadRecord = LoadRecord - power_factor*dspeed;
          else
            LoadRecord = LoadRecord + power_factor*dspeed;
          end
          ME.MechanicalSystem.LoadFunction = @(Speed) LoadRecord;
        end
      end
    end

    AdjustTime = ME.curTime;
  end
  assignDynamic(ME,ME.Inc,false); % Initialize the dynamic function
 end
end
progressbar(1);

if ~ME.Model.recordOnlyLastCycle
 Results.Data.dA = Results.Data.dA(1:n-1);
 Results.Data.t = Results.Data.t(1:n-1);
 if grab_Pressure; Results.Data.P = Results.Data.P(:,1:n-1); end
 if grab_Temperature; Results.Data.T = Results.Data.T(:,1:n-1); end
 if grab_Velocity; Results.Data.U = Results.Data.U(:,1:n-1); end
 if grab_PressureDrop; Results.Data.dP = Results.Data.dP(:,1:n-1); end
 if grab_Turbulence; Results.Data.turb = Results.Data.turb(:,1:n-1); end
 if grab_ConductionFlux; Results.Data.cond = Results.Data.cond(:,1:n-1); end
 if ME.Model.recordStatistics
  Results.Data.QEnv = Results.Data.QEnv(:,1:n-1);
  Results.Data.QSource = Results.Data.QSource(:,1:n-1);
  Results.Data.QSink = Results.Data.QSink(:,1:n-1);
  Results.Data.Flow_Loss = Results.Data.Flow_Loss(:,1:n-1);
  Results.Data.Power = Results.Data.Power(:,1:n-1);
  Results.Data.CR(:) = ME.VolMax(:)./ME.VolMin(:);
 end
end

%% Save Data
if record_data
 if ME.Model.recordStatistics
  statistics = struct(...
   'Time',Results.Data.t,...
   'Angle',Results.Data.A,...
   'Omega',Results.Data.dA,...
   'To_Environment',Results.Data.QEnv,...
   'To_Source',Results.Data.QSource,...
   'To_Sink',Results.Data.QSink,...
   'Flow_Loss',Results.Data.Flow_Loss,...
   'Power',Results.Data.Power,...
   'TotalPower',Plot_Powers,...
   'Gas_Nodes',length(ME.P)-1,...
   'Solid_Nodes',length(ME.T)-length(ME.P)+1,...
   'Gas_Faces',length(ME.Fc_V),...
   'Mixed_Faces',length(ME.Fc_R)-length(ME.Fc_V),...
   'Solid_Faces',length(ME.Fc_Cond)-length(ME.Fc_R),...
   'CR',Results.Data.CR,...
   'VMin',sum(ME.VolMin(:)),...
   'VMax',sum(ME.VolMax(:)));
 end
 if ME.Model.recordStatistics
  if nargin > 4
   if isempty(ME.Model.outputPath)
    save([options.title '_Statistics'],'statistics');
   else
    save([ME.Model.outputPath '\' options.title '_Statistics'],'statistics');
   end
  else
   if isempty(ME.Model.outputPath)
    save([ME.Model.name '_Statistics'],'statistics');
   else
    save([ME.Model.outputPath '\' ME.Model.name '_Statistics'],'statistics');
   end
  end
```

```
    end
    if nargin > 4
      if ~isempty(ME.Model.Sensors)
        for iSensor = ME.Model.Sensors; iSensor.plotData(true,options.title); end
      end
      if ~isempty(ME.Model.PVoutputs)
        for iPVoutput = ME.Model.PVoutputs; iPVoutput.plotData(true,options.title); end
      end
    else
      if ~isempty(ME.Model.Sensors)
        for iSensor = ME.Model.Sensors; iSensor.plotData(true,ME.Model.name); end
      end
      if ~isempty(ME.Model.PVoutputs)
        for iPVoutput = ME.Model.PVoutputs; iPVoutput.plotData(true,ME.Model.name); end
      end
    end
  end
  if Load_Function_is_Not_Given
    ME.MechanicalSystem.LoadFunction = function_handle.empty;
  end
  %% Clean up
  clear assignDynamic;
  clear implicitSolve;
  % clear dUFunc;
  clear KValue;
  clear solve_loops;
end

function implicitSolve(ME,initialize) %#ok<INUSD>
  persistent indf;
  persistent indS;
  persistent indmf;
  persistent indn;
  persistent sindn;
  persistent indnminus;
  persistent indmfminus;
  persistent totalNodes;
  persistent isDynVol;
  persistent dvind;
  persistent lenf;
  persistent lenn;
  persistent nd0;
  persistent nd1;
  persistent nd2;
  persistent nd3;
  persistent nd1mf;
  persistent nd2mf;
  persistent Cfcs;
  persistent Cnd1;
  persistent Cnd2;
  persistent Pi;
  persistent Ti;
  persistent rhoEnv;
  persistent PEnv;
  persistent uEnv;
  persistent TEnv;
  persistent Fcrho;
  persistent Fcu;
  persistent Fcmu;
  persistent FcT;
  persistent FcP;
  persistent theta_FL;
  persistent Q;
  persistent Qtd;
  persistent ReCritComparitor;
  persistent F2C;
  persistent ExFc;
  persistent ExR1;
  persistent ExR2;
  persistent ExLFc;
  persistent ExLC;
```

```
persistent ExLN;
persistent FlowTimeStep;
persistent RecordStatistics;
persistent facesES;
persistent sgnES;
persistent facesEG;
persistent sgnEG;
persistent facesSr;
persistent sgnSr;
persistent facesSi;
persistent sgnSi;
persistent Ci;
persistent Cs;
persistent Qi;
persistent Qs;
persistent C1;
persistent C2;
persistent C3;
persistent C4;
persistent CT;
persistent nlambda;
% persistent dP_dt;
if nargin == 2
  % dP_dt = zeros(length(ME.Regions),1);
  ME.Fc_V_averager = zeros(size(ME.Fc_V));
  ME.Fc_turb_averager = ME.Fc_V_averager;
  ME.assignDynamic(ME.Inc);
  indf = (1:length(ME.Fc_U))';
  if ~isempty(ME.Fc_DynShear_Factor)
    indS = ME.Fc_DynShear_Factor(1,:);
  else
    indS = [];
  end
  Cs = ME.m(ME.Fc_Nd(ME.FcApprox,2))./ME.dT_dU(ME.Fc_Nd(ME.FcApprox,2));
  Cs(isinf(Cs)) = 1e6;
  indmf = ME.Mix_Fc;
  indn = (1:length(ME.P))';
  totalNodes = length(ME.T);
  lenf = length(indf);
  lenn = length(indn);
  sindn = (lenn+1:totalNodes);
  indnminus = (1:lenn-1)';
  nd0 = ME.Fc_Nd03(indf,1);
  nd1 = ME.Fc_Nd(indf,1);
  nd2 = ME.Fc_Nd(indf,2);
  nd3 = ME.Fc_Nd03(indf,2);
  nd1mf = ME.Fc_Nd(indmf,1);
  nd2mf = ME.Fc_Nd(indmf,2);
  isDynVol = logical(ME.isDynVol(indn));
  dvind = indn(isDynVol);
  elements = ME.dT_dU(nd2mf)>0;
  indmfminus = indmf(elements);
  nd2mf = nd2mf(elements);
  Ti = zeros(size(ME.T));
  Pi = zeros(size(ME.P));
  rhoEnv = ME.rho(lenn);
  PEnv = ME.P(end);
  uEnv = ME.u(lenn);
  TEnv = ME.T(lenn);
  Q = zeros(totalNodes,1);
  Qtd = Q;
  Cfcs = ME.Cond_Fcs;
  Cnd1 = ME.Cond_Nds1;
  Cnd2 = ME.Cond_Nds2;
  ReCritComparitor = [zeros(1,lenn-1); ...
                      11.5*ones(1,lenn-1)];
  ExR1 = ME.ExplicitNorm(:,2);
  ExR2 = ME.ExplicitNorm(:,3);
  F2C = ME.Fc2Col;
  ExFc = ME.ExplicitNorm(:,1);
  ExLFc = ME.ExplicitLeak(:,1);
```

```
  ExLC = ME.ExplicitLeak(:,2);
  ExLN = ME.ExplicitLeak(:,3);
  ME.Fc_V = zeros(lenf,1);
  Fcu = zeros(lenf,1);
  Fcrho = Fcu;
  Fcmu = Fcu;
  FcT = Fcu;
  FcP = Fcu;
  theta_FL = Fcu;
  FlowTimeStep = 1;
  RecordStatistics = ME.Model.recordStatistics;
  if RecordStatistics
    facesES = ME.ToEnvironmentSolid(1,:);
    sgnES = ME.ToEnvironmentSolid(2,:)';
    facesEG = ME.ToEnvironmentGas(1,:);
    sgnEG = ME.ToEnvironmentGas(2,:)';
    facesSr = ME.ToSource(1,:); sgnSr = ME.ToSource(2,:)';
    facesSi = ME.ToSink(1,:); sgnSi = ME.ToSink(2,:)';
    ME.E_ToEnvironment = 0;
    ME.E_ToSource = 0;
    ME.E_ToSink = 0;
    ME.E_Flow_Loss = 0;
  end
  return
end
t = 0; done = false;
ME.Fc_V_averager(:) = 0;
ME.Fc_turb_averager(:) = 0;
while ~done
  hmax = min(ME.dt_max-t, ME.Solid_dt_max(ME.Inc));

  %% Assign Properties
  mi = ME.m(indn);
  ui = [ME.u; ME.T(sindn)./ME.dT_dU(sindn)];
  signU = sign(ME.Fc_U);
  Tnew = zeros(size(ME.vol(indn)));
  dm_dt = Tnew;
  unew = Tnew;
  mnew = Tnew;

  inc = ME.Inc + t/ME.dt_max;
%   if inc == 1
%     fprintf('start');
%   end
  time = ME.curTime + t;
  ME.assignDynamic(inc);
  ME.vol(ME.vol<=0) = 1e-8;
  Areai = ME.Fc_Area(indf);

  % Density - Upwinding
  rhoi = mi./ME.vol(indn);
  rhoi(end) = rhoEnv;

  % Pressure
  n = length(ME.Regions);
  for i = 1:n
    nodes = ME.Regions{i};
    uTemp = ui(nodes);
    TTemp = ME.u2T{i}(uTemp);
    ME.k(nodes) = ME.kFunc{i}(TTemp);
    ME.mu(nodes) = ME.muFunc{i}(TTemp);
    ME.dT_dU(nodes) = ME.dT_duFunc{i}(uTemp);
    ME.dh_dT(nodes) = ME.dh_dTFunc{i}(TTemp);
    Ti(nodes) = TTemp;
  end
  Ti(sindn) = ME.T(sindn);
  ME.Fc_turb = 0.5*(ME.turb(nd1) + ME.turb(nd2));

  Pi = Ti(indn).*rhoi.*ME.Rs;
%   fprintf([num2str(std(Pi(1:end-1))) '\n']);
  Pi(end) = PEnv;
```

```
FcP = 0.5*(Pi(nd1) + Pi(nd2));
% Thermal Conductivity
ME.k(dvind) = ME.k(dvind) + ...
  0.021*rhoi(dvind).*ME.Dh(dvind).*...
  (ME.Rs(dvind) + 1./ME.dT_dU(dvind)).*sqrt(ME.turb(dvind));
%   ME.Fc_k = (ME.k(nd1) + ME.k(nd2))/2;
%   ME.k(ME.k>100) = 100;
% Viscosity
ME.mu(dvind) = ME.mu(dvind) + ...
  0.021*rhoi(dvind).*ME.Dh(dvind).*sqrt(ME.turb(dvind));
%   Fcmu = (ME.mu(nd1) + ME.mu(nd2))/2;
% Do flux limiting on the int energy, then calculate T from u2T
forward = (ME.Fc_V > 0);
Fcu(forward) = ui(nd1(forward));
Fcu(~forward) = ui(nd2(~forward));
theta_FL(forward) = (ui(nd1(forward))-ui(nd0(forward)))./...
  (ui(nd2(forward))-ui(nd1(forward)));
theta_FL(~forward) = (ui(nd2(~forward))-ui(nd3(~forward)))./...
  (ui(nd1(~forward))-ui(nd2(~forward)));
theta_FL(isnan(theta_FL)) = 1;
theta_FL(theta_FL > 1) = 1;
theta_FL(theta_FL < -1) = -1;
Fcu = Fcu + ((theta_FL.^2 + theta_FL)./(theta_FL.^2 + 1)).*...
  (ME.Fc_A.*ui(nd0) + ME.Fc_B.*ui(nd1) + ...
  ME.Fc_C.*ui(nd2) + ME.Fc_D.*ui(nd3) - Fcu);
n = length(ME.Regions);
for i = 1:n
  faces = ME.RegionFcs{i};
  FcT(faces) = ME.u2T{i}(Fcu(faces));
  ME.Fc_k(faces) = ME.kFunc{i}(FcT(faces));
  Fcmu(faces) = ME.muFunc{i}(FcT(faces));
end
Fcrho(indf) = 2.*FcP(indf)./((ME.Rs(nd1(indf)) + ME.Rs(nd2(indf))).*FcT(indf));
ME.PR = abs((1./ME.dT_dU(indn) + ME.Rs).*ME.mu./ME.k);
ME.Fc_PR = 0.5*(ME.PR(nd1)+ME.PR(nd2));

% Parameters used by outside calculation
ME.Fc_RE = abs(ME.Fc_U.*Fcrho.*ME.Fc_Dh./Fcmu);
ME.Fc_RE(ME.Fc_RE==0) = 1e-8;
ME.getWeight();

% Assign Node Reynold's Number
area = zeros(lenn-1,1);
ME.RE = area;
for i = 1:3:length(ME.TransNet)-2
  ME.RE(ME.TransNet{i+1}) = ME.RE(ME.TransNet{i+1}) + ...
    ME.Fc_RE(ME.TransNet{i+2}).*Areai(ME.TransNet{i+2});
  area(ME.TransNet{i+1}) = area(ME.TransNet{i+1}) + ...
    Areai(ME.TransNet{i+2});
end
ME.RE = ME.RE./(area);
ME.RE(isnan(ME.RE)) = 1e-8;

%% Calculate Flow Independent Energy Flux to Nodes
invConv = ME.Dh(indnminus)./(ME.k(indnminus).*ME.Nusselt());
ME.Fc_Cond(indmf) = ME.Fc_Area(indmf)./(ME.Fc_R(indmf)' + invConv(nd1mf));
ME.Fc_Cond(indf) = ME.NkFunc().*ME.Fc_k(indf).*Areai./ME.Fc_Cond_Dist(indf);
ME.Fc_Cond(indS) = ME.Fc_Cond(indS) + abs(...
  (ME.dA/4)*(1./ME.dT_dU(indS)).*...
  ME.Fc_Shear_Factor(indS).*Fcrho(indS).*Areai(indS));

Q(:) = 0;
Qfc = ME.Fc_Cond(Cfcs).*(Ti(Cnd1) - Ti(Cnd2));
for i = 1:3:length(ME.CondNet)-2
  Q(ME.CondNet{i+1}) = ...
    Q(ME.CondNet{i+1}) + ME.CondNet{i}.*Qfc(ME.CondNet{i+2});
end

fcs = ME.FcApprox;
Ci = mi(ME.Fc_Nd(fcs,1))./ME.dT_dU(ME.Fc_Nd(fcs,1));
C1 = Ci + Cs;
```

```
        CT = (Ti(ME.Fc_Nd(fcs,1)).*Ci + Ti(ME.Fc_Nd(fcs,2)).*Cs)./C1 - Ti(ME.Fc_Nd(fcs,1));
        nlambda = -ME.Fc_Cond(fcs).*(1./Cs + 1./Ci);
        Qs = Q(ME.Fc_Nd(fcs,2));

%         ME.MaxFourier = 0.025;
%         ME.MaxCourant = 0.025;

        % Assign TimeStep
        if ~isempty(ME.Fc_dx)
          if ~isempty(ME.Fc_Cond)
            hmax = min([hmax FlowTimeStep ...
              ME.MaxFourier*...
                min(min(mi(nd1)./(ME.dT_dU(nd1).*ME.Fc_Cond(indf))), ...
                    min(mi(nd2)./(ME.dT_dU(nd2).*ME.Fc_Cond(indf)))) ...
              ME.MaxFourier*min(mi(nd1mf)./(ME.dT_dU(nd1mf).*ME.Fc_Cond(indmf))) ...
              ME.MaxFourier*min(ME.m(nd2mf)./(ME.dT_dU(nd2mf).*ME.Fc_Cond(indmfminus)))]);
          else
            hmax = min([hmax FlowTimeStep ...
              ME.MaxFourier*min(mi(nd1mf)./(ME.dT_dU(nd1mf).*ME.Fc_Cond(indmf))) ...
              ME.MaxFourier*min(ME.m(nd2mf)./(ME.dT_dU(nd2mf).*ME.Fc_Cond(indmfminus)))]);
          end
        else
          if ~isempty(ME.Fc_Cond)
            hmax = min([hmax ...
              ME.MaxFourier*...
                min(min(mi(nd1)./(ME.dT_dU(nd1).*ME.Fc_Cond(indf))), ...
                    min(mi(nd2)./(ME.dT_dU(nd2).*ME.Fc_Cond(indf))))]);
          end
        end
        % hmax = 1e-4;

        RegionPressure = zeros(n,1);
%         dm_region = RegionPressure;
%         m_region = RegionPressure;
%         V_region = RegionPressure;
%         dV_region = RegionPressure;
        E_region = RegionPressure;

        %% Calculate Explicit Volume Flow - Normal
        if ~isempty(ME.ExplicitNorm)
          ME.Fc_dP(ExFc) = Pi(nd1(ExFc)) - Pi(nd2(ExFc));
          x = sign(ME.Fc_dP(ExFc)).*...
            sqrt(2*(Areai(ExFc).^2).*abs(ME.Fc_dP(ExFc))./Fcrho(ExFc));
          V = ME.Fc_V(ExFc);
          V_max = 350*Areai(ExFc);
          V(V > V_max) = V_max(V > V_max);
          iteration = 1;
          while iteration < 100
            oldV = V;
            K = ME.KValue(ExFc);
            V = x./sqrt(K);
            V(V > V_max) = V_max(V > V_max);
            V(isnan(V)) = 1;
            if CustomRSSQ(oldV-V) < 1e-8; break; end
          end
          ME.Fc_V(ExFc) = V;
          for i = 1:length(ExR1)
            E = ME.Fc_V(ExFc(i)).*FcP(ExFc(i));
            E_region(ExR1(i)) = E_region(ExR1(i)) - E;
            E_region(ExR2(i)) = E_region(ExR2(i)) + E;
          end
        end

        %% Calculate Explicit Volume Flow - Leak
        if ~isempty(ME.ExplicitLeak)
          dP = Pi(nd1(ExLFc)) - Pi(nd2(ExLFc));
          ME.Fc_V(ExLFc) = sign(dP).*ExLC.*(abs(dP)).^ExLN;
          for i = 1:length(ExLR1)
            if ME.Fc_V(ExLFc(i)) > 0; x = Pi(nd2(ExLFc(i)));
            else; x = Pi(nd1(ExLFc(i)));
            end
```

```
            E = ME.Fc_V(ExLFc(i)).*x;
            E_region(ExLR1(i)) = E_region(ExLR1(i)) - E;
            E_region(ExLR2(i)) = E_region(ExLR2(i)) + E;
          end
        end

        % Assume that flow can't change that much
        if ~isempty(ME.Fc_dx); h = min(hmax, 0.8*FlowTimeStep);
        else; h = hmax;
        end

        % Boundary Work
        P0 = zeros(length(ME.Regions),1);
        for i = 1:length(ME.Regions)
          if ME.isEnvironmentRegion(i)
            P0(i) = PEnv;
          else
%             nodes = ME.Regions{i};
%             ni = nodes(1);
%             P0(i) = Ti(ni)*ME.R(i)*mi(ni)/ME.vol(ni);
%             dV_dt_region = sum(ME.dV_dt(nodes));
%             M_region = sum(mi(nodes));
%             E_region(i) = E_region(i) - P0(i)*dV_dt_region;
%             Q(nodes) = (mi(nodes)/M_region).*E_region(i);
%             nodes = ME.Regions{i}(isDynVol(ME.Regions{i}));
            nodes = ME.Regions{i}(:);
            P0(i) = sum(Ti(nodes).*ME.R(i).*mi(nodes))/sum(ME.vol(nodes));
%             for ni = nodes
%               Q(ni) = Q(ni) - ME.dV_dt(ni)*P0(i);
%             end
          end
        end


        %% Setup Variables for Volume Flux Solving
        not_done = true;
        while not_done
          i = 1;
          Qi = Q(ME.Fc_Nd(fcs,1));
          for nd = ME.Fc_Nd(fcs,1)'
            data = ME.Faces{nd,1};
            mdot = ME.Fc_V(data(:,1)).*double(data(:,2)).*Fcrho(data(:,1));
            dm_dt(nd) = sum(mdot);
            Qi(i) = Qi(i) + ...
              sum(mdot.*(Fcu(data(:,1)) + P0(i)./Fcrho(data(:,1)))) - ...
              P0(i).*ME.dV_dt(nd);
%             Qi(i) = Qi(i) + ...
%               sum(mdot.*(Fcu(data(:,1)) + (P0(i) + dP_dt(i,ME.Inc))./Fcrho(data(:,1)))) - ...
%               P0(i).*ME.dV_dt(nd) - h*(ME.vol(nd) + 0.5*ME.dV_dt(nd)).*dP_dt(i,ME.Inc);
            i = i + 1;
          end
          C2 =(Qi + Qs)./C1;
          C3 = (Ci.*Qs - Cs.*Qi)./(ME.Fc_Cond(fcs).*C1.^2);
          C3(isnan(C3)) = 0;
          C3(isinf(C3)) = 0;
          C4 = (Ti(ME.Fc_Nd(fcs,1)) - Ti(ME.Fc_Nd(fcs,2)))./(C3.*C1);
          C4(isnan(C4)) = 0;
          C4(isinf(C4)) = 0;
          Qtd(:) = 0;
          Qtemp = -(Ci.*(CT - Cs.*C3.*(1 - (1 + C4)).*exp(nlambda*h))...
            + (Ci.*C2 - Qi)*h);
          for i = 1:length(ME.FcApprox)
            fc = ME.FcApprox(i);
            % 1st is gas, it can have multiple connections
            Qtd(ME.Fc_Nd(fc,1)) = Qtd(ME.Fc_Nd(fc,1)) - Qtemp(i);
            % 2nd is solid, it can only have 1 connection
            Qtd(ME.Fc_Nd(fc,2)) = Qtemp(i);
          end

          not_done = false;
          Vnew = ME.vol(indn) + h*ME.dV_dt(indn);
```

```
            for ind = find(Vnew<=0); Vnew(ind) = 1e-8; end

            %% Enter Volume Flux Solving Loop
            for i = 1:length(ME.Regions)
              if ~isempty(ME.RegionFcs{i})
                faces = ME.ActiveRegionFcs{i};
                nodes = ME.Regions{i};
                A = zeros(ME.RegionFcCount(i));
                b = zeros(ME.RegionFcCount(i),1);
                if ME.isEnvironmentRegion(i)
                  % Vdot Rows
                  for row = 1:length(faces)
                    ni = nodes(row);
                    b(row) = Vnew(ni)*PEnv/ME.R(i) - ...
                      Ti(ni)*mi(ni) + ME.dT_dU(ni)*(h*Q(ni) + Qtd(ni) ...
                      - PEnv.*(Vnew(ni)-ME.vol(ni)));
                    data = ME.Faces{ni,1};
                    for p = 1:size(data,1)
                      fc = data(p,1);
                      X = h*double(data(p,2))*Fcrho(fc)*(...
                        Ti(ni) + ME.dT_dU(ni)*...
                          (Fcu(fc) - ui(ni) + PEnv/Fcrho(fc)));
                      if data(p,3); b(row) = b(row) - ME.Fc_V(fc)*X;
                      else; A(row,F2C(fc)) = A(row,F2C(fc)) + X;
                      end
                    end
                  end
                  if isempty(ME.RegionLoops{i})
                    As = sparse(A);
                    V = As\b;
                    ME.Fc_V(faces) = V(F2C(faces));
                    ME.Fc_U(faces) = ME.Fc_V(faces)./ME.Fc_Area(faces) +
ME.Fc_Vel_Factor(faces)*ME.dA;
                  else
                    solve_loops(ME,i,F2C,length(faces)+1,A,b,Fcrho,Fcmu,time);
                  end
                else
                  % Solve for Vdot
                  for row = 1:length(faces)
                    ni = nd1(faces(row));
                    nj = nd2(faces(row));
                    b(row) = ...
                      (Ti(ni)*mi(ni) + ME.dT_dU(ni)*(h*Q(ni) + Qtd(ni) ...
                      - h*P0(i).*ME.dV_dt(ni)))/Vnew(ni) - ...
                      (Ti(nj)*mi(nj) + ME.dT_dU(nj)*(h*Q(nj) + Qtd(nj)...
                      - h*P0(i).*ME.dV_dt(nj)))/Vnew(nj);
%                     b(row) = ...
%                       (Ti(ni)*mi(ni) + ME.dT_dU(ni)*(h*Q(ni) + Qtd(ni) ...
%                       - (P0(i) + 0.5*h*dP_dt(i,ME.Inc)).*(Vnew(ni)-ME.vol(ni)) ...
%                       - h*(ME.vol(ni)).*dP_dt(i)))/Vnew(ni) - ...
%                       (Ti(nj)*mi(nj) + ME.dT_dU(nj)*(h*Q(nj) + Qtd(nj)...
%                       - (P0(i) + 0.5*h*dP_dt(i,ME.Inc)).*(Vnew(nj)-ME.vol(nj)) ...
%                       - h*(ME.vol(nj)).*dP_dt(i)))/Vnew(nj);
                    data = ME.Faces{ni,1};
                    for p = 1:size(data,1)
                      fc = data(p,1);
                      X = h*double(data(p,2))*Fcrho(fc)*(...
                        Ti(ni) + ME.dT_dU(ni)*(Fcu(fc) - ui(ni)...
                        + P0(i)/Fcrho(fc)))/Vnew(ni);
%                       X = h*double(data(p,2))*Fcrho(fc)*(...
%                         Ti(ni) + ME.dT_dU(ni)*(Fcu(fc) - ui(ni)...
%                         + (P0(i) + 0.5*h*dP_dt(i,ME.Inc))/Fcrho(fc)))/Vnew(ni);
                      if data(p,3); b(row) = b(row) + ME.Fc_V(fc)*X;
                      else; A(row,F2C(fc)) = A(row,F2C(fc)) - X;
                      end
                    end
                    data = ME.Faces{nj,1};
                    for p = 1:size(data,1)
                      fc = data(p,1);
                      X = h*double(data(p,2))*Fcrho(fc)*(...
```

```
                    Ti(nj) + ME.dT_dU(nj)*(Fcu(fc) - ui(nj)...
                    + P0(i)/Fcrho(fc)))/Vnew(nj);
%                   X = h*double(data(p,2))*Fcrho(fc)*(...
%                     Ti(nj) + ME.dT_dU(nj)*(Fcu(fc) - ui(nj)...
%                     + (P0(i) + 0.5*h*dP_dt(i,ME.Inc))/Fcrho(fc)))/Vnew(nj);
                  if data(p,3); b(row) = b(row) - ME.Fc_V(fc)*X;
                  else; A(row,F2C(fc)) = A(row,F2C(fc)) + X;
                  end
                end
              end
              if isempty(ME.RegionLoops{i})
                As = sparse(A);
                %fprintf([num2str(condest(A)) '\n']);
                V = As\b;
                if any(isnan(V)) || any(any(isnan(A))) || any(isnan(b))
                  ME.stop = true;
                end
                ME.Fc_V(faces) = V(F2C(faces));
                ME.Fc_U(faces) = ME.Fc_V(faces)./ME.Fc_Area(faces) +
ME.Fc_Vel_Factor(faces)*ME.dA;
              else
                solve_loops(ME,i,F2C,length(faces)+1,A,b,Fcrho,Fcmu,time);
              end
              % Calculate dP
              %{
              ni = ME.Regions{i}(1);
              data = ME.Faces{ni,1};
              mdot = ME.Fc_V(data(:,1)).*double(data(:,2)).*Fcrho(data(:,1));
              mnewi = ME.m(ni) + h*sum(mdot);
              unewi = ui(ni) + (... u +
                h*Q(ni) + Qtd(ni) ...
                - (P0(i) + 0.5*h.*dP_dt(i,ME.Inc)).*(Vnew(ni) - ME.vol(ni)) ...
                - 0.5*h*(Vnew(ni) + ME.vol(ni)).*dP_dt(i,ME.Inc) ... (dU
                - ui(ni).*dm_dt(ni).*h)./mnew(ni); % - u dm)/mnew;
              newValue = (mnewi*ME.u2T{i}(unewi)*ME.R(i)/Vnew(ni) - Pi(ni))/h;
              if newValue ~= 0
                if abs(dP_dt(i,ME.Inc)-newValue) > 1e-4 && abs((dP_dt(i,ME.Inc)-
newValue)/dP_dt(i,ME.Inc)) > 0.01
                  not_done = true;
                  dP_dt(i,ME.Inc) = newValue;
                else
                  if ME.Inc < Frame.NTheta
                    if dP_dt(i,ME.Inc+1) == 0
                      dP_dt(i,ME.Inc+1) = dP_dt(i,ME.Inc);
                    end
                  end
                end
              end
              %}
            end
          end
        end
        if ~isempty(ME.Fc_dx)
          FlowTimeStep = max(1e-4,
min(ME.MaxCourant*ME.Fc_dx./(abs(ME.Fc_V./(ME.Fc_Area(1:lenf)+1e-8)))));
          if FlowTimeStep < h
            not_done = true;
            h = FlowTimeStep;
          end
        end
        if isnan(FlowTimeStep)
          ME.stop = true;
          break;
        end
      end

      % Vnew = ME.vol(indn) + h*ME.dV_dt(indn);
      % Update Parameters
      for i = 1:n
        nodes = ME.Regions{i};
%         Pregion_avg(i) = Pi(nodes(1)) + 0.5*h*dP_dt(i,ME.Inc);
```

```
      if ME.isEnvironmentRegion(i); nodes = nodes(nodes~=lenn); end
      for nd = nodes'
        data = ME.Faces{nd,1};
        mdot = ME.Fc_V(data(:,1)).*double(data(:,2)).*Fcrho(data(:,1));
        dm_dt(nd) = sum(mdot);
        Q(nd) = Q(nd) + sum(mdot.*(Fcu(data(:,1)) + P0(i)./Fcrho(data(:,1))));
      end
      mnew(nodes) = ME.m(nodes) + h*dm_dt(nodes);
      unew(nodes) = (mi(nodes).*ui(nodes) + Qtd(nodes) + h*(Q(nodes)...
        - P0(i).*ME.dV_dt(nodes)))./mnew(nodes);
      Tnew(nodes) = ME.u2T{i}(unew(nodes));
      ME.P(nodes) = ME.R(i).*mnew(nodes).*Tnew(nodes)./Vnew(nodes);
      % Fix The parameters to ensure that the pressure is constant
      if ME.isEnvironmentRegion(i)
        Pavg = PEnv; % dP_dt(i) = 0;
      else
        Pavg = sum(ME.P(nodes).*ME.vol(nodes))/sum(ME.vol(nodes));
%         if ME.Inc == 1 && t == 0
%           dP_dt(i) = dP_dt(i);
%         else
%           dP_dt(i) = (Pavg - P0(i))/h;
%         end
      end
      Tnew(nodes) = Pavg./ME.P(nodes).*Tnew(nodes);
    end
    ME.P(lenn) = PEnv;

    %% TURBULENCE ITEMS
    if lenf ~= 0
      change = indf(sign(ME.Fc_U(indf))~=signU);
      ME.Fc_to(change) = ME.curTime + t;
      changed_nodes = false(lenn,1);
      changed_nodes(nd1(change)) = true;
      changed_nodes(nd2(change)) = true;
      changed_nodes(isDynVol) = false;
      ME.to(changed_nodes) = ME.curTime + t;
      ME.turb(changed_nodes) = 0;
      % Define (for those that care) the critcal reynolds number
      ME.Va(indnminus) = ME.dA*rhoi(indnminus).*(ME.Dh(indnminus).^2)./ME.mu(indnminus);
      ReCritComparitor(1,:) = (sqrt(ME.Va(indnminus))./...
        (0.075+0.112.*(ME.curTime + t - ME.to(1:lenn-1))))';
      ME.REcrit(indnminus) = 200*max(ReCritComparitor);
      TurbTime = 0;
      steps = ME.Fc_K12 > 0;
      while TurbTime < h
        ME.Fc_turb =  0.5*(ME.turb(nd1) + ME.turb(nd2));
        h_turb = h - TurbTime;
        dturb_dt = zeros(lenn,1);
        % Turbulence Transport
        for i = indf(steps)'
          n1 = nd1(i);
          n2 = nd2(i);
          % dturb_dt = turb*(dKE_dt / KE - dm_dt / m)
          if ME.Fc_V(i) > 0
            % Leaving n1
            % Leaving a variable volume space ... No change to kappa
            if ~isDynVol(n1)
              dturb_dt(n1) = dturb_dt(n1) + (- ME.Fc_turb(i) + ME.turb(n1));
            end
            % Entering n2
            if isDynVol(n2)
              dKE_dm = 0.5*(ME.Fc_V(i)/Areai(i))^2;
              dturb_dt(n2) = dturb_dt(n2) + (dKE_dm - ME.turb(n2));
            else
              dturb_dt(n2) = dturb_dt(n2) + (1 - ME.turb(n2));
            end
          else
            % Entering n1
            if isDynVol(n1)
              dKE_dm = 0.5*(ME.Fc_V(i)/Areai(i))^2;
              dturb_dt(n1) = dturb_dt(n1) + (dKE_dm - ME.turb(n1));
```

```
        else
          dturb_dt(n1) = dturb_dt(n1) + (1 - ME.turb(n1));
        end
        % Leaving n2
        % Leaving a variable volume space ... No change to kappa
        if ~isDynVol(n2)
          dturb_dt(n2) = dturb_dt(n2) + (- ME.Fc_turb(i) + ME.turb(n2));
        end
      end
    end
    for i = indf(~steps)'
      % dturb_dt = turb*(dKE_dt / KE - dm_dt / m)
      % dturb_dt = turb * (dKE_dm / ke - 1) * dm_dt / m
      % dturb_dt = .... * (dKE_dm / ke - 1) * ..... / ..
      dKE_dm = ME.Fc_turb(i);
      dturb_dt(nd1(i)) = dturb_dt(nd1(i)) - ...
        (dKE_dm - ME.turb(nd1(i))) * sign(ME.Fc_V(i));
      dturb_dt(nd2(i)) = dturb_dt(nd2(i)) + ...
        (dKE_dm - ME.turb(nd2(i))) * sign(ME.Fc_V(i));
    end
    dturb_dt = dturb_dt .* (dm_dt ./ mi);

    %% Turbulence Decay/Generation Within Nodes
    for i = 1:lenn-1
      if isDynVol(i)
        % Variable Volume
        % F. J. Cantelmi, Measurement and Modeling of In-Cylinder Heat Transfer
        %    with Inflow-Produced Turbulence, MS Thesis, Virginia Polytechnic Institute
        %    and State University, June (1995)
        dturb_dt(i) = dturb_dt(i) - ...
          5.8*(abs(ME.turb(i) + dturb_dt(i)*h)^(3/2))/ME.Dh(i) - ...
          ME.turb(i)/mi(i)*dm_dt(i);
      else
        if ME.RE(i) > ME.REcrit(i)
          % Generate
          dturb_dt(i) = dturb_dt(i) + ...
            (0.008*ME.dA*ME.RE(i)/ME.Va(i))*(1-ME.turb(i));
        else
          % Decay
          dturb_dt(i) = dturb_dt(i) - ...
            (0.25*ME.dA*2300/ME.Va(i))*abs(ME.turb(i))^(3/2);
        end
      end
    end
    % Test - To limit timestep
    d_turb = zeros(size(ME.turb(indn)));
    for i = indn'
      if isDynVol(i)
        d_turb(i) = h_turb*dturb_dt(i);
      else
        d_turb(i) = max(0,min(1,ME.turb(i) + ...
          h_turb*dturb_dt(i))) - ME.turb(i);
      end
    end
    max_d_turb = max(abs(d_turb(~isDynVol(indn))));
    if max_d_turb > 0.1; h_turb = h_turb*0.1/max_d_turb; end
    % Assign Values
    ME.turb = ME.turb + h_turb*dturb_dt;
    ME.turb(ME.turb<0) = 0;
    for i = indn'
      if ME.turb(i) > 1 && ~isDynVol(i)
        ME.turb(i) = 1;
      end
    end
    ME.turb(lenn) = 0;
    TurbTime = TurbTime + h_turb;
  end
end

if ME.Model.recordOnlyLastCycle
  for i = 1:length(ME.Regions)
```

```
            if ~ME.isEnvironmentRegion(i)
              nodes = ME.Regions{i};
              ME.PRegion(i) = ME.PRegion(i) + ME.P(nodes(1))*h;
            end
          end
          ME.PRegionTime = ME.PRegionTime + h;
%           i = 1;
%           for iPVoutput = ME.Model.PVoutputs
%             ME.PRegion(i) = ME.PRegion(i) + ME.P(iPVoutput.RegionNodes(1))*h;
%             ME.PRegionTime(i) = ME.PRegionTime(i) + h;
%             i = i + 1;
%           end
        end

        % Mass Change
        ME.m(indn) = mnew(indn);

        % Internal Energy Change
        ME.u(indn) = unew(indn);

        % Temperature
        ME.T(indn) = Tnew(indn);
        ME.T(sindn) = ME.T(sindn) + ...
          ME.dT_dU(sindn).*(h*Q(sindn) + Qtd(sindn))./ME.m(sindn);

        % Environment
        ME.m(lenn) = inf;
        ME.u(lenn) = uEnv;
        ME.T(lenn) = TEnv;

        % Basic Boundary Work
        ME.CycledE = ME.CycledE + h*(0.5*sum(ME.dV_dt.*(Pi + ME.P)));

        % Parameters used by functions that are called after each
        % ... angular increment.
        if lenf ~= 0
          ME.Fc_V_averager = ME.Fc_V_averager + h*ME.Fc_V;
          ME.Fc_turb_averager = ME.Fc_turb_averager + h*ME.Fc_turb;
        end
        t = t + h;
        if t >= ME.dt_max
          done = true;
          % Setup for Flow Loss Calculation
          ME.Fc_V = ME.Fc_V_averager / ME.dt_max;
          ME.Fc_turb = ME.Fc_turb_averager / ME.dt_max;
          for i = 1:length(ME.Regions)
            if isempty(ME.RegionLoops{i})
              faces = ME.ActiveRegionFcs{i};
              ME.Fc_RE(faces) = abs(ME.Fc_U(faces).*Fcrho(faces).*ME.Fc_Dh(faces)./Fcmu(faces));
              ME.Fc_RE(ME.Fc_RE==0) = 1e-7;
              ME.getWeight(faces);
              ME.KpU_2A(faces) = ME.KValue(faces).*Fcrho(faces).*ME.Fc_U(faces)./Areai(faces);
            end
          end

          if ME.ss_condition || ~ME.continuetoSS
            % Get cycle time for averaging the effective conductance and
            % ... conductance temperatures
            ME.CycleTime = ME.CycleTime + ME.dt_max;

            % Calculate Effective Conduction for mixed faces
            ME.CondEff(indmf) = ME.CondEff(indmf) + ...
              ME.dt_max * ME.Fc_Cond(indmf);

            % Calculate the Effective Conduction * Temperature of mixed faces
            ME.CondTempEff(indmf) = ME.CondTempEff(indmf) + ...
              ME.dt_max * ME.Fc_Cond(indmf).* ME.T(nd1mf);

            % Test The reynold's number
%             if isempty(ME.EffRE); ME.EffRE = zeros(size(indn)); end
%             ME.EffRE = ME.EffRE + ...
```

```
%               (ME.dt_max/sum(ME.vol(indnminus))) * sum(ME.Dh(indnminus).*ME.vol(indnminus));
        end

        % Record statistics
        if ME.Model.recordConductionFlux
          ME.CondFlux(:) = 0;
          for i = 1:3:length(ME.CondNet)-2
            ME.CondFlux(ME.CondNet{i+1}) = ...
              ME.CondFlux(ME.CondNet{i+1}) + ...
              abs(ME.CondNet{i}.*Qfc(ME.CondNet{i+2}));
          end
          if any(~isreal(Qtd(:)))
            fprintf('err');
          end
          ME.CondFlux = (ME.CondFlux + real(Qtd(:)))./ME.vol;
        end
        if RecordStatistics
          ME.E_ToEnvironment = ME.E_ToEnvironment + ...
            ME.dt_max*(sum(Qfc(facesES).*sgnES) + ...
            sum(sgnEG.*(Qfc(facesEG) + ...
            ME.Fc_V(facesEG).*rhoi(facesEG).*ui(facesEG))));
          ME.E_ToSource = ME.E_ToSource + ...
            ME.dt_max*sum(Qfc(facesSr).*sgnSr);
          ME.E_ToSink = ME.E_ToSink + ...
            ME.dt_max*sum(Qfc(facesSi).*sgnSi);
          if length(ME.VolMin) < length(ME.Regions)
            ME.VolMin = 100000*ones(size(ME.Regions));
            ME.VolMax = zeros(size(ME.Regions));
          end
          for i = 1:length(ME.Regions)
            if ~ME.isEnvironmentRegion(i)
              nodes = ME.Regions{i};
              Vol = sum(ME.vol(nodes));
              ME.VolMin(i) = min(ME.VolMin(i),Vol);
              ME.VolMax(i) = max(ME.VolMax(i),Vol);
            else
              ME.VolMin(i) = 0;
              ME.VolMax(i) = 0;
            end
          end
          % Qfc = ME.Fc_Cond(Cfcs).*(Ti(Cnd1) - Ti(Cnd2));
          TRatio = Ti(Cnd1)./Ti(Cnd2);
          TRatio(TRatio>1) = 1./TRatio(TRatio>1);
          ME.ExergyLossStatic = ME.ExergyLossStatic + ...
            ME.dt_max*sum(abs(Qfc(ME.StaticFaces).*(1-TRatio(ME.StaticFaces))));
          ME.ExergyLossShuttle = ME.ExergyLossShuttle + ...
            ME.dt_max*sum(abs(Qfc(ME.ShuttleFaces).*(1-TRatio(ME.ShuttleFaces))));
        end
      end
    end
  end

  function solve_loops(ME,region,F2C,startrow,A,b,Fcrho,Fcmu,time)
    persistent recordValues;
    persistent recordTimes;
    if isempty(recordValues)
      recordValues = cell(length(ME.Regions),1);
      recordTimes = recordValues;
      for indl = 1:length(ME.Regions)
        recordValues{indl} = [];
        recordTimes{indl} = [];
      end
    end

    % Loop Definitions
    loop = ME.RegionLoops{region};
    Ind = ME.RegionLoops_Ind{region};
    Nloops = size(Ind, 2);

    % UnCollapsed References
    rows = startrow:startrow + Nloops-1;
```

```
% Predict Values at this time-step
if size(recordValues{region},2) == 3
  % Quadratically Extrapolate
  y0 = recordValues{region}(:,1);
  y1 = recordValues{region}(:,2);
  y2 = recordValues{region}(:,3);
  x0 = recordTimes{region}(1);
  x1 = recordTimes{region}(2);
  x2 = recordTimes{region}(3);
  prediction = ...
    y0*(((time-x1)*(time-x2)) / ((x0-x1)*(x0-x2))) + ...
    y1*(((time-x0)*(time-x2)) / ((x1-x0)*(x1-x2))) + ...
    y2*(((time-x0)*(time-x1)) / ((x2-x0)*(x2-x1)));
end

skipLoop = false(Nloops,1);
% Define loops that participate
for p = 1:Nloops
  if Ind(3, p) && ME.Fc_Area(Ind(3, p)) == 0
    % The Area has gone to 0, therefore the volume flow rate is 0
    A(rows(p), F2C(Ind(3, p))) = 1;
    skipLoop(p) = true;
  else
    % The entry in "A" will be a 1, to set the volume flow rate to the
    % ... value defined in "b". The Last entry of the loop is the
    % ... only one that cannot be a part of another loop.
    A(rows(p), F2C(loop(2,Ind(2,p)))) = 1;
    if size(recordValues,2) == 3
      b(rows(p)) = prediction(p);
    else
      b(rows(p)) = ME.Fc_V(loop(2, Ind(2, p)));
    end
  end
end

% Calculate inverse of matrix
Ainv = inv(A);

% Eliminate the rows that are not useful outputs
indl = 1:length(skipLoop);
rows(skipLoop) = [];
indl(skipLoop) = [];
x = Ainv*b;

% Initialize Solving Loop
iteration = 1;
max_iterations = 300;
fn = ones(length(indl),1);

tol = 1e-8;
if ~isempty(indl)

  %  Newton's Method
  J = zeros(length(indl));

  while iteration < max_iterations

    for i = 1:length(indl)
      Sgni = loop(3,Ind(1,indl(i)):Ind(2,indl(i)))';
      Fcsi = loop(2,Ind(1,indl(i)):Ind(2,indl(i)));
      for j = 1:length(indl)
        DeltaV = Ainv(:,rows(j));
        if i == j
          [dfi_dxj, fni] = getCost(...
            ME,x(F2C(Fcsi)), Sgni, Fcsi, Fcmu(Fcsi), ...
            Fcrho(Fcsi), DeltaV(F2C(Fcsi)));
          J(i,j) = dfi_dxj;
          fn(i) = fni;
        else
          [dfi_dxj] = getCost(...
```

```
                ME,x(F2C(Fcsi)), Sgni, Fcsi, Fcmu(Fcsi), ...
                Fcrho(Fcsi), DeltaV(F2C(Fcsi)));
              J(i,j) = dfi_dxj;
            end
          end
        end

        % Test Convergence
        if sum(abs(fn)) < tol; break; end

        % x = x + J\(-f); - Calculate the shift in x
        x = x + Ainv(:,rows)*(J\(-fn));

        iteration = iteration + 1;
      end
    end

    if iteration == max_iterations
      fprintf('XXX Failed to Converge 300 iterations. XXX\n');
%     else
%       fprintf(['Converged in ' num2str(iteration) ' iterations. \n']);
    end

    % Record for extrapolation
    if size(recordValues{region},2) == 3
      recordValues{region}(:,1:2) = recordValues{region}(:,2:3);
      recordTimes{region}(1:2) = recordTimes{region}(2:3);
      recordValues{region}(:,end) = x(rows(:));
      recordTimes{region}(end) = time;
    else
      recordValues{region}(:,end+1) = x(rows(:));
      recordTimes{region}(end+1) = time;
    end

    ME.Fc_V(ME.RegionFcs{region}) = x(F2C(ME.RegionFcs{region}));
  end

  %{
  function dP = p_drop(ME,fc)
    nd1 = ME.Fc_Nd(fc,1);
    nd2 = ME.Fc_Nd(fc,2);
    rho1 = ME.m(nd1)/ME.vol(nd1);
    rho2 = ME.m(nd2)/ME.vol(nd2);
    rho = (rho1 + rho2)/2;
    mu1 = ME.muFunc(ME.T(nd1));
    mu2 = ME.muFunc(ME.T(nd2));
    mu = (mu1 + mu2)/2;
    U = ME.Fc_V(fc)./ME.Fc_Area(fc) + ME.Fc_Vel_Factor(fc)*ME.dA;
    RE = abs(rho*U*ME.Fc_Dh(fc)./mu) + 1e-7;
    ME.getWeight(fc);
    [K,~] = ME.KValue(fc);
    dP = K*rho*abs(U)*U;
  end
  %}

  function [derivative, cost] = getCost(ME, Vnew, Sgn, Fcs, Fcmu, Fcrho, DeltaV)
    ME.Fc_U(Fcs) = Vnew./ME.Fc_Area(Fcs) + ME.Fc_Vel_Factor(Fcs)*ME.dA;
    ME.Fc_RE(Fcs) = abs(ME.Fc_U(Fcs).*Fcrho.*ME.Fc_Dh(Fcs)./Fcmu) + 1e-7;
    ME.getWeight(Fcs);
    if nargout == 2
      [K, derv] = ME.KValue(Fcs);
      cost = sum(Sgn.*K.*Fcrho.*abs(ME.Fc_U(Fcs)).*ME.Fc_U(Fcs));
      derivative = sum(...
        (DeltaV.*Sgn.*Fcrho.*abs(ME.Fc_U(Fcs))./ME.Fc_Area(Fcs)).*(...
        sign(ME.Fc_U(Fcs)).*ME.Fc_RE(Fcs).*derv + 2*K));
    else
      [K, derv] = ME.KValue(Fcs);
      derivative = sum(...
        (DeltaV.*Sgn.*Fcrho.*abs(ME.Fc_U(Fcs))./ME.Fc_Area(Fcs)).*(...
        sign(ME.Fc_U(Fcs)).*ME.Fc_RE(Fcs).*derv + 2*K));
      return;
```

```
  end
end

function Forces = Iteration_Solve(ME)
  % Inc = next position, iterate up to this position, where dynamics
  % ... are calculated

  %% Step 2: Start Recursive Algorithm
  ME.implicitSolve();
  if ME.stop
    fprintf('Simulation Finished Prematurely. (In Iteration_Solve)\n');
  end

  %% Step 5: Collect Information for Dynamics, in the form of "Forces"
  % Pressure Boundaries
  Forces = ME.CalcForces();
end

function assignAvgDynamic(ME)
  if ~isempty(ME.Dynamic)
    p = mean(ME.Dynamic);
    if ~isempty(ME.DynDh)
      ME.Dh(ME.DynDh(1,:)) = p(ME.DynDh(2,:));
    end
    % Dynamic Volume
    if ~isempty(ME.DynVol)
      ME.vol(ME.DynVol(1,:)) = p(ME.DynVol(2,:));
    end
    % Dynamic Area
    if ~isempty(ME.Fc_DynArea)
      ME.Fc_Area(ME.Fc_DynArea(1,:)) = p(ME.Fc_DynArea(2,:));
    end
    % Dynamic Conductance
    if ~isempty(ME.Fc_DynCond)
      ME.Fc_Cond(ME.Fc_DynCond(1,:)) = p(ME.Fc_DynCond(2,:));
    end
    % Dynamic Distance
    if ~isempty(ME.Fc_DynDist)
      ME.Fc_Dist(ME.Fc_DynDist(1,:)) = p(ME.Fc_DynDist(2,:));
    end
    if ~isempty(ME.Fc_DynCond_Dist)
      ME.Fc_Cond_Dist(ME.Fc_DynCond_Dist(1,:)) = ...
        p(ME.Fc_DynCond_Dist(2,:));
    end
    % Dynamic dx for Courant Calculation
    if ~isempty(ME.Fc_Dyndx)
      ME.Fc_dx(ME.Fc_Dyndx(1,:)) = p(ME.Fc_Dyndx(2,:));
    end
  end
end

function Assign_Engine_Pressure(ME, P)
  for i = 1:length(ME.Regions)
    if ~ME.isEnvironmentRegion(i)
      Nds = ME.Regions{i};
      ME.m(Nds) = P*(ME.vol(Nds)./ME.T(Nds))./ME.R(i);
    else
      Nds = ME.Regions{i};
      ME.m(Nds) = ME.P(end)*(ME.vol(Nds)./ME.T(Nds))./ME.R(i);
    end
  end
end

function assignDynamic(ME,Inc,initialize)
  persistent A;
  persistent B;
  persistent C;
  persistent D;
  persistent DynLength;
  persistent IncBase;
  if nargin == 3
```

```
  if initialize == false
    if ~isempty(ME.Dynamic)
      % Define A,B,C,D for all variables
      DynLength = size(ME.Dynamic,1);
      IncBase = floor(Inc);
      if IncBase >= 2
        V0 = ME.Dynamic(IncBase - 1,:);
        V1 = ME.Dynamic(IncBase,:);
        if IncBase < DynLength - 1
          V2 = ME.Dynamic(IncBase+1,:);
          V3 = ME.Dynamic(IncBase+2,:);
        elseif IncBase < DynLength
          V2 = ME.Dynamic(IncBase+1,:);
          V3 = ME.Dynamic(2,:);
        else
          V2 = ME.Dynamic(2,:);
          V3 = ME.Dynamic(3,:);
        end
      else
        V2 = ME.Dynamic(IncBase+1,:);
        V3 = ME.Dynamic(IncBase+2,:);
        if IncBase >= 1
          V0 = ME.Dynamic(DynLength-1,:);
          V1 = ME.Dynamic(1,:);
        else
          V0 = ME.Dynamic(DynLength-2,:);
          V1 = ME.Dynamic(DynLength-1,:);
        end
      end
      dV1 = (V2 - V0) / (2 * ME.A_Inc / ME.dA_old);
      dV2 = (V3 - V1) / (2 * ME.A_Inc / ME.dA);
      A = ME.dt_max * (dV1 + dV2) - 2 * (V2 - V1);
      B = ME.dt_max * (-2*dV1 - dV2) + 3 * (V2 - V1);
      C = ME.dt_max * dV1;
      D = V1;
    end
  end
  return;
end
if ~isempty(ME.Dynamic)
  Inc_p = Inc-IncBase;
  if Inc_p > 1; frac = 1; else; frac = Inc_p; end
  point = A*frac^3 + B*frac^2 + C*frac + D;


  % Dynamic Velocity Factor
  if ~isempty(ME.Fc_DynVel_Factor)
    ME.Fc_Vel_Factor(ME.Fc_DynVel_Factor(1,:)) = ...
      point(ME.Fc_DynVel_Factor(2,:));
  end
  if ~isempty(ME.Fc_DynShear_Factor)
    ME.Fc_Shear_Factor(ME.Fc_DynShear_Factor(1,:)) = ...
      point(ME.Fc_DynShear_Factor(2,:));
  end

  point(point<0) = 0;
  % Dynamic Area
  if ~isempty(ME.Fc_DynArea)
    ME.Fc_Area(ME.Fc_DynArea(1,:)) = point(ME.Fc_DynArea(2,:));
  end
  % Dynamic Conductance
  if ~isempty(ME.Fc_DynCond)
    ME.Fc_Cond(ME.Fc_DynCond(1,:)) = point(ME.Fc_DynCond(2,:));
  end
  % Dynamic Fc_A
  if ~isempty(ME.Fc_DynA)
    ME.Fc_A(ME.Fc_DynA(1,:)) = point(ME.Fc_DynA(2,:));
  end
  % Dynamic Fc_B
  if ~isempty(ME.Fc_DynB)
    ME.Fc_B(ME.Fc_DynB(1,:)) = point(ME.Fc_DynB(2,:));
```

```
    end
    % Dynamic Fc_C
    if ~isempty(ME.Fc_DynC)
      ME.Fc_C(ME.Fc_DynC(1,:)) = point(ME.Fc_DynC(2,:));
    end
    % Dynamic Fc_D
    if ~isempty(ME.Fc_DynD)
      ME.Fc_D(ME.Fc_DynD(1,:)) = point(ME.Fc_DynD(2,:));
    end
    if any(isnan(ME.Fc_A)) || any(isnan(ME.Fc_B)) || ...
        any(isnan(ME.Fc_C)) || any(isnan(ME.Fc_D))
      fprintf('err');
    end

    point(point<1e-8) = 1e-8;
    % Dynamic Volume
    if ~isempty(ME.DynVol)
      ME.vol(ME.DynVol(1,:)) = point(ME.DynVol(2,:));
      ME.dV_dt(ME.DynVol(1,:)) = (1/ME.dt_max)*(...
          3*A(ME.DynVol(2,:))*frac^2 + ...
          2*B(ME.DynVol(2,:))*frac + ...
          C(ME.DynVol(2,:)));
    end
    % Dynamic Active Times for ShearContacts
    if ~isempty(ME.SC_Active)
      ME.Shear_Contact(6,ME.SC_Active(1,:)) = ...
        round(point(ME.SC_Active(2,:)));
    end
    % Dynamic K12
    if ~isempty(ME.Fc_DynK12)
      ME.Fc_K12(ME.Fc_DynK12(1,:)) = point(ME.Fc_DynK12(2,:));
    end
    if ~isempty(ME.Fc_DynK21)
      ME.Fc_K21(ME.Fc_DynK21(1,:)) = point(ME.Fc_DynK21(2,:));
    end

    point(point<1e-4) = 1e-4;
    % Dynamic Dh (node)
    if ~isempty(ME.DynDh)
      ME.Dh(ME.DynDh(1,:)) = point(ME.DynDh(2,:));
    end
    % Dynamic Dh (face)
    if ~isempty(ME.Fc_DynDh)
      ME.Fc_Dh(ME.Fc_DynDh(1,:)) = point(ME.Fc_DynDh(2,:));
    end
    % Dynamic Distance
    if ~isempty(ME.Fc_DynDist)
      ME.Fc_Dist(ME.Fc_DynDist(1,:)) = point(ME.Fc_DynDist(2,:));
    end
    if ~isempty(ME.Fc_DynCond_Dist)
      ME.Fc_Cond_Dist(ME.Fc_DynCond_Dist(1,:)) = ...
        point(ME.Fc_DynCond_Dist(2,:));
      if any(ME.Fc_Cond_Dist==0)
        ME.Fc_Cond_Dist(ME.Fc_Cond_Dist==0) = 0.0001;
      end
    end
    % Dynamic dx for Courant Calculation
    if ~isempty(ME.Fc_Dyndx)
      ME.Fc_dx(ME.Fc_Dyndx(1,:)) = point(ME.Fc_Dyndx(2,:));
    end
  end
end

function Forces = CalcForces(ME)
  % Distribute pressure losses

  fcs = 1:length(ME.Fc_U);
  nds = 1:length(ME.P);
  nd1 = ME.Fc_Nd(fcs,1);
  nd2 = ME.Fc_Nd(fcs,2);
  rhoi = ME.m(nds)./ME.vol(nds);
```

```
rhoi(end) = ME.rho(end);
Fcrho = 0.5*(rhoi(nd1) + rhoi(nd2));
for i = 1:length(ME.Regions)
  nodes = ME.Regions{i};
  if ~isempty(ME.ActiveRegionFcs{i})
    faces = ME.ActiveRegionFcs{i};
    % Calculate KpU_2A
    ME.Fc_U(faces) = ME.Fc_V(faces)./ME.Fc_Area(faces) - ...
      ME.Fc_Vel_Factor(faces)*ME.dA;
    ME.Fc_RE(faces) = ...
      abs(2*ME.Fc_U(faces).*Fcrho(faces).*ME.Fc_Dh(faces)./...
      (ME.mu(nd1(faces)) + ME.mu(nd2(faces))));
    ME.Fc_RE(ME.Fc_RE==0) = 1e-7;
    ME.getWeight();
    len = length(faces) + 1;
    A = ME.A_Press{i};
    b = zeros(len,1);
    A(len,:) = ME.vol(nodes);
    if ME.isEnvironmentRegion(i)
      b(len) = ME.P(end);
      A(len,len) = 1e8; % Some large value that is not infinity
    else
      b(len) = ME.R(i)*sum(ME.vol(nodes))*...
        ME.T(nodes(1)).*ME.m(nodes(1))./ME.vol(nodes(1));
    end
    ME.Fc_dP(faces) = ME.KValue(faces).*Fcrho(faces).*...
      abs(ME.Fc_U(faces)).*ME.Fc_U(faces);
    b(1:len-1) = ME.Fc_dP(faces);
    A = sparse(A);
    ME.P(nodes) = A\b;
    ME.dP(nodes) = ME.P(nodes) -  ME.R(i)*ME.T(nodes(1))*ME.m(nodes(1))/ME.vol(nodes(1));
  else
    if ~ME.isEnvironmentRegion(i)
      ME.P(nodes) = ...
        ME.R(i)*ME.T(nodes(1)).*ME.m(nodes(1))./ME.vol(nodes(1));
    end
    ME.dP(nodes) = 0;
  end

end
ME.E_Flow_Loss = ME.E_Flow_Loss + ...
      ME.dt_max * sum(abs(ME.Fc_V(fcs).*(ME.P(nd1)-ME.P(nd2))));

% Make forces
if ~isempty(ME.MechanicalSystem)
  Forces = cell(1,length(ME.MechanicalSystem.Converters));
else
  Forces = cell(0);
end
if ~isempty(Forces)
  for i = 1:length(Forces)
    Forces{i} = zeros(1,length(ME.MechanicalSystem.Converters(i).Stroke));
  end
  for i = 1:size(ME.Press_Contact,2)
    conv = ME.Press_Contact(1,i);
    subconv = ME.Press_Contact(2,i);
    area = ME.Press_Contact(3,i);
    index = ME.Press_Contact(4,i);
    Forces{conv}(subconv) = Forces{conv}(subconv) + area.*ME.P(index);
  end
  for i = 1:size(ME.Shear_Contact,2)
    if ME.Shear_Contact(6,i)
      conv = ME.Shear_Contact(1,i);
      subconv = ME.Shear_Contact(2,i);
      area = ME.Shear_Contact(3,i);
      ind1 = ME.Shear_Contact(4,i);
      ind2 = ME.Shear_Contact(5,i);
      Forces{conv}(subconv) = Forces{conv}(subconv) + ...
        area*(ME.P(ind1)-ME.P(ind2));
    end
  end
```

```
      end
    end

    function getWeight(ME,faces)
      if nargin == 1; faces = 1:length(ME.Fc_U); end
      W = zeros(length(faces),1);

      % Ignore turbulence transport
      ind = ~ME.useTurbulenceFc(faces);
      W(ind) = (ME.Fc_RE(faces(ind))-2300)/1700;
      W(W>1) = 1;
      W(W<0) = 0;
      W = W.*W.*(3 - 2*W);

      % Use turubulence transport
      ind = ~ind;
      W(ind) = ME.Fc_turb(faces(ind));
      W(W>1) = 1;
      W(W<0) = 0;
      ME.Fc_W(faces) = W;
    end

    function [K, derv] = KValue(ME,faces)
      K = zeros(length(faces),1);
      if nargout == 2
        derv = K;
      end
      for i = 1:length(faces)
        fc = faces(i);
        if ME.Fc_K12(fc) > 0
          if ME.Fc_V(fc) > 0
            K(i) = ME.Fc_K12(fc)/2;
          else
            K(i) = ME.Fc_K21(fc)/2;
          end
        else
          if ME.Fc_W(fc) == 0
              if nargout == 2
                K(i) = ME.Fc_fFunc_l{fc}(ME.Fc_RE(fc))*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2);
                derv(i) = (ME.Fc_fFunc_l{fc}(ME.Fc_RE(fc) + 1e-8)*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2)
- ...
                  K(i))/1e-8;
              else
                K(i) = ME.Fc_fFunc_l{fc}(ME.Fc_RE(fc))*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2);
              end
          elseif ME.Fc_W(fc) == 1
            K(i) = ME.Fc_fFunc_t{fc}(ME.Fc_RE(fc))*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2);
            derv(i) = (ME.Fc_fFunc_t{fc}(ME.Fc_RE(fc) + 1e-8)*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2) -
...
              K(i))/1e-8;
          else
            K(i) = ((1-ME.Fc_W(fc))*ME.Fc_fFunc_l{fc}(ME.Fc_RE(fc)) + ...
              ME.Fc_W(fc)*ME.Fc_fFunc_t{fc}(ME.Fc_RE(fc)))*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2);
            derv(i) = (((1-ME.Fc_W(fc))*ME.Fc_fFunc_l{fc}(ME.Fc_RE(fc) + 1e-8) + ...
              ME.Fc_W(fc)*ME.Fc_fFunc_t{fc}(ME.Fc_RE(fc) + 1e-8))*ME.Fc_Dist(fc)/(ME.Fc_Dh(fc)*2)
- ...
              K(i))/1e-8;
          end
        end
      end
    end

    function Nk = NkFunc(ME)
      Nk = zeros(size(ME.Fc_U));
      Nkt = Nk;
      % Laminar Functions
      for i = 1:length(ME.Fc_NkFunc_l)
        fcs = ME.Fc_NkFunc_l_el{i};
        if nargin(ME.Fc_NkFunc_l{i}) == 1
          Nk(fcs) = (1-ME.Fc_W(fcs)).*ME.Fc_NkFunc_l{i}(ME.Fc_RE(fcs));
        else
```

```
        Nk(fcs) = (1-ME.Fc_W(fcs)).*...
          ME.Fc_NkFunc_l{i}(ME.Fc_RE(fcs),ME.Fc_PR(fcs));
      end
    end
    % Turbulent Functions
    for i = 1:length(ME.Fc_NkFunc_t)
      fcs = ME.Fc_NkFunc_t_el{i};
      if nargin(ME.Fc_NkFunc_t{i}) == 1
        Nkt(fcs) = ME.Fc_W(fcs).*ME.Fc_NkFunc_t{i}(ME.Fc_RE(fcs));
      else
        Nkt(fcs) = ME.Fc_W(fcs).*...
          ME.Fc_NkFunc_t{i}(ME.Fc_RE(fcs),ME.Fc_PR(fcs));
      end
    end
    Nk = Nk + Nkt;
    Nk(Nk<1) = 1; % Nothing can be worse than pure conduction
  end

  function Nu = Nusselt(ME)
    Nu = zeros(length(ME.P)-1,1);
    Nut = Nu;
    ME.RE = abs(ME.RE);
    W = (ME.RE-2300)/1700;
    W(W<0) = 0; W(W>1) = 1;
    W = W.*(W.*(3 - 2*W) - 1);
    W(ME.useTurbulenceNd) = ME.turb(ME.useTurbulenceNd);
    W(W<0) = 0; W(W>1) = 1;
    % Laminar Functions
    for i = 1:length(ME.NuFunc_l)
      nds = ME.NuFunc_l_el{i};
      if nargin(ME.NuFunc_l{i}) == 1
        Nu(nds) = (1-W(nds)).*ME.NuFunc_l{i}(ME.RE(nds));
      else
        Nu(nds) = (1-W(nds)).*ME.NuFunc_l{i}(ME.RE(nds),ME.PR(nds));
      end
    end
    % Turbulent Function
    for i = 1:length(ME.NuFunc_t)
      nds = ME.NuFunc_t_el{i};
      if nargin(ME.NuFunc_t{i}) == 1
        Nut(nds) = W(nds).*ME.NuFunc_t{i}(ME.RE(nds));
      else
        Nut(nds) = W(nds).*ME.NuFunc_t{i}(ME.RE(nds),ME.PR(nds));
      end
    end
    Nu = Nu + Nut;
   % Nu(Nu<1) = 1;% Pure Conduction Nusselt Number
  end

 end

end
```

Result

The result is a class that includes the following functionality:

A function for animating colored node plots. Input properties are produced in the model.run function.

A function for animating velocity or pressure drop plots, centered on faces.

A function for capturing a snapshot.

```
classdef Result < handle
  %UNTITLED Summary of this class goes here
  %   Detailed explanation goes here

  properties
    % For Display
    Model Model;

    XDATA
    YDATA
    Cmap
    Data
    % Data.t
    % Data.T
    % Data.P
    % Data.rho
    % Data.U

    OriginalAxes;
    Fig;
    Axes;
    GraphicsObjects;
  end

  methods

    function this = Result()
    end

    % Plot
    function animateNode(this,propertyname,cornerpnts,bodypnts,frequency,~,~,input_title)
      %% Currently this is restricted to constructs lying on the vertical axis
      if isfield(this.Data,propertyname)
        data = this.Data.(propertyname);

        start = 1;
        % With Each column in data
        % Get coordinates

        h = figure();
        try
            set(h,'color','w');
            a = gca;
            axis tight manual;
            a.XLim = oldaxes.XLim;
            a.YLim = oldaxes.YLim;
            a.XAxis.TickLabelFormat = '%.2f';
            a.YAxis.TickLabelFormat = '%.2f';
            switch propertyname
              case 'T'; colorLabel = 'Temperature (K)';
              case 'P'; colorLabel = 'Pressure (Pa)';
              case 'dP'; colorLabel = 'Pressure Buildup (Pa)';
```

```
              case 'turb'; colorLabel = 'Proportion of Fully Turbulence (0-1)';
              case 'cond'
                colorLabel = 'Natural Logarithm of Sum of absolute Power Exchange per unit Volume
(ln(W/m^3))';
                data = log(data+1);
            end
            xlabel('X (m)');
            ylabel('Y (m)');
            timepnts = this.Data.t;

            if nargin > 7
              if ~isempty(this.Model.outputPath)
                filename = [this.Model.outputPath '\' input_title '_Animated ' propertyname
'.gif'];
              else
                filename = [input_title '_Animated ' propertyname '.gif'];
              end
            else
              if ~isempty(this.Model.outputPath)
                filename = [this.Model.outputPath '\' this.Model.name '_Animated ' propertyname
'.gif'];
              else
                filename = [this.Model.name '_Animated ' propertyname '.gif'];
              end
            end
            cmap = jet(100);
            colormap(cmap);
            data(data==0) = NaN();
            vals = linspace(min(min(data(start:end,:))),max(max(data(start:end,:))),7);
            mapper =
linspace(min(min(data(start:end,:))),max(max(data(start:end,:))),size(cmap,1));
            if vals(1) == vals(end)
              fprintf('ERR: minimum == maximum (in result.animateNode) \n');
              fprintf(['... Error occured with property: ' propertyname '\n']);
              try
                 close(h);
              catch
              end
              return;
            end
            if isnan(vals(1)) || isnan(vals(end))
              try
                close(h);
              catch
              end
              return;
            end
            caxis([vals(1) vals(end)]);

            if mapper(1) ~= mapper(2)
              data(isnan(data)) = 0;
              N_XData = zeros(4,size(data,1));
              N_YData = N_XData;
              B_XData = zeros(4,length(bodypnts));
              B_YData = B_XData;
              TextHandle = text(a.XLim(1)+0.01*(a.XLim(2)-a.XLim(1)),...
                a.YLim(2)-0.05*(a.YLim(2)-a.YLim(1)),'');
              hcb = colorbar('Ticks',vals,'Limits',[vals(1) vals(end)]);
              ylabel(hcb, colorLabel);
              yt=get(hcb,'Ticks');
              switch propertyname
                case 'T'
                  set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.1f'))));
                case 'P'
                  set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.2e'))));
                case 'turb'
                  set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.2f'))));
                case 'cond'
                  set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.2f'))));
                case 'dP'
                  set(hcb,'XTickLabel',strtrim(cellstr(num2str(yt','%.1e'))));
```

```
end
C = zeros(size(data,1),1);
%C = zeros(size(data,1),1,3);
for i = 1:size(data,2)-1
  angindex = 1+mod(i,Frame.NTheta-1);
  if i == 1
    proceed = true;
    FirstTime = true;
  else
    FirstTime = false;
    t = t + timepnts(i) - timepnts(i-1);
    if t > frequency
      proceed = true;
    else
      proceed = false;
    end
  end
  if proceed
    if true || ~any(data(:,i)==0) || strcmp(propertyname,'turb')
      t = 0;
      n = 1;
      if FirstTime
        for item = start:size(data,1)
          %C(n,1,:) = interp1(mapper,cmap,data(item,i));
          C(n) = data(item,i);
          switch cornerpnts{item}(1,1)
            case 1 % Static Position
              % Cut off the first column
              p = cornerpnts{item}(:,2:5);
              N_XData(:,n) = [p(1,4) - p(1,1); p(1,4) + p(1,2); ...
                              p(1,4) + p(1,1); p(1,4) - p(1,2)];
              N_YData(:,n) = [p(2,4) - p(2,1); p(2,4) + p(2,2); ...
                              p(2,4) + p(2,1); p(2,4) - p(2,2)];
              if all(p(:,3) == 0)
                % Origin Centered
                n = n + 1;
              else
                % Ring Shaped
                N_XData(:,n+1) = N_XData(:,n) + p(1,3);
                N_YData(:,n+1) = N_YData(:,n) + p(2,3);
                C(n+1) = C(n);
                n = n + 2;
              end
            case 2 % One Dimension Stretch
              % Cut off the first column
              temp = 4+angindex;
              p = [cornerpnts{item}(:,2:4) ...
                cornerpnts{item}(:,temp)];
              N_XData(:,n) = [p(1,1); ...
                              p(1,1) + p(1,2); ...
                              p(1,1) + p(1,2) + p(1,4); ...
                              p(1,1) + p(1,4)];
              N_YData(:,n) = [p(2,1); p(2,1) + p(2,2); ...
                              p(2,1) + p(2,2) + p(2,4); ...
                              p(2,1) + p(2,4)];
              if all(p(:,3) == 0)
                % Origin Centered
                n = n + 1;
              else
                % Ring Shaped
                N_XData(:,n+1) = N_XData(:,n) + p(1,3);
                N_YData(:,n+1) = N_YData(:,n) + p(2,3);
                C(n+1) = C(n);
                n = n + 2;
              end
            case 3 % Two Dimension Stretch
              temp = 2+angindex;
              p = [cornerpnts{item}(1:2,temp) ...
                cornerpnts{item}(1:2,2) ...
                cornerpnts{item}(3:4,2) ...
                cornerpnts{item}(3:4,temp)];
```

```
                    N_XData(:,n) = [p(1,1); p(1,1) + p(1,2); ...
                                    p(1,1) + p(1,2) + p(1,4); ...
                                    p(1,1) + p(1,4)];
                    N_YData(:,n) = [p(2,1); p(2,1) + p(2,2); ...
                                    p(2,1) + p(2,2) + p(2,4); ...
                                    p(2,1) + p(2,4)];
                    if all(p(:,3) == 0)
                      % Origin Centered
                      n = n + 1;
                    else
                      % Ring Shaped
                      N_XData(:,n+1) = N_XData(:,n) + p(1,3);
                      N_YData(:,n+1) = N_YData(:,n) + p(2,3);
                      C(n+1) = C(n);
                      n = n + 2;
                    end
                  case 4 % Translation
                    temp = 4+angindex;
                    p = [cornerpnts{item}(:,2:4) ...
                      cornerpnts{item}(:,temp)];
                    N_XData(:,n) = [p(1,4) - p(1,1); p(1,4) + p(1,2); ...
                                    p(1,4) + p(1,1); p(1,4) - p(1,2)];
                    N_YData(:,n) = [p(2,4) - p(2,1); p(2,4) + p(2,2); ...
                                    p(2,4) + p(2,1); p(2,4) - p(2,2)];
                    if all(p(:,3) == 0)
                      % Origin Centered
                      n = n + 1;
                    else
                      % Ring Shaped
                      N_XData(:,n+1) = N_XData(:,n) + p(1,3);
                      N_YData(:,n+1) = N_YData(:,n) + p(2,3);
                      C(n+1) = C(n);
                      n = n + 2;
                    end
                end
              end
              for b = 1:length(bodypnts)
                if ndims(bodypnts{b}) == 2 %#ok<ISMAT>
                  B_XData(:,b) = bodypnts{b}(1,:);
                  B_YData(:,b) = bodypnts{b}(2,:);
                else
                  B_XData(:,b) = bodypnts{b}(1,:,angindex);
                  B_YData(:,b) = bodypnts{b}(2,:,angindex);
                end
              end
              C(n+1:end) = [];
              %C(n+1:end,1,:) = zeros(0,1,3);
              N_XData(:,n+1:end) = zeros(4,0);
              N_YData(:,n+1:end) = zeros(4,0);
              PatchHandle = patch(N_XData,N_YData,real(C),'LineStyle','none');
              PatchHandleBodies =
patch(B_XData,B_YData,zeros(length(bodypnts),1),'EdgeColor','k',...
                'FaceColor','none','LineWidth',1);
            else
              for item = start:size(data,1)
                C(n) = data(item,i);
                switch cornerpnts{item}(1,1)
                  case 1 % Static Position
                    if all(cornerpnts{item}(:,4) == 0)
                      % Origin Centered
                      n = n + 1;
                    else
                      % Ring Shaped
                      C(n+1) = C(n);
                      n = n + 2;
                    end
                  case 2 % One Dimension Stretch
                    % Cut off the first column
                    temp = 5+mod(i,Frame.NTheta-1);
                    p = [cornerpnts{item}(:,2:4) ...
                      cornerpnts{item}(:,temp)];
```

```
        N_XData(3:4,n) = [p(1,1) + p(1,2) + p(1,4); ...
                          p(1,1) + p(1,4)];
        N_YData(3:4,n) = [p(2,1) + p(2,2) + p(2,4); ...
                          p(2,1) + p(2,4)];
        if all(p(:,3) == 0)
          % Origin Centered
          n = n + 1;
        else
          % Ring Shaped
          N_XData(:,n+1) = N_XData(:,n) + p(1,3);
          N_YData(:,n+1) = N_YData(:,n) + p(2,3);
          C(n+1) = C(n);
          n = n + 2;
        end
      case 3 % Two Dimension Stretch
        temp = 3+mod(i,Frame.NTheta-1);
        p = [cornerpnts{item}(1:2,temp) ...
          cornerpnts{item}(1:2,2) ...
          cornerpnts{item}(3:4,2) ...
          cornerpnts{item}(3:4,temp)];
        N_XData(:,n) = [p(1,1); p(1,1) + p(1,2); ...
                        p(1,1) + p(1,2) + p(1,4); ...
                        p(1,1) + p(1,4)];
        N_YData(:,n) = [p(2,1); p(2,1) + p(2,2); ...
                        p(2,1) + p(2,2) + p(2,4); ...
                        p(2,1) + p(2,4)];
        if all(p(:,3) == 0)
          % Origin Centered
          n = n + 1;
        else
          % Ring Shaped
          N_XData(:,n+1) = N_XData(:,n) + p(1,3);
          N_YData(:,n+1) = N_YData(:,n) + p(2,3);
          C(n+1) = C(n);
          n = n + 2;
        end
      case 4 % Translation
        temp = 5+mod(i,Frame.NTheta-1);
        p = [cornerpnts{item}(:,2:4) ...
          cornerpnts{item}(:,temp)];
        N_XData(:,n) = [p(1,4) - p(1,1); p(1,4) + p(1,2); ...
                        p(1,4) + p(1,1); p(1,4) - p(1,2)];
        N_YData(:,n) = [p(2,4) - p(2,1); p(2,4) + p(2,2); ...
                        p(2,4) + p(2,1); p(2,4) - p(2,2)];
        if all(p(:,3) == 0)
          % Origin Centered
          n = n + 1;
        else
          % Ring Shaped
          N_XData(:,n+1) = N_XData(:,n) + p(1,3);
          N_YData(:,n+1) = N_YData(:,n) + p(2,3);
          C(n+1) = C(n);
          n = n + 2;
        end
    end
  end
  for b = 1:length(bodypnts)
    if ndims(bodypnts{b}) == 2 %#ok<ISMAT>
      %B_XData(:,b) = bodypnts{b}(1,:);
      %B_YData(:,b) = bodypnts{b}(2,:);
    else
      temp = 1 + mod(i,Frame.NTheta-1);
      B_XData(:,b) = bodypnts{b}(1,:,temp);
      B_YData(:,b) = bodypnts{b}(2,:,temp);
    end
  end
end
set(PatchHandle,'XData',N_XData);
set(PatchHandle,'YData',N_YData);
set(PatchHandleBodies,'XData',B_XData);
set(PatchHandleBodies,'YData',B_YData);
```

```
                    set(PatchHandle,'CData',real(C));
                    set(TextHandle,'String',[num2str(round(timepnts(i),2)) ' seconds']);
                    drawnow;

                    % Capture the plot as an image
    %                 try
                      frame = getframe(h);
    %                 catch
    %                   return;
    %                 end
                    im = frame2im(frame);
                    [imind,cm] = rgb2ind(im,256);

                    % Write to the GIF File
                    try
                      if i == 1
                        imwrite(imind,cm,filename,'gif','Loopcount',inf,'DelayTime',0);
                      else
                        imwrite(imind,cm,filename,'gif','WriteMode','append','DelayTime',0);
                      end
                    catch
                      fprintf('XXX GIF write error XXX\n');
                      fprintf(['... propertyname = ' propertyname 'XXX\n']);
                    end
                  else
                    fprintf('XXX: Not ~any(data(:,i)==0) || strcmp(propertyname,"turb") in
Result.AnimateNode\n');
                    fprintf('... Error occured in the animation generation, where it is expected
that ... \n');
                    fprintf('... properties, other than Turbulence should not have a value of 0.
\n');
                    fprintf(['... propertyname = ' propertyname 'XXX\n']);
                    break;
                  end
                end
              end
            end
        catch
        end
        try
          close(h);
        catch
        end
      end
    end

    function animateFace(this,propertyname,cornerpnts,bodypnts,frequency,~,~,input_title)
      %% Currently this is restricted to constructs lying on the vertical axis
      if isfield(this.Data,propertyname)
        data = this.Data.(propertyname);
        start = 1;
        % With Each column in data
        % Get coordinates

        h = figure();
        try
            set(h,'color','w');
            a = gca;
            axis tight manual;
            a.XLim = oldaxes.XLim;
            a.YLim = oldaxes.YLim;
            xlabel('X (m)');
            ylabel('Y (m)');
            timepnts = this.Data.t;

            if nargin > 7
              if ~isempty(this.Model.outputPath)
                filename = [this.Model.outputPath '\' input_title '_Animated ' propertyname
'.gif'];
              else
                filename = [input_title '_Animated ' propertyname '.gif'];
```

```
            end
          else
            if ~isempty(this.Model.outputPath)
              filename = [this.Model.outputPath '\' this.Model.name '_Animated ' propertyname
'.gif'];
            else
              filename = [this.Model.name '_Animated ' propertyname '.gif'];
            end
          end
          minimum = 0;
          var = abs(data(start:end,:));
          maximum = prctile(var(:),100);
          %vals = linspace(min(min(data(start:end,:))),max(max(data(start:end,:))),7);
          %mapper =
linspace(min(min(data(start:end,:))),max(max(data(start:end,:))),size(cmap,1));
          if minimum == maximum
            fprintf('ERR: minimum == maximum (in result.animateFace) \n');
            fprintf(['... Error occured with property: ' propertyname '\n']);
            try
              close(h);
            catch
            end
            return;
          end

          data(isnan(data)) = 0;
          F_XData = zeros(1,size(data,1));
          F_YData = F_XData;
          F_UxData = F_XData;
          F_UyData = F_XData;
          B_XData = zeros(4,length(bodypnts));
          B_YData = B_XData;
          TextHandle = text(a.XLim(1)+0.01*(a.XLim(2)-a.XLim(1)),...
            a.YLim(2)-0.05*(a.YLim(2)-a.YLim(1)),'');
          hold on;
          switch propertyname
            case 'U'
              base_size = 0.1;
            case 'dP'
              base_size = 20;
          end
          for i = 1:size(data,2)-1
            angindex = 1+mod(i,Frame.NTheta-1);
            if i == 1; proceed = true; FirstTime = true;
            else
              FirstTime = false;
              t = t + timepnts(i) - timepnts(i-1);
              if t > frequency; proceed = true;
              else; proceed = false;
              end
            end
            if proceed
              t = 0;
              if FirstTime
                for item = start:size(data,1)
                  value = data(item,i)*base_size/maximum;
                  p = cornerpnts{item};
                  if size(p,2) < 3
                    % It is a static face
                    F_UxData(item) = p(1,1)*value;
                    F_UyData(item) = p(2,1)*value;
                    F_XData(item) = p(1,2);
                    F_YData(item) = p(2,2);
                  else
                    % It is a dynamic face
                    F_UxData(item) = p(1,1)*value;
                    F_UyData(item) = p(2,1)*value;
                    F_XData(item) = p(1,1+angindex);
                    F_YData(item) = p(2,1+angindex);
                  end
                end
```

```
  for b = 1:length(bodypnts)
    if ndims(bodypnts{b}) == 2 %#ok<ISMAT>
      B_XData(:,b) = bodypnts{b}(1,:);
      B_YData(:,b) = bodypnts{b}(2,:);
    else
      B_XData(:,b) = bodypnts{b}(1,:,angindex);
      B_YData(:,b) = bodypnts{b}(2,:,angindex);
    end
  end
  switch propertyname
    case 'U'
      QuiverHandle = quiver(...
        F_XData,F_YData,...
        F_UxData,F_UyData,...
        'Color','k');
    case 'dP'
      if exist('QuiverHandle','var')

      end
      for x = 1:length(F_XData)
        QuiverHandle(x) = plot(...
          F_XData(x),...
          F_YData(x),...
          'Marker','o',...
          'MarkerEdgeColor','b',...
          'MarkerFaceColor','b',...
          'MarkerSize',sqrt(F_UxData(x)^2 + F_UyData(x)^2)+1e-8,...
          'LineStyle','none');
      end
  end
  PatchHandleBodies = patch(...
    B_XData,B_YData,zeros(length(bodypnts),1),...
    'EdgeColor','k',...
    'FaceColor','none',...
    'LineWidth',1);
else
  for item = start:size(data,1)
    value = data(item,i)*base_size/maximum;
    p = cornerpnts{item};
    if size(p,2) < 3
      % It is a static face
      F_UxData(item) = p(1,1)*value;
      F_UyData(item) = p(2,1)*value;
    else
      % It is a dynamic face
      F_UxData(item) = p(1,1)*value;
      F_UyData(item) = p(2,1)*value;
      F_XData(item) = p(1,1+angindex);
      F_YData(item) = p(2,1+angindex);
    end
  end
  for b = 1:length(bodypnts)
    if ndims(bodypnts{b}) == 2 %#ok<ISMAT>
      %B_XData(:,b) = bodypnts{b}(1,:);
      %B_YData(:,b) = bodypnts{b}(2,:);
    else
      temp = 1 + mod(i,Frame.NTheta-1);
      B_XData(:,b) = bodypnts{b}(1,:,temp);
      B_YData(:,b) = bodypnts{b}(2,:,temp);
    end
  end
end
switch propertyname
  case 'U'
    set(QuiverHandle,'XData',F_XData);
    set(QuiverHandle,'YData',F_YData);
    set(QuiverHandle,'UData',F_UxData);
    set(QuiverHandle,'VData',F_UyData);
  case 'dP'
    for x = 1:length(F_XData)
      set(QuiverHandle(x),'XData',F_XData(x));
```

```
                    set(QuiverHandle(x),'YData',F_YData(x));
                    set(QuiverHandle(x),'MarkerSize',...
                      sqrt(F_UxData(x)^2 + F_UyData(x)^2)+1e-8);
                  end
                end
                set(PatchHandleBodies,'XData',B_XData);
                set(PatchHandleBodies,'YData',B_YData);
                set(TextHandle,'String',[num2str(round(timepnts(i),2)) ' seconds']);
                drawnow;

                % Capture the plot as an image
                try
                  frame = getframe(h);
                catch
                  fprintf('ERR: Failed to Get Frame in Result.AnimateFace \n')
                  fprintf(['... Error occured with property: ' ...
                    propertyname '\n']);
                  try
                    close(h);
                  catch
                  end
                  return;
                end
                im = frame2im(frame);
                [imind,cm] = rgb2ind(im,256);

                % Write to the GIF File
                try
                  if i == 1
                    imwrite(imind,cm,filename,'gif','Loopcount',inf,'DelayTime',0);
                  else
                    imwrite(imind,cm,filename,'gif','WriteMode','append','DelayTime',0);
                  end
                catch
                  fprintf('XXX GIF write error XXX\n');
                  fprintf(['... propertyname = ' propertyname 'XXX\n']);
                end
              end
            end
        catch
        end
        try
          close(h);
        catch
        end
      end
    end

    function Start2DPlot(this,property,t)
      if isempty(this.Axes)
        this.OriginalAxes = gca;
      else
        this.Close2DPlot();
      end
      this.Fig = figure();
      this.Axes = gca;
      this.GraphicsObjects(length(XData,1)) = patch();
      this.Cmap = colormap();
      differences = abs(this.Data.t - t);
      [value1, index1] = min(differences);
      [value2, index2] = min(differences ~= value1);
      if index1 < index2
        index2 = index2 + 1;
      end
      scalar = abs(value1/(value1-value2))*this.Data.(property)(index2,:) + abs(value2/(value1-
value2))*this.Data.(property)(index1,:);
      ulimit = max(scalar);
      llimit = min(scalar);
      mapper = linspace(llimit,ulimit,size(cmap,1));

      %% LOOP
```

```
  for i = 1:length(this.XDATA,1)
    rgb = interp1(mapper,cmap,scalar(i));
    this.GraphicsObjects(i) = fill(this.XDATA(i,:),this.YDATA(i,:),rgb);
  end
end

function Close2DPlot(this)
  % Delete the current figure
  close(this.Fig);
  delete(this.Fig);
  delete(this.Axes);
end

function getSnapShot(this,Model,name)
  if isempty(name); return; end
  if ~isfield(this.Data,'T'); return; end
  % Find Snapshot position
  N = Frame.NTheta-1;
  LEN = size(this.Data.T,2);
  if LEN == N
    ind = LEN;
  else
    if mod(LEN,N) == 0
      ind = LEN;
    else
      ind = LEN - mod(LEN,N) + 1;
    end
  end

  while all(this.Data.T(:,ind) == 0)
    ind = ind - 1;
    if ind == 0
      return;
    end
  end

  % Define number of cells
  n = 0;
  for iGroup = Model.Groups
    n = n + length(iGroup.Bodies);
  end
  BData(n) = BodyData();
  SnapShot = struct('Name',name,'Data',BData);
  index = 1;
  for iGroup = Model.Groups
    for iBody = iGroup.Bodies
      % Get a new ID for bodies without one
      if iBody.ID == 0; iBody.ID = Model.getBodyID(); end

      %% Create XData and YData vectors
      XData = zeros(length(iBody.Nodes),1);
      YData = XData;
      AltXData = XData;
      AltYData = YData;

      %% Get X & Y Data
      i = 1;
      Alti = 1;
      for k = 1:length(iBody.Nodes)
        Nd = iBody.Nodes(k);
        if isfield(Nd.data,'matl') && ...
            Nd.data.matl.Phase ~= iBody.matl.Phase
          AltXData(Alti) = (Nd.xmin + Nd.xmax)/2;
          Alti = Alti + 1;
        else
          XData(i) = (Nd.xmin + Nd.xmax)/2;
          i = i + 1;
        end
      end
      XData = unique(XData(1:i-1));
      AltXData = unique(AltXData(1:Alti-1));
```

```
i = 1;
Alti = 1;
for k = 1:length(iBody.Nodes)
  Nd = iBody.Nodes(k);
  if isfield(Nd.data,'matl') && ...
      Nd.data.matl.Phase ~= iBody.matl.Phase
    AltYData(Alti) = (Nd.ymin(1) + Nd.ymax(1))/2;
    Alti = Alti + 1;
  else
    YData(i) = (Nd.ymin(1) + Nd.ymax(1))/2;
    i = i + 1;
  end
end
YData = unique(YData(1:i-1));
AltYData = unique(AltYData(1:Alti-1));

%% Assign T array
TData = zeros(length(YData),length(XData));
AltTData = zeros(length(AltYData),length(AltXData));
if iBody.matl.Phase == enumMaterial.Gas
  TurbData = TData;
else
  TurbData = zeros(0,0);
end
PData = 0;
for k = 1:length(iBody.Nodes)
  Nd = iBody.Nodes(k);
  if isfield(Nd.data,'matl') && ...
      Nd.data.matl.Phase ~= iBody.matl.Phase
    i = find(AltYData == (Nd.ymin(1) + Nd.ymax(1))/2);
    j = find(AltXData == (Nd.xmin + Nd.xmax)/2);
    AltTData(i, j) = this.Data.T(Nd.index,ind);
  else
    i = find(YData == (Nd.ymin(1) + Nd.ymax(1))/2);
    j = find(XData == (Nd.xmin + Nd.xmax)/2);
    TData(i, j) = this.Data.T(Nd.index,ind);
    if ~isempty(TurbData) && isfield(this.Data,'turb')
      TurbData(i,j) = this.Data.turb(Nd.index,ind);
    end
    if iBody.matl.Phase == enumMaterial.Gas
      if isfield(this.Data,'SnapShot_P')
        PData = this.Data.SnapShot_P(Nd.index);
      end
    end
  end
end

if length(XData) > 1 && XData(1) > XData(2)
  XData = flip(XData); TData = flip(TData,2);
  TurbData = flip(TurbData,2);
end
if length(YData) > 1 && YData(1) > YData(2)
  YData = flip(YData); TData = flip(TData,1);
  TurbData = flip(TurbData,1);
end
if length(AltXData) > 1 && AltXData(1) > AltXData(2)
  AltXData = flip(AltXData); AltTData = flip(AltTData,2);
end
if length(AltYData) > 1 && AltYData(1) > AltYData(2)
  AltYData = flip(AltYData); AltTData = flip(AltTData,1);
end

%% Normalize positions
[~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
[y1,y2,~,~] = iBody.limits(enumOrient.Horizontal);
XData = (XData - x1)/(x2-x1);
YData = (YData - y1(1))/(y2(1)-y1(1));
AltXData = (AltXData - x1)/(x2-x1);
AltYData = (AltYData - y1(1))/(y2(1)-y1(1));

% Assign the Body
```

```
          SnapShot.Data(index) =
BodyData(iBody.ID,XData,YData,TData,PData,AltXData,AltYData,AltTData,TurbData);
          % End
          index = index + 1;
        end
      end
      this.Model.addSnapShot(SnapShot);
    end

  end

end
```

BodyData

Bodydata is a class that represents a single body inside of a snapshot. This class contains the following functionality:

A constructor.

A function for applying the data to the nodes of a body.

```
classdef BodyData < handle

  properties
    ID;
    XData;
    YData;
    TData;
    PData;
    AltXData;
    AltYData;
    AltTData;
    TurbData;
  end

  methods
    function this = BodyData(...
            iID,iXData,iYData,...
            iTData,iPData,...
            iAltXData,iAltYData,...
            iAltTData,iTurbData)
      if nargin > 0; this.ID = iID; end
      if nargin > 1; this.XData = iXData; end
      if nargin > 2; this.YData = iYData; end
      if nargin > 3; this.TData = iTData; end
      if nargin > 4; this.PData = iPData; end
      if nargin > 5; this.AltXData = iAltXData; end
      if nargin > 6; this.AltYData = iAltYData; end
      if nargin > 7; this.AltTData = iAltTData; end
      if nargin > 8; this.TurbData = iTurbData; end
  end

    function [success] = applyBody(this,iBody)
      success = false;
      if isempty(this.TData) && isempty(this.AltTData)
        return;
      else
        if iBody.ID == this.ID
          % It is a valid pair, Gas-Gas
          % ... Over all the nodes of the body
          if iBody.isDiscretized()
            % Process the stored data into a grid
            Xs = zeros(length(this.YData)+2,length(this.XData)+2);
            Ys = Xs;
            for r = 1:length(this.YData)+2; Xs(r,:) = [0; this.XData; 1]'; end
            for c = 1:length(this.XData)+2; Ys(:,c) = [0; this.YData; 1]; end
            PaddedT = CustExpandArray(this.TData);
            FT = griddedInterpolant(Xs',Ys',PaddedT','linear','linear');
            if ~isempty(this.TurbData)
                PaddedTurb = CustExpandArray(this.TurbData);
                FTurb = griddedInterpolant(...
                    Xs',Ys',PaddedTurb','linear','linear');
            end
            if ~isempty(this.AltXData)
                AltXs = zeros(...
                    length(this.AltYData)+2,length(this.AltXData)+2);
```

```
    AltYs = AltXs;
    for r = 1:length(this.AltYData)+2
        AltXs(r,:) = [0; this.AltXData; 1]';
    end
    for c = 1:length(this.AltXData)+2
        AltYs(:,c) = [0; this.AltYData; 1];
    end
    PaddedAltT = CustExpandArray(this.AltTData);
    FAltT = griddedInterpolant(...
        AltXs',AltYs',PaddedAltT','linear','linear');
end

success = true;
[~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
[y1,y2,~,~] = iBody.limits(enumOrient.Horizontal);
y1 = y1(1);
y2 = y2(1);
for Nd = iBody.Nodes
  % Consider what type of node it is
  assignAltTemp = false;
  assignTemp = false;
  assignTurb = false;
  if isfield(Nd.data,'matl')
    if strcmp(Nd.data.matl.name,'Constant Temperature') || ...
        strcmp(Nd.data.matl.name,'Perfect Insulator')
      assignTemp = false;
    elseif Nd.data.matl.Phase == iBody.matl.Phase
      assignTemp = true;
      if iBody.matl.Phase == enumMaterial.Gas
        if ~isempty(this.PData) && this.PData ~= 0
          Nd.data.P = this.PData;
        end
        assignTurb = ~isempty(this.TurbData);
      end
    else
      if isempty(this.AltTData)
        assignTemp = true;
      else
        assignAltTemp = true;
      end
    end
  else
    assignTemp = true;
    if iBody.matl.Phase == enumMaterial.Gas
      if ~isempty(this.PData) && this.PData ~= 0
        Nd.data.P = this.PData;
      end
      assignTurb = ~isempty(this.TurbData);
    end
  end
  cx = ((Nd.xmax + Nd.xmin)/2 - x1)/(x2-x1);
  cy = ((Nd.ymin(1) + Nd.ymax(1))/2 - y1)/(y2-y1);
  T = Nd.data.T;
  Turb = 0;
  if assignTemp && ~isempty(this.TData)
      T = FT(cx,cy);
      if assignTurb; Turb = FTurb(cx,cy); end
      %{
    if length(this.XData) == 1
      if length(this.YData) == 1
        % No interpolation
        T = this.TData(1,1);
        if assignTurb
          Turb = this.TurbData(1,1);
        end
      else
        % Linear Interpolation
        try
          T = interp1(this.YData,this.TData,cy,'pchip','extrap');
          if assignTurb
            Turb = interp1(this.YData,this.TurbData,cy,'pchip','extrap');
```

```
        end
      catch
        this.TData = [];
        this.TurbData = [];
        success = false;
        return;
      end
    end
  else
    if length(this.YData) == 1
      % Linear Interpolation
      try
        T = interp1(this.XData,this.TData,cx,'pchip','extrap');
        if assignTurb
          Turb = interp1(this.XData,this.TurbData,cx,'pchip','extrap');
        end
      catch
        this.TData = [];
        this.TurbData = [];
        success = false;
        return;
      end
    else
      % Double Linear Interpolation
      try
        T2 = interp1(this.YData,this.TData,cy,'pchip','extrap');
        T = interp1(this.XData,T2',cx,'pchip','extrap');
        if assignTurb
          Turb2 = interp1(this.YData,this.TurbData,cy,'pchip','extrap');
          Turb = interp1(this.XData,Turb2',cx,'pchip','extrap');
        end
      catch
        this.TData = [];
        this.TurbData = [];
        success = false;
        return;
      end
    end
  end
  %}
elseif assignAltTemp && ~isempty(this.AltTData)
    T = FAltT(cx,cy);
    %{
  if length(this.AltXData) == 1
    if length(this.AltYData) == 1
      % No interpolation
      T = this.AltTData(1,1);
    else
      % Linear Interpolation
      try
        T = interp1(this.AltYData,this.AltTData,cy,'pchip','extrap');
      catch
        this.AltTData = [];
        success = false;
        return;
      end
    end
  else
    if length(this.AltYData) == 1
      % Linear Interpolation
      try
        T = interp1(this.AltXData,this.AltTData,cx,'pchip','extrap');
      catch
        this.AltTData = [];
        success = false;
        return;
      end
    else
      % Double Linear Interpolation
      try
        T2 = interp1(this.AltYData,this.AltTData,cy,'pchip','extrap');
```

```
                    T = interp1(this.AltXData,T2',cx,'pchip','extrap');
                  catch
                    this.AltTData = [];
                    success = false;
                    return;
                  end
                end
              end
              %}
            end
            if ~isnan(T)
              Nd.data.T = T;
              if assignTurb
                  Nd.data.Turb = Turb;
              end
            else
              fprintf('err');
            end
          end
        end
      end
    end

  end

end

function [C] = Cubehelix(N)
%CUBEHELIX Returns the colormap corresponding to the cubehelix colormap by
% Dave Green
% Described in:
% ... Green, D. A., 2011, `A colour scheme for the display of astronomical
% ... intensity images', Bulletin of the Astronomical Society of India, 39,
% ... 289. (2011BASI...39..289G at ADS.)
% Chosen because it is readeable in both color and gray-scale. The
% following is a fit to the colormap for simplicity
C = zeros(N,3);
inc = linspace(0,1,N);
for i = 1:N
    C(i,1) = inc(i) + inc(i)*(1-inc(i))*(-0.89364167360231)*...
        sin(-9.42709701246915*inc(i)-2.17665661962626);
    C(i,2) = inc(i) + inc(i)*(1-inc(i))*0.476808544884337*...
        sin(9.41893653572546*inc(i)+4.92713139814227);
    C(i,3) = inc(i) + inc(i)*(1-inc(i))*0.986358536351536*...
        sin(-9.43408675851738*inc(i)+2.62243462096891);
end
C(C>1) = 1;
C(C<0) = 0;
end
```

G.7. ListObjs

List Object

ListObj represents objects in the property drop down. It is a class with the following functionality:

A constructor.

A function which is called when the entry in the listbox is clicked.

A function that gets the objects children, given its type.

A function that gets the string that is displayed in the listbox editor.

```
classdef ListObj < handle
    %LISTOBJ Summary of this class goes here
    %   Detailed explanation goes here

    properties
        MODE = '';
        lvl int8;
        isExpanded logical = false;
        Parent;
        Child; % Various
        Info; % Various
        Subs ListObj;
    end

    methods
        function this = ListObj(MODE,lvl,Parent,Child,info)
            if nargin > 0
                this.MODE = MODE;
                this.lvl = lvl;
                this.Parent = Parent;
                this.Child = Child;
                if nargin > 4
                    this.Info = info;
                end
            end
        end

        function on_click(this)
            switch this.MODE
                case 'Editstr'
                    % Bring up user form inputdlg
                    newvalue = get(this.Parent,this.Child);
                    if isempty(newvalue); newvalue = ''; end
                    newvalue = inputdlg(['Property: ' this.Child ': '],...
                        'Edit Properties',1,{newvalue});
                    if ~isempty(newvalue) && isa(newvalue{1},'char')
                        set(this.Parent,this.Child,newvalue{1});
                    end
                case 'Editnum'
                    % Bring up user form inputdlg
                    newvalue = inputdlg(['Edit the value of ' this.Child ' in ' this.Info],...
                        'Edit Properties',1,...
                        {num2str(get(this.Parent,this.Child))});
                    number = SymbolicMath(newvalue{1});
                    if isnan(number)
                        msgbox('Invalid formula: Ensure that your formula is complete and avoids
scientific notation.');
                    else
```

```
                        set(this.Parent,this.Child,number);
                    end
                case 'Editnumconvert'
                    % Bring up user form inputdlg
                    newvalue = (inputdlg(['Edit the value of ' this.Child ' in '
this.Info{2}],...
                        'Edit Properties',1,...
                        {num2str(round(get(this.Parent,this.Child)*this.Info{1})))));
                    number = SymbolicMath(newvalue{1});
                    if isnan(number)
                        msgbox('Invalid formula: Ensure that your formula is complete and avoids
scientific notation.');
                    else
                        set(this.Parent,this.Child,number/this.Info{1});
                    end
                case {'Expandobj', 'Expandlist'}
                    this.isExpanded = ~this.isExpanded;
                case 'Configureobj'
                    % the Parent has a child that has a parameter labeled 'Source'
                    % this source is used as an input into the child's constructor
                    % Bring up a user form
                    if ischar(this.Child)
                        Item = get(this.Parent,this.Child);
                        Item.Modify();
                    else
                        this.Child.Modify();
                    end
                case 'Pickobj'
                    % Info is a objarray
                    Item = get(this.Parent,this.Child);
                    objs = this.Info;
                    names = {'...'};
                    for index = length(objs):-1:1
                        names{index+1} = objs(index).name;
                    end
                    if ~isempty(Item)
                        for index = 1:length(objs)
                            if Item == objs(index)
                                break;
                            end
                        end
                    end
                    index = listdlg('ListString',names,...
                        'SelectionMode','single',...
                        'InitialValue',index); % ADD WIDTH, HEIGHT CONSTRAINTS
                    if index == 1
                        set(this.Parent,this.Child,[]);
                    else
                        set(this.Parent,this.Child,objs(index-1));
                    end
                case 'Pickfunction'
                    % Info is a folder name
                    % Bring up a user form listdlg from folder: Item
                    % Get index of current value
                    temp = get(this.Parent,this.Child);
                    if isempty(temp)
                        Item = '';
                    else
                        Item = func2str(temp);
                    end
                    files = dir(this.Info);
                    names = {files.name};
                    names = names{3:end}; % Remove the first couple
                    if ~iscell(names)
                        names = {names};
                    end
                    for index = size(names,1):-1:1
                        names{index} = names{index}(1:end-2);
                    end
                    for index = 1:length(names)
                        if strcmp(names{index},Item); break; end
```

```
                end
                index = listdlg('ListString',names,...
                    'SelectionMode','single',...
                    'InitialValue',index);
                if isempty(index)
                    set(this.Parent,this.Child,function_handle.empty);
                else
                    set(this.Parent,this.Child,str2func(names{index}));
                end
            case 'Function'
                functions(this.Parent,this.Child);
            case 'Deleteobj'
                this.Parent.deReference();
            case 'NamedList'
                names = get(this.Parent,this.Child);
                if ~isempty(names)
                    [indx, tf] = listdlg(...
                        'PromptString',['Select ' this.Child ' to Remove'],...
                        'ListString',names);
                    if tf
                        answers = false(length(names),1);
                        answers(indx) = true;
                        set(this.Parent,this.Child,answers);
                    end
                end
        end
    end

    function [objects] = getObjs(this,expanded)
        if ischar(this.Child)
            if ~strcmp(this.Child,'Deleteobj')
                Item = get(this.Parent,this.Child);
            end
            Text = this.Child;
        else
            Item = this.Child;
            Text = class(this.Child);
        end
        slvl = this.lvl+1;
        if nargin == 2
            switch this.MODE
                case 'Expandobj'
                    if isempty(Item)
                        objects = this;
                    else
                        switch class(Item)
                            case 'Model'
                                objects = [this; ...
                                    ListObj('Editstr',slvl,Item,'Name'); ...
                                    ListObj('Expandlist',slvl,Item,'Groups'); ...
                                    ListObj('Expandlist',slvl,Item,'Bridges'); ...
                                    ListObj('Expandlist',slvl,Item,'Leaks'); ...
                                    ListObj('Expandlist',slvl,Item,'Sensors'); ...
                                    ListObj('Expandlist',slvl,Item,'PVoutputs'); ...
                                    ListObj('NamedList',slvl,Item,'SnapShots'); ...
                                    ListObj('NamedList',slvl,Item,'NonConnections'); ...
                                    ListObj('NamedList',slvl,Item,'Custom Minor Losses'); ...
                                    ListObj('Expandlist',slvl,Item,'Lin. to Rot.
Mechanisms'); ...
                                    ListObj('Expandlist',slvl,Item,'Optimization Studies');
...
                                    ListObj('Expandobj',slvl,Item,'Initial Internal
Conditions'); ...
                                    ListObj('Expandobj',slvl,Item,'External Conditions'); ...
                                    ListObj('Editnum',slvl,Item,'Engine Temperature','K');
...
                                    ListObj('Editnum',slvl,Item,'Engine Pressure','Pa'); ...
                                    ListObj('Editnum',slvl,Item,'Minimum Speed','Hz'); ...
                                    ListObj('Expandobj',slvl,Item,'Mechanical System'); ...
                                    ListObj('Expandobj',slvl,Item,'Mesher'); ...
                                    ListObj('Editnum',slvl,Item,'Max Courant Final'); ...
```

```
                                        ListObj('Editnum',slvl,Item,'Max Fourier Final'); ...
                                        ListObj('Editnum',slvl,Item,'Max Courant Converging');
...
                                        ListObj('Editnum',slvl,Item,'Max Fourier Converging')];
                                case 'Group'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
                                        ListObj('Expandobj',slvl,Item,get(Item,'Position')); ...
                                        ListObj('Expandlist',slvl,Item,'Bodies'); ...
                                        ListObj('Expandlist',slvl,Item,'Connections'); ...
                                        ListObj('Expandlist',slvl,Item,'Relation Managers'); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'Body'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
                                        ListObj('Expandobj',slvl,Item,'Bottom Connection'); ...
                                        ListObj('Expandobj',slvl,Item,'Top Connection'); ...
                                        ListObj('Expandobj',slvl,Item,'Inner Connection'); ...
                                        ListObj('Expandobj',slvl,Item,'Outer Connection'); ...
                                        ListObj('Configureobj',slvl,Item,'Material'); ...
                                        ListObj('Editnum',slvl,Item,'Temperature'); ...
                                        ListObj('Editnum',slvl,Item,'Pressure'); ...
                                        ListObj('Editnum',slvl,Item,'Radial
Divides','divisions'); ...
                                        ListObj('Editnum',slvl,Item,'Axial Divides','divisions');
...

ListObj('Pickobj',slvl,Item,'RefFrame',Item.Group.Model.RefFrames); ...
                                        ListObj('Configureobj',slvl,Item,'Change Matrix');...
                                        ListObj('Expandobj',slvl,Item,'Expand Matrix');...
                                        ListObj('Pickfunction',slvl,Item,'Radial Discretization
Function','Function - Discretization'); ...
                                        ListObj('Pickfunction',slvl,Item,'Axial Discretization
Function','Function - Discretization'); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'Connection'
                                    objects = [this; ...
                                        ListObj('Editnum',slvl,Item,'x','m'); ...

ListObj('Pickobj',slvl,Item,'RefFrame',Item.Group.Model.RefFrames); ...
                                        ListObj('Expandlist',slvl,Item,'Bodies'); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete'); ...
                                        ListObj('Expandlist',slvl,Item,'Isolated Bodies'); ...
                                        ListObj('Function',slvl,Item,'Add Bodies To Not Join');
...
                                        ListObj('Function',slvl,Item,'Remove Bodies To Not
Join')];
                                case 'Bridge'
                                    objects = [this; ...
                                        ListObj('Expandobj',slvl,Item,'Connection 1'); ...
                                        ListObj('Expandobj',slvl,Item,'Connection 2'); ...
                                        ListObj('Expandobj',slvl,Item,'Body 1'); ...
                                        ListObj('Expandobj',slvl,Item,'Body 2'); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'LeakConnection'
                                    objects = [this; ...
                                        ListObj('Expandobj',slvl,Item,'Connection 1'); ...
                                        ListObj('Expandobj',slvl,Item,'Connection 2'); ...
                                        ListObj('Expandobj',slvl,Item,'Object 1'); ...
                                        ListObj('Expandobj',slvl,Item,'Object 2'); ...
                                        ListObj('Pickfunction',slvl,Item,'LeakFunc','Function -
Leakage'); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'Environment'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
                                        ListObj('Editnum',slvl,Item,'Pressure','Pa'); ...
                                        ListObj('Editnum',slvl,Item,'Temperature','K'); ...
                                        ListObj('Editnum',slvl,Item,'h','W/mK'); ...
                                        ListObj('Configureobj',slvl,Item,'Gas')];
                                case 'Position'
```

```
                                    objects = [this; ...
                                        ListObj('Editnum',slvl,Item,'x','m'); ...
                                        ListObj('Editnum',slvl,Item,'y','m'); ...
                                        ListObj('Editnumconvert',slvl,Item,'Theta',{180/pi;
'degrees'})];
                                case 'Matrix'
                                    objects = [this; ...
                                        ListObj('Configureobj',slvl,Item,'Material'); ...
                                        ListObj('Pickfunction',slvl,Item,'Laminar Friction
Function','Function - Laminar Friction'); ...
                                        ListObj('Pickfunction',slvl,Item,'Turbulent Friction
Function','Function - Turb Friction'); ...
                                        ListObj('Pickfunction',slvl,Item,'Laminar Nusselt
Function','Function - Laminar Nusselt'); ...
                                        ListObj('Pickfunction',slvl,Item,'Turbulent Nusselt
Function','Function - Turb Nusselt'); ...
                                        ListObj('Pickfunction',slvl,Item,'Laminar Streamwise
Cond. Enhancement','Function - Laminar Cond Enhancement'); ...
                                        ListObj('Pickfunction',slvl,Item,'Turbulent Streamwise
Cond. Enhancement','Function - Turb Cond Enhancement'); ...
                                        ListObj('Editnum',slvl,Item,'Source Temperature','K');
...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'Mesher'
                                    objects = [this; ...
                                        ListObj('Editnum',slvl,Item,'Nodes through Oscillation
Depth'); ...
                                        ListObj('Editnum',slvl,Item,'Maximum Node Thickness');
...
                                        ListObj('Editnum',slvl,Item,'Maximum Growth Rate'); ...
                                        ListObj('Editnum',slvl,Item,'Heat Exchanger Fin
Divisions'); ...
                                        ListObj('Editnum',slvl,Item,'Minimum Solid Time Step');
...
                                        ListObj('Editnum',slvl,Item,'Gas Entrance Exit N'); ...
                                        ListObj('Editnum',slvl,Item,'Gas Maximum Size'); ...
                                        ListObj('Editnum',slvl,Item,'Gas Minimum Size')];
                                case 'Sensor'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
                                        ListObj('Editnum',slvl,Item,'Samples'); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'PVoutput'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'name'); ...
                                        ListObj('Pickobj',slvl,Item,'Source
Body/Region',Item.Model.BodyList); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'MechanicalSystem'
                                    objects = [this; ...
                                        ListObj('Editnum',slvl,Item,'Flywheel Inertia'); ...
                                        ListObj('Editnum',slvl,Item,'Drive Train Weight'); ...
                                        ListObj('Editnum',slvl,Item,'Drive Train Normal Friction
Coefficient'); ...
                                        ListObj('Pickfunction',slvl,Item,'Load
Function','Function - Load Function')];
                                case 'RelationManager'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
                                        ListObj('Expandlist',slvl,Item,'Relations')];
                                case 'Relation'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
                                        ListObj('Expandobj',slvl,Item,'Connection1'); ...
                                        ListObj('Expandobj',slvl,Item,'Connection2'); ...

ListObj('Pickobj',slvl,Item,'Frame',Item.manager.Group.Model.RefFrames); ...
                                        ListObj('Deleteobj',slvl,Item,'[X] Delete')];
                                case 'OptimizationScheme'
                                    objects = [this; ...
                                        ListObj('Editstr',slvl,Item,'Name'); ...
```

```
                                    ListObj('NamedList',slvl,Item,'DOFs')];
                            end
                        end
                    case 'Expandlist'
                        objs = get(this.Parent,Text);
                        LEN = length(objs);
                        objects(LEN+1,1) = ListObj();
                        switch class(objs)
                            case {'LinRotMechanism', 'Material'}
                                % Modify rather than expand
                                for i = LEN:-1:1
                                    objects(i+1) = ListObj('Configureobj',slvl,Item,objs(i));
                                end
                            otherwise
                                for i = LEN:-1:1
                                    objects(i+1) = ListObj('Expandobj',slvl,Item,objs(i));
                                end
                        end
                        objects(1) = this;
                    otherwise
                        objects = this;
                end
            else % do not expand
                objects = this;
            end
        end

        function [output] = getString(this)
            starter = repmat('. . . ',1,this.lvl);
            if ischar(this.Child)
                if ~strcmp(this.Child,'[X] Delete') && ~strcmp(this.MODE,'Function')
                    Item = get(this.Parent,this.Child);
                end
                Text = this.Child;
            else
                Item = this.Child;
                Text = class(this.Child);
            end
            switch this.MODE
                case 'Editstr'
                    output = [starter Text ': [' Item ']'];
                case 'Editnum'
                    output = [starter Text ': [' num2str(Item) ' ' this.Info ']'];
                case 'Editnumconvert'
                    output = [starter Text ': [' num2str(Item*this.Info{1}) ' (' this.Info{2}
')]'];
                case 'Expandobj'
                    if isvalid(Item)
                        output = [starter Text ' (' class(Item) '): [' Item.name ']'];
                    else
                        output = [starter Text ' (' class(Item) '): [X Deleted Object]'];
                    end
                case 'Expandlist'
                    objs = get(this.Parent,Text);
                    if ~isempty(objs)
                        objs = objs(isvalid(objs));
                    end
                    if length(objs) < 1; output = [starter Text '[empty]'];
                    else; output = [starter Text '[...]'];
                    end
                case 'Configureobj'
                    output = [starter Text ': [' Item.name ']'];
                case 'Pickobj'
                    % info is the list of frames
                    output = [starter class(Item) ': ' Item.name];
                case 'Pickfunction'
                    if isempty(Item)
                        output = [starter Text ': [...]'];
                    else
                        output = [starter Text ': [@' func2str(Item) ']'];
                    end
```

```
                case 'Function'
                    output = [starter Text];
                case 'Deleteobj'
                    output = [starter Text];
                case 'NamedList'
                    if isempty(Item); output = [starter Text '[empty]'];
                    else; output = [starter Text '[...]'];
                    end
            end
        end

        function [indicator] = isExpandable(this)
            switch this.MODE
                case {'Expandobj', 'Expandlist'}
                    indicator = true;
                otherwise
                    indicator = false;
            end
        end
    end

end
```

Make Code

This function makes a string code that stores the state of what is displayed on the property listbox. This was introduced so that the structure could be recreated after edits.

```
function [ Code ] = MakeCode( ListObjs, ClickedIndex)
Code = '';
lvl = 0;
n = ones(1,16); % Current Index on Level
i = 1;
while i <= length(ListObjs)
  % Handle Step downs and step ups
  if ListObjs(i).lvl > lvl
    % Step Down
    % ... Parent        n(lvl+1)
    % ... ... Child     n(lvl+2) = 1
    if isempty(Code); Code = [num2str(int8(n(lvl+1)-1)) '['];
    elseif Code(end) == '['; Code = [Code num2str(int8(n(lvl+1)-1)) '['];
    else; Code = [Code ',' num2str(int8(n(lvl+1)-1)) '['];
    end
    lvl = lvl + 1;
    % Iterate the "Child" node
    n(lvl+1) = 2;
  elseif ListObjs(i).lvl < lvl
    % Step Up
    % ... ... Child    n(lvl)
    % ... Next-Parent  n(lvl+1)
    while lvl > ListObjs(i).lvl
      Code = [Code ']'];
      n(lvl+1) = 1;
      lvl = lvl - 1;
    end
    % Iterate the "Next-Parent" node
    n(lvl+1) = n(lvl+1) + 1;
  else
    % Iterate the node
    n(lvl+1) = n(lvl+1) + 1;
  end

  % Handle the click
  if nargin == 2 && ClickedIndex == i
    if ListObjs(i).isExpandable()
      if i < length(ListObjs)
        if ListObjs(i+1).lvl > ListObjs(i).lvl
          % This one is already expanded, collapse
          i = i + 1;
          while i <= length(ListObjs) && ListObjs(i).lvl > lvl
            i = i + 1;
          end
          % Iterate the level forward, we are skipping to another node
          n(lvl+1) = n(lvl+1) + 1;
        else
          % This one should be expanded
          if isempty(Code); Code = num2str(int8(n(lvl+1)-1));
          elseif Code(end) == '['; Code = [Code num2str(int8(n(lvl+1)-1))];
          else; Code = [Code ',' num2str(int8(n(lvl+1)-1))];
          end
        end
      else
        % This one should be expanded
        if isempty(Code); Code = num2str(int8(n(lvl+1)-1));
        elseif Code(end) == '['; Code = [Code num2str(int8(n(lvl+1)-1))];
        else; Code = [Code ',' num2str(int8(n(lvl+1)-1))];
        end
      end
    end
```

```
  end
  i = i + 1;
end
while lvl > 0
  Code = [Code ']'];
  lvl = lvl - 1;
end
Code = strrep(Code,'[]','');
if ~isempty(Code) && Code(end) == '['
  Code(end) = '';
end
end
```

Read Code

This reads the code an produces the active list that is displayed on the property lisbox.

```
function [ newListObjs ] = ReadCode( Code, ListObjs )
i = 1;
num = 0;
newListObjs = ListObj.empty;
close = false;
while i <= length(Code)
  k = i+1;
  while k <= length(Code) ...
      && Code(k) ~= '[' ...
      && Code(k) ~= ']' ...
      && Code(k) ~= ','
    k = k + 1;
  end
  onum = num;
  num = int16(str2double(Code(i:k-1)));
  if num ~= onum + 1
    if length(ListObjs) >= num-1
      newListObjs = [newListObjs; ListObjs(onum+1:num-1)];
    else
      return;
    end
  end
  if num > length(ListObjs) || num < 1
    return;
  end
  Internals = ListObjs(num).getObjs(true);
  newListObjs = [newListObjs; Internals(1)];
  if length(Internals) > 1
    if k <= length(Code)
      switch Code(k)
        case '['
          % Enter Recursion on Contents with contents of element "num"
          i = k + 1;
          lvlcount = -1;
          while i <= length(Code) && lvlcount < 0
            switch Code(i)
              case '['; lvlcount = lvlcount - 1;
              case ']'; lvlcount = lvlcount + 1;
            end
            i = i + 1;
          end
          if i < length(Code)
            if Code(i) == ','
              i = i + 1;
              newCode = Code(k+1:i-3);
            else
              newCode = Code(k+1:i-2);
            end
          else
            newCode = Code(k+1:i-2);
          end
          newListObjs = [newListObjs; ReadCode(newCode,Internals(2:end))];
        case ']'
          % End of Recursion Layer
          newListObjs = [newListObjs; Internals(2:end)];
          return;
        case ','
          % New expansion, add elements between expanded elements
          newListObjs = [newListObjs; Internals(2:end)];
      end
    else
      newListObjs = [newListObjs; Internals(2:end)];
    end
```

```
  end
  i = max(i,k);
end
if num < length(ListObjs)
  newListObjs = [newListObjs; ListObjs(num+1:end)];
end
end
```

Reset Code

This resets the code to be just the default entry (model).

```
function [Code] = ResetCode(Code)
if ~isempty(Code)
  if Code(1) == '1'
    % Model may maintain its expansion
    if length(Code) > 1
      if Code(2) == '['
        i = 3; lvlcount = -1;
        while i < length(Code) && lvlcount < 0
          switch Code(i)
            case '['; lvlcount = lvlcount - 1;
            case ']'; lvlcount = lvlcount + 1;
          end
          i = i + 1;
        end
        if length(Code) > i; Code(i+1:end) = ''; end
      end
    end
  else
    % Everything else is presumed to have changed
    Code = '';
  end
end
end
```

Selection List Data

Simple class that stores the list-objects and state code of the property list-box.

```
classdef SelectionListData < handle

  properties
    ListObjs;
    Code;
  end

end
```

G.8. Geometry

Line 1D

Line 1D is a class whose purpose is to represent a group of 1D line segments. This line segment can lie upon any axis, provided that a distance along the axis can be measured. Line 1D contains the following functionality:

A constructor.

A function (**DestroyInterscept**) that finds and destroys the intercept between two line 1D objects (which is acted upon in both participating objects). This may split one of the objects resulting in the addition of an other row to the bounds matrix.

A second function (**Subtract**) that removes the area covered by the second input line1D from the current object.

A third function (**MergeAndAppend**) adds the another line1D object to the current object.

The last function (**CreateLine2Ds**) creates a series of line2D given an orientation and extra position. (assuming axial or radial directions)

```
classdef Line1D < handle
  %Line1D Summary of this class goes here
  %   Detailed explanation goes here

  properties
    bounds;
  end

  methods
    function this = Line1D(lb,ub)
      if nargin == 2
        this.bounds(1,1) = lb;
        this.bounds(1,2) = ub;
      end
    end

    function DestroyInterscept(this,other)
      n1 = 1; n2 = 1;
      s1 = 1; s2 = 1;
      notdone = true;
      while notdone

        notdone = false;

        for thisrow = s1:size(this.bounds,1)
          lb1 = this.bounds(thisrow,1);
          ub1 = this.bounds(thisrow,2);
          for otherrow = s2:size(other.bounds,1)
            lb2 = other.bounds(otherrow,1);
            ub2 = other.bounds(otherrow,2);
            if lb1 < lb2
```

```
      if ub1 > ub2% && lb1 < lb2
        % Split this, delete other
        other.bounds(otherrow,1:2) = inf;
        extra1(n1,1) = ub2;
        extra1(n1,2) = this.bounds(thisrow,2);
        this.bounds(thisrow,2) = lb2;
        n1 = n1 + 1;
      elseif ub1 < ub2% && lb1 < lb2
        % this ------       ->  ----xx
        % other    ------   ->      xx----
        % Chop
        this.bounds(thisrow,2) = lb2;
        other.bounds(otherrow,1) = ub1;
      else % ub1 == ub2 && lb1 < lb2
        % chop this, delete other
        other.bounds(otherrow,1:2) = inf;
        this.bounds(thisrow,2) = lb2;
      end
    elseif lb1 > lb2
      if ub1 > ub2% && lb1 > lb2
        % this     ------   ->      xx----
        % other------       ->  ----xx
        % Chop
        this.bounds(thisrow,1) = ub2;
        other.bounds(otherrow,2) = lb1;
      elseif ub1 < ub2% && lb1 > lb2
        % Split other, delete this
        this.bounds(thisrow,1:2) = inf;
        extra2(n2,1) = ub1;
        extra2(n2,2) = other.bounds(otherrow,2);
        other.bounds(otherrow,2) = lb1;
        n2 = n2 + 1;
      else % ub1 == ub2 && lb1 > lb2
        % chop other, delete this
        this.bounds(thisrow,1:2) = inf;
        other.bounds(otherrow,2) = lb1;
      end
    else % lb1 == lb2
      if ub1 > ub2 % && lb1 == lb2
        % Chop this, delete other
        this.bounds(thisrow,1) = ub2;
        other.bounds(otherrow,1:2) = inf;
      elseif ub1 < ub2 % && lb1 == lb2
        % Chop other, delete this
        this.bounds(thisrow,1:2) = inf;
        other.bounds(otherrow,1) = ub1;
      else % ub1 == ub2 && lb1 == lb2
        % delete other, delete this
        this.bounds(thisrow,1:2) = inf;
        other.bounds(otherrow,1:2) = inf;
      end
    end
  end
end

% Clean up both
r = 1:size(this.bounds,1);
this.bounds(isinf(this.bounds(r,1)),:) = [];
r = 1:size(other.bounds,1);
other.bounds(isinf(other.bounds(r,1)),:) = [];

if ~(size(this.bounds,1) == 0 || size(other.bounds,1) == 0)
  if n1 > 1
    s1 = size(this.bounds,1)+1;
    s2 = 1;
    this.bounds = [this.bounds; extra1];
    notdone = true;
  end
```

```
      if ~notdone && n2 > 1
        s1 = 1;
        s2 = size(other.bounds,1)+1;
        other.bounds = [other.bounds; extra2];
        notdone = true;
      end
    end

  end

end

function Subtract(this,other)
  n1 = 1;
  s1 = 1;
  notdone = true;
  while notdone

    notdone = false;

    for thisrow = s1:size(this.bounds,1)
      lb1 = this.bounds(thisrow,1);
      ub1 = this.bounds(thisrow,2);
      for otherrow = 1:size(other.bounds,1)
        lb2 = other.bounds(otherrow,1);
        ub2 = other.bounds(otherrow,2);
        if ~(lb1 > ub2 || lb2 > ub1)
          if lb1 < lb2
            if ub1 > ub2% && lb1 < lb2
              % Split this, delete other
              extra1(n1,1) = ub2;
              extra1(n1,2) = this.bounds(thisrow,2);
              this.bounds(thisrow,2) = lb2;
              n1 = n1 + 1;
            elseif ub1 < ub2% && lb1 < lb2
              % this ------       ->  ----xx
              % other    ------   ->      xx----
              % Chop
              this.bounds(thisrow,2) = lb2;
            else % ub1 == ub2 && lb1 < lb2
              % chop this, delete other
              this.bounds(thisrow,2) = lb2;
            end
          elseif lb1 > lb2
            if ub1 > ub2% && lb1 > lb2
              % this     ------   ->      xx----
              % other------       ->  ----xx
              % Chop
              this.bounds(thisrow,1) = ub2;
            elseif ub1 < ub2% && lb1 > lb2
              % Split other, delete this
              this.bounds(thisrow,1:2) = inf;
            else % ub1 == ub2 && lb1 > lb2
              % chop other, delete this
              this.bounds(thisrow,1:2) = inf;
            end
          else % lb1 == lb2
            if ub1 > ub2 % && lb1 == lb2
              % Chop this, delete other
              this.bounds(thisrow,1) = ub2;
            elseif ub1 < ub2 % && lb1 == lb2
              % Chop other, delete this
              this.bounds(thisrow,1:2) = inf;
            else % ub1 == ub2 && lb1 == lb2
              % delete other, delete this
              this.bounds(thisrow,1:2) = inf;
            end
          end
```

```
        end
      end
    end

    % Clean up both
    r = 1:size(this.bounds,1);
    this.bounds(isinf(this.bounds(r,1)),:) = [];

    if ~(size(this.bounds,1) == 0)
      if n1 > 1
        this.bounds = [this.bounds; extra1];
      end
    end

  end
end

function MergeAndAppend(this,other)
  removeThis = false(1,length(this.bounds,1));
  removeOther = false(1,length(other.bounds,1));
  % See if the endpoints match up, then merge, it is assumed that the
  % lines have been subjected to DestroyInterscepts already
  % ... Add the merged lines to "this"
  for i = 1:length(this.bounds,1)
    for j = 1:length(other.bounds,1)
      if ~removeOther(j)
        if this.bounds(i,1) == other.bounds(j,2)
          this.bounds(i,1) = other.bounds(j,1);
          removeOther(j) = true;
          i = i - 1; %#ok<FXSET>
        elseif this.bounds(i,2) == other.bounds(j,1)
          this.bounds(i,2) = other.bounds(j,2);
          removeOther(j) = true;
          i = i - 1; %#ok<FXSET>
        end
      end
    end
  end
  % See if the modified entries of "this" can be merged
  for i = 1:length(this.bounds,1)-1
    if ~removeThis(i)
      for j = i+1:length(this.bounds,1)
        if ~removeThis(j)
          if this.bounds(i,1) == this.bounds(j,2)
            this.bounds(i,1) = this.bounds(j,1);
            removeThis(j) = true;
            i = i - 1; %#ok<FXSET>
          elseif this.bounds(i,2) == this.bounds(j,1)
            this.bounds(i,2) = this.bounds(j,2);
            removeThis(j) = true;
            i = i - 1; %#ok<FXSET>
          end
        end
      end
    end
  end
  % Remove entries
  this.bounds(removeOther,:) = [];
  this.bounds = [this.bounds; other.bounds];
end

function Line2DOutput = CreateLine2Ds(this,Orient,x)
  Line2DOutput(1,length(this.bounds,1)) = Line2DChain();
  if Orient == enumOrient.Vertical
    for i = 1:length(this.bounds,1)
      Line2DOutput(i) = ...
        Line2DChain(x,this.bounds(i,1),x,this.bounds(i,2));
    end
```

```
      else
        for i = 1:length(this.bounds,1)
          Line2DOutput(i) = ...
            Line2DChain(this.bounds(i,1),x,this.bounds(i,2),x);
        end
      end
    end
  end

end
```

Line 2D Chain

Line 2D chain is a class that represents a set of connected points in 2D space. It contains the following functionality:

A constructor.

A function (**attemptToMerge**), which tries to link up the beginning and end points of two line 2D chains, returning if the merging was successful. This is used by the solid-environment boundary detection algorithm.

A function (**get.isFinished**) which checks if both the start and end points are on the middle axis, or if they are equal to each other. If so then nothing can be added to the loop.

A series of functions that retrieve particular defining points from the arrays. (such as the ends or an extracted series of x or y data from the point lists).

```
classdef Line2DChain < handle
  %LINECHAIN Summary of this class goes here
  %   Detailed explanation goes here

  properties
    Pnts Pnt2D = Pnt2D.empty;
  end

  properties (Dependent)
    XData double;
    YData double;
    Start Pnt2D;
    End Pnt2D;
    isFinished logical;
  end

  methods
    function this = Line2DChain(x1,y1,x2,y2)
      if nargin > 0
        this.Pnts = [Pnt2D(x1,y1) Pnt2D(x2,y2)];
      end
    end
    function successful = attemptToMerge(this,other)
      successful = false;
      if this.Pnts(end) == other.Pnts(1)
        this.Pnts = [this.Pnts other.Pnts(2:end)]; successful = true;
      elseif this.Pnts(end) == other.Pnts(end)
        this.Pnts = [this.Pnts other.Pnts(end-1:-1:1)]; successful = true;
      elseif this.Pnts(1) == other.Pnts(end)
        this.Pnts = [other.Pnts this.Pnts(2:end)]; successful = true;
      elseif this.Pnts(1) == other.Pnts(1)
        this.Pnts = [other.Pnts(end:-1:2) this.Pnts]; successful = true;
      end
    end
    function isFinished = get.isFinished(this)
      isFinished = (this.Pnts(1).x == 0 && this.Pnts(end).x == 0) || ...
        (this.Pnts(1) == this.Pnts(end));
    end
    function Start = get.Start(this)
```

```
      Start = this.Pnts(1);
    end
    function End = get.End(this)
      End = this.Pnts(end);
    end
    function XData = get.XData(this)
      XData = zeros(1,length(this.Pnts));
      for i = 1:length(this.Pnts)
        XData(i) = this.Pnts(i).x;
      end
    end
    function YData = get.YData(this)
      YData = zeros(1,length(this.Pnts));
      for i = 1:length(this.Pnts)
        YData(i) = this.Pnts(i).y;
      end
    end
  end
end
```

Loop Node

Loop Node is a class that serves to facilitate the finding of loops in the gas network. It contains the following functionality:

A constructor.

A recursive function (**get.lvl**) used to determine the length of a chain of loopNodes.

```
classdef LoopNode
  %LOOPNODE Summary of this class goes here
  %   Detailed explanation goes here

  properties
    parent LoopNode;
    parentFc Face;
    Nd Node;
  end

  properties (Dependent)
    lvl int8;
  end

  methods
    function this = LoopNode(iparent, iparentFc, iNd)
      if nargin == 1
        this.Nd = iparent;
      elseif nargin == 3
        this.parent = iparent;
        this.parentFc = iparentFc;
        this.Nd = iNd;
      end
    end

    function lvl = get.lvl(this)
      if ~isempty(this.parent)
        lvl = this.parent.lvl + 1;
      else
        lvl = 1;
      end
    end
  end

end
```

Pnt 2D

Pnt2D is a class that is the basic x, y data structure of most of the geometry functions. It contains additional functionality:

Constructor.

A **rotate** function which takes a rotation matrix and updates its positions.

A **shift** function that adds a length 2 position vector to the x, y position.

```
classdef Pnt2D < handle
  %PNT2D Summary of this class goes here
  %   Detailed explanation goes here

  properties
    x double;
    y double;
  end

  methods
    function this = Pnt2D(x,y)
      if nargin == 0
        return;
      end
      this.x = x;
      this.y = y;
    end

    function isequal = eq(Pnt1,Pnt2)
      isequal = (Pnt1.x == Pnt2.x && Pnt1.y == Pnt2.y);
    end

    function rotate(this, RotationMatrix)
      newx = RotationMatrix(1,1)*this.x + RotationMatrix(1,2)*this.y;
      this.y = RotationMatrix(2,1)*this.x + RotationMatrix(2,2)*this.y;
      this.x = newx;
    end

    function shift(this, PositionVector)
      this.x = PositionVector(1) + this.x;
      this.y = PositionVector(2) + this.y;
    end
  end
end
```

G.1. Enum

Enumeration of Face Types

```
classdef enumFType
   enumeration
      Mix,...
      Gas,...
      Leak,...
      Solid,...
      Environment,...
      MatrixTransition
   end
end
```

Enumeration of Types of Materials (Phase)

```
classdef enumMaterial
   enumeration
      Gas, Solid, Liquid
   end
end
```

Enumeration of Types of Matrix

```
classdef enumMatrix
  enumeration
    WovenScreen,
    RandomFiber,
    PackedSphere,
    StackedFoil,
    HeatExchanger
  end
end
```

Enumeration of Movement States

```
classdef enumMove
  enumeration
    Moving, Static, Stretching
  end
end
```

Enumeration of Node Types

```
classdef enumNType
```

```
   enumeration
      SVGN,...  Static Volume Gas Node
      VVGN,...Variable Volume Gas Node
      SAGN,...Shearing Annular Gas Node
      SN,...Solid Node
      EN %    Environment Node
   end
end
```

Enumeration of Orientations

```
classdef enumOrient
   enumeration
      Vertical, Horizontal
   end
end
```

Enumeration of Shapes

```
classdef enumShape
   enumeration
      Cylinder, Annulus, Cuboid
   end
end
```

G.2. Startup

This function automatically runs whenever this project is opened in MATLAB, due to being named “startup”.

```
function startup()
  addpath(...
    'enum',...
    'Helper Function',...
    'Saved Files',...
    'Geometry',...
    'MinorElements',...
    'MajorElements',...
    'Mechanical',...
    'Mechanical/Mechanical Helper',...
    'Function - Turb Nusselt',...
    'Function - Turb Friction',...
    'Function - Turb Cond Enhancement',...
    'Function - Leakage',...
    'Function - Laminar Nusselt',...
    'Function - Laminar Friction',...
    'Function - Laminar Cond Enhancement',...
    'Function - Discretization',...
    'Function - Load Function',...
    'GUI',...
    'Simulation',...
    'ListObjs',...
    'Motion',...
    'Test_Running',...
    'Relations',...
    'Optimization',...
    'Output Helpers'...
    );

  % mex anyEq.c -largeArrayDims;
end
```

G.1. Helper Function

Add Row:

adds a number (N) rows to a 2D cell matrix

```
function Output = AddRow(Input,N)
  Output = Input;
  for i = size(Output,1)+1:N+size(Output,1)
    for j = 1:size(Output,2)
      Output{i,j} = '';
    end
  end
end
```

Annular Conduction:

Determines the conductance from the center of a node to a radius “r” given the node is made up of a material “matl” and the interaction is over a length of “L”.

```
function [ U ] = AnnularConduction(Node,r,L,matl)
  if Node.xmin ~= 0
    mid_r = sqrt(Node.xmin*Node.xmax);
    if mid_r < r
      U = (2*pi*matl.ThermalConductivity/log(r/mid_r)).*L;
    else
      U = ((2*pi*matl.ThermalConductivity)/log(mid_r/r)).*L;
    end
  else
    % The Constant comes from 1/log(1/0.570524), which is the center
    % ... Non-dimensional radius of: Resistance*Area of a cylinder.
    U = 2*pi*matl.ThermalConductivity*1.781896.*L;
  end
end
```

Arcsin:

Modifies the regular discontinuous ouput of the asin function to be continues over a given array of sequential values.

```
function [output] = asin_omni(input)
intermittent = zeros(size(input));
for i = 1:length(input)
  intermittent(i) = asin(input(i));
end
count = 0;
output = zeros(size(input));
i = 2;
output(1) = intermittent(1);
d = diff(intermittent);
while i < length(input)+1 && count < 100
  while i < length(input)+1 && d(i-1) >= 0
    output(i) = intermittent(i) + count*pi;
    i = i + 1;
```

```
  end
  count = count + 1;
  while i < length(input)+1 && d(i-1) <= 0
    output(i) = count*pi - intermittent(i);
    i = i + 1;
  end
  count = count + 1;
end
end
```

Assess Triad:

Assess whether or not any of the faces of a triad can be permanently closed, and what the gain or closing each face would be. The use of this is that each triad can be scored, then the faces can be closed via a greedy algorithm. Each triad is reassessed after any faces are closed, as they may interact significantly.

```
function [ scores ] = assessTriad( Triad, derefinement_factor)
a = Triad(1);
b = Triad(2);
c = Triad(3);
modification = sqrt(derefinement_factor);
threshold = 0.1/modification;

scores = [0, 0, 0];

canCloseA = canClose(a);
canCloseB = canClose(b);
canCloseC = canClose(c);

if canCloseA
  for i = 1:Frame.NTheta-1
    Aa = getArea(a,i);
    if Aa == 0; continue; end
    Ab = getArea(b,i);
    if Ab == 0; continue; end
    Ac = getArea(c,i);
    if Ac == 0; continue; end
    r_a = Aa/min(Ab,Ac);
    if r_a < threshold; scores(1) = scores(1) + 1; end
  end
end

if canCloseB
  for i = 1:Frame.NTheta-1
    Aa = getArea(a,i);
    if Aa == 0; continue; end
    Ab = getArea(b,i);
    if Ab == 0; continue; end
    Ac = getArea(c,i);
    if Ac == 0; continue; end
    r_b = Ab/min(Aa,Ac);
    if r_b < threshold; scores(2) = scores(2) + 1; end
  end
end

if canCloseC
  for i = 1:Frame.NTheta-1
    Aa = getArea(a,i);
    if Aa == 0; continue; end
    Ab = getArea(b,i);
    if Ab == 0; continue; end
```

```
    Ac = getArea(c,i);
    if Ac == 0; continue; end
    r_c = Ac/min(Aa,Ab);
    if r_c < threshold; scores(3) = scores(3) + 1; end
  end
end
end
```

Atan:

Modified to provide a continuous output over a set of sequential input values.

```
function [input] = atanSmooth(input)
input = atan(input);
for i = 2:length(input)
  if abs(input(i-1) - input(i)) > 3
    input(i:end) = input(i:end) + sign(input(i-1)-input(i))*pi;
  end
end
end
```

Can Close:

determines if a face can be closed without dividing the region

```
function [itcan] = canClose( fc )
  if isfield(fc.data,'Area')
    if all(fc.data.Area > 0)
      % Path from one side to the other
      [itcan] = canPathTo(fc, fc.Nodes(1), fc.Nodes(2));
    else; itcan = true;
    end
  else
    itcan = false;
  end
end

function [canPath, visited] = canPathTo(visited, target, start)
  canPath = false;
  for fc = start.Faces
    if (fc.Type == enumFType.Gas || ...
        fc.Type == enumFType.MatrixTransition) && ...
        ~any(fc == visited)
      % Make sure the face is traversible
      if all(fc.data.Area > 0)
        if fc.Nodes(1) == start; i = 2; else; i = 1; end
        % Test for completion
        if fc.Nodes(i) == target
          canPath = true; return;
        else
          % Continue Searching
          for fci = fc.Nodes(i).Faces
            [canPath, visited] = ...
              canPathTo([visited fc], target, fc.Nodes(i));
            if canPath; return; end
          end
        end
      end
    end
  end
end
```

Collapse vector:

collapses vector that are repetitive to save effort later.

```
function [ Input ] = CollapseVector( Input )
  if all(Input(1) - 1e-8 < Input) && all(Input(1) + 1e-8 > Input)
    Input = Input(1);
  end
end
```

Combine Conduction in Series:

combines a pair of conductance's as if they were attached in series.

```
function [ U ] = combine_Conduction_Series( U1, U2 )
if U1 == 0
  U = U2;
else
  if U2 == 0
    U = 0;
  else
    U = 1/(1/U1+1/U2);
  end
end
```

Copy Class:

Copies a handle object, property for property. Children objects are not copied, by default.

```
function newObj = CopyClass(existingObj)
  newObj = feval(class(existingObj));
  props = properties(existingObj);
  for i = 1:length(props)
    newObj.(props{i}) = existingObj.(props{i});
  end
end
```

Custom Expand Array

Expands array by padding it in all directions

```
function [newarray] = CustExpandArray(array)
    newarray = zeros(size(array) + [2 2]);
    % Identical core of the array
    newarray(2:(1+size(array,1)),2:(1+size(array,2))) = array(:,:);
    % Four Edges
    newarray(1,2:(1+size(array,2))) = array(1,:);
    newarray(end,2:(1+size(array,2))) = array(end,:);
    newarray(2:(1+size(array,1)),1) = array(:,1);
    newarray(2:(1+size(array,1)),end) = array(:,end);
    % Four Corners
    newarray(1,1) = newarray(1,2);
    newarray(1,end) = newarray(1,end-1);
    newarray(end,1) = newarray(end,2);
    newarray(end,end) = newarray(end,end-1);
end
```

Custom RSSQ

Calculates the root sum of squares of a vector. This function exists but is the only function that comes from an add-on library to MATLAB.

```
function [out] = CustomRSSQ(in)
    out = sqrt(sum(in.*in));
end
```

Debug_loop plot:

Plots all loops on the GUI window

```
function [ ] = debug_loopPlot( Model, Closed)
h = figure();
if nargin > 1
  if length(Closed) == 1
    if ~Closed
      for fc = Model.Faces
        if fc.Type == enumFType.Gas || fc.Type == enumFType.MatrixTransition
          c1 = fc.Nodes(1).minCenterCoords();
          c2 = fc.Nodes(2).minCenterCoords();
          line([c1.x; c2.x], [c1.y; c2.y]);
        end
      end
    end
  else
    for fc = Model.Faces
      if fc.Type == enumFType.Gas || fc.Type == enumFType.MatrixTransition
        if ~Closed(fc.index)
          c1 = fc.Nodes(1).minCenterCoords();
          c2 = fc.Nodes(2).minCenterCoords();
          line([c1.x; c2.x], [c1.y; c2.y]);
        end
      end
    end
  end
else
  for fc = Model.Faces
    if fc.Type == enumFType.Gas || fc.Type == enumFType.MatrixTransition
      if all(fc.data.Area > 0)
        c1 = fc.Nodes(1).minCenterCoords();
        c2 = fc.Nodes(2).minCenterCoords();
        line([c1.x; c2.x], [c1.y; c2.y]);
      end
    end
  end
end
close(h);
end
```

Distance to Rectangle

Returns the distance that a point “P” composed of Px and Py is from a rectangle with center “Cx, Cy”, width and height.

```
function [ d ] = Dist2Rect( Px,Py,Cx,Cy,width,height )
  % 9 cases
  w = width/2;
  h = height/2;
  if Px < Cx+w
    if Px > Cx-w
      if Py < Cy+h
        if Py > Cy-h % Bounded, Bounded (Inside)
          d = 0;
        else % Under, Bounded
          d = ((Cy-h)-Py)^2;
        end
      else % Above, Bounded
        d = (Py-(Cy+h))^2;
      end
    else
      if Py < Cy+h % Under Top Surface, Left
        if Py > Cy-h % Bounded, Left
          d = (Cx-w-Px)^2;
        else % Under, Left
          d = ((Cx-w)-Px)^2+((Cy-h)-Py)^2;
        end
      else % Above, Left
        d = ((Cx-w)-Px)^2+(Py-(Cy+h))^2;
      end
    end
  else
    if Py < Cy+h
      if Py > Cy-h % Bounded, Right
        d = (Px-(Cx+w))^2;
      else % Under, Right
        d = ((Cy-h)-Py)^2+(Px-(Cx+w))^2;
      end
    else % Above, Right
      d = (Py-(Cy+h))^2+(Px-(Cx+w))^2;
    end
  end
end
```

Distance for comparison

Calculates the square distance, avoiding the square root.

```
function [d] = Dist4Compare(A,B)
d = (A(1)-B(1))^2+(A(2)-B(2))^2;
end
```

Distort Position Vector

Distorts a set of x and y vectors, representing a set of points by a rotation and then a shift in 2D space.

```
function [oXData,oYData] = DistortPositionVectors(iXData,iYData,shift,rotate)
  if nargin > 3 && all(size(rotate) == [2 2])
    oXData = rotate(1,1)*iXData + rotate(1,2)*iYData;
    oYData = rotate(2,1)*iXData + rotate(2,2)*iYData;
    if length(shift) == 2
      oXData = shift(1) + oXData;
      oYData = shift(2) + oYData;
```

```
    end
    return;
  end
  if nargin > 2 && length(shift) == 2
    oXData = shift(1) + iXData;
    oYData = shift(2) + iYData;
  end
end
```

Face Motion

Given a face calculates (if any) the shear and velocity factors and if possible returns these values in addition to a new shear contact in the event of a shear. If may return more than 1 shear contact.

```
function [ V, S, SContact ] = FaceMotion(Fc)
V = [];
S = [];
SContact = ShearContact.empty;
% Only if the face is horizontal and is gas
if Fc.Orient ~= enumOrient.Horizontal; return; end
n1 = Fc.Nodes(1);
n2 = Fc.Nodes(2);
if n1.Type == enumNType.SN || n2.Type == enumNType.SN; return; end

% factor = omega/N [rad/step]
h = 2*pi/(Frame.NTheta-1);

%% Self Motion
% Produce V_middle - of units [m/rad]
if all(n1.ymin == n2.ymax)
  % Oriented towards the negative
  sgn = 1;
  V_middle = zeros(1,Frame.NTheta);
  y = n1.ymin;
  if ~isscalar(y)
    V_middle(1) = (y(2)-y(end-1))/(2*h);
    V_middle(2:end) = (y(3:end)-y(1:end-2))/(2*h);
  end
elseif all(n1.ymax == n2.ymin)
  % Oriented towards the positive
  sgn = -1;
  V_middle = zeros(1,Frame.NTheta);
  y = n2.ymin;
  if ~isscalar(y)
    V_middle(1) = (y(2)-y(end-1))/(2*h);
    V_middle(2:end-1) = (y(3:end)-y(1:end-2))/(2*h);
    V_middle(end) = V_middle(1);
  end
else
  % They are connected, but through a bridge.
  return;
end

%% Adjacent Motion
% Find the adjacent surfaces motion
% For each frame of motion detect whether or not the face is adjacent to a
% ... solid surface.
Bodies_1_inside = Body.empty;
Area_1_inside = cell_of_zeros(length(n1.Faces));
Bodies_1_outside = Body.empty;
Area_1_outside = cell_of_zeros(length(n1.Faces));
Bodies_2_inside = Body.empty;
Area_2_inside = cell_of_zeros(length(n2.Faces));
Bodies_2_outside = Body.empty;
Area_2_outside = cell_of_zeros(length(n2.Faces));
```

```
% Test the connections of node 1
for fc = n1.Faces
  if fc.Orient == enumOrient.Vertical
    % Only if it is a mixed face will it populate "nd"
    nd = [];
    if fc.Nodes(1).Type == enumNType.SN; nd = fc.Nodes(1);
    elseif fc.Nodes(2).Type == enumNType.SN; nd = fc.Nodes(2);
    end
    if ~isempty(nd)
      found = false;

      if nd.xmin < n1.xmin % It is closer to the axis than the original node
        for i = 1:length(Bodies_1_inside)
          if Bodies_1_inside(i) == nd.Body
            Area_1_inside{i} = Area_1_inside{i} + fc.data.Area;
            found = true;
          end
        end
        if ~found
          Bodies_1_inside(end+1) = nd.Body;
          Area_1_inside{length(Bodies_1_inside)} = ...
            Area_1_inside{length(Bodies_1_inside)} + fc.data.Area;
        end
      else % It is farther from the axis than the original node
        for i = 1:length(Bodies_1_outside)
          if Bodies_1_outside(i) == nd.Body
            Area_1_outside{i} = Area_1_outside{i} + fc.data.Area;
            found = true;
          end
        end
        if ~found
          Bodies_1_outside(end+1) = nd.Body;
          Area_1_outside{length(Bodies_1_outside)} = ...
            Area_1_outside{length(Bodies_1_outside)} + fc.data.Area;
        end
      end
    end
  end
end

% Test the connections of node 2
for fc = n2.Faces
  if fc.Orient == enumOrient.Vertical
    % Only if it is a mixed face will it populate "nd"
    nd = [];
    if fc.Nodes(1).Type == enumNType.SN
      nd = fc.Nodes(1);
    elseif fc.Nodes(2).Type == enumNType.SN
      nd = fc.Nodes(2);
    end
    if ~isempty(nd)
      found = false;
      if nd.xmin < n2.xmin % It is closer to the axis than the original node
        for i = 1:length(Bodies_2_inside)
          if Bodies_2_inside(i) == nd.Body
            Area_2_inside{i} = Area_2_inside{i} + fc.data.Area;
            found = true;
          end
        end
        if ~found
          Bodies_2_inside(end+1) = nd.Body;
          Area_2_inside{length(Bodies_2_inside)} = ...
            Area_2_inside{length(Bodies_2_inside)} + fc.data.Area;
        end
      else % It is farther from the axis than the original node
        for i = 1:length(Bodies_2_outside)
          if Bodies_2_outside(i) == nd.Body
            Area_2_outside{i} = Area_2_outside{i} + fc.data.Area;
            found = true;
          end
```

```
        end
        if ~found
          Bodies_2_outside(end+1) = nd.Body;
          Area_2_outside{length(Bodies_2_outside)} = ...
            Area_2_outside{length(Bodies_2_outside)} + fc.data.Area;
        end
      end
    end
  end
end

% Determine inner absolute speeds
% ... If no bodies are shared, then speed is equal to the face velocity to
% ... represent a low shear condition.
V_inner = V_middle; i = 1;
shared_inner = false(size(Bodies_1_inside));
for iBody = Bodies_1_inside
  j = 1;
  for oBody = Bodies_2_inside
    if iBody == oBody
      shared_inner(i) = true;
      overlap = and(Area_1_inside{i} > 0, Area_2_inside{j} > 0);
      motion = get_motion(iBody);
      if length(overlap) == 1 && overlap
        V_inner = motion;
        break;
      else
        V_inner(overlap) = motion(overlap);
      end
    end
    j = j + 1;
  end
  i = i + 1;
end


% Determine outer absolute speeds
% ... If no bodies are shared, then speed is equal to the face velocity to
% ... represent a low shear condition.
shared_outer = false(size(Bodies_1_outside));
V_outer = V_middle; i = 1;
for iBody = Bodies_1_outside
  j = 1;
  for oBody = Bodies_2_outside
    if iBody == oBody
      shared_outer(i) = true;
      overlap = and(Area_1_outside{i} > 0, Area_2_outside{j} > 0);
      motion = get_motion(iBody);
      if length(overlap) == 1 && overlap
        V_outer = motion;
        break;
      else
        V_outer(overlap) = motion(overlap);
      end
    end
    j = j + 1;
  end
  i = i + 1;
end

% Assign V and S vectors
if n1.xmin == 0 && n2. xmin == 0
  V = (V_middle - V_outer);
  S = [];
else
  V = V_middle - (V_inner + V_outer)/2;
  S = abs(V_inner - V_outer);
end

Frames = Frame.empty;
N = length(Bodies_1_inside(shared_inner)) + ...
```

```
  length(Bodies_1_outside(shared_outer));
ActiveTimes = cell(N, 1);
for i = 1:N; ActiveTimes{i} = 0; end
for i = 1:length(Bodies_1_inside)
  if shared_inner(i)
    Frm = Bodies_1_inside(i).get('RefFrame');
    if ~isempty(Frm)
      found = false;
      for j = 1:length(Frames)
        if Frames(j) == Frm
          found = true;
          % Add active Points to array
          ActiveTimes{j} = or(ActiveTimes{j}, ...
            and(Area_1_inside{i} > 0, Area_2_inside{i} > 0));
          break;
        end
      end
      if ~found
        Frames(end+1) = Frm;
        ActiveTimes{length(ActiveTimes),1} = ...
          and(Area_1_inside{i} > 0, Area_2_inside{i} > 0);
      end
    end
  end
end
for i = 1:length(Bodies_1_outside)
  if shared_outer(i)
    Frm = Bodies_1_outside(i).get('RefFrame');
    if ~isempty(Frm)
      found = false;
      for j = 1:length(Frames)
        if Frames(j) == Frm
          found = true;
          % Add active Points to array
          ActiveTimes{j} = or(ActiveTimes{j}, ...
            and(Area_1_outside{i} > 0, Area_2_outside{i} > 0));
          break;
        end
      end
      if ~found
        Frames(end+1) = Frm;
        ActiveTimes{length(ActiveTimes),1} = ...
          and(Area_1_outside{i} > 0, Area_2_outside{i} > 0);
      end
    end
  end
end

% So we now have the reference frames that move past the face, as well as
% ... the times that they are active for.
if isempty(Frames)
  SContact = ShearContact.empty;
else
  SContact(length(Frames)) = ShearContact(0);
  Converters = n1.Body.Group.Model.Converters;
  i = 1;
  for Frm = Frames
    for Converter_id = 1:length(Converters)
      if Frm.Mechanism == Converters(Converter_id)
        break;
      end
    end
    if n1.ymin(1) < n2.ymin(1)
      SContact(i) = ShearContact(...
        Converter_id, Frm.MechanismIndex, Fc.data.Area/2, n1, n2, ActiveTimes{i});
    else
      SContact(i) = ShearContact(...
        Converter_id, Frm.MechanismIndex, Fc.data.Area/2, n2, n1, ActiveTimes{i});
    end
    i = i + 1;
  end
```

```
end

% Currently the gas velocity is oriented towards the negative direction
% ... Correct
if all(V < 1e-4) && all(V > -1e-4)
  V = [];
else
  V = sgn*V;
end

if all(S < 1e-4)
  S = [];
end
end

function [a] = cell_of_zeros(len)
  a = cell(len,1);
  for i = 1:len; a{i} = 0; end
end

function [motion] = get_motion(iBody)
  [y, ~, ~, ~] = iBody.limits(enumOrient.Horizontal);
  % factor = omega/N [rad/step]
  h = 2*pi/(Frame.NTheta-1);
  motion = zeros(1,Frame.NTheta);
  if ~isscalar(y)
    motion(1) = (y(2)-y(end-1))/(2*h);
    motion(2:end-1) = (y(3:end)-y(1:end-2))/(2*h);
    motion(end) = motion(1);
  end
end
```

Find Closest 2 Nodes

Determines, from a set of nodes the set of 2 nodes that are closest to a position.

```
function [ iNodes ] = findClosest2(loc, iNodes )
selection = zeros(1,2);
d = zeros(1,4);
for i = 1:length(iNodes)
  pnts = iNodes.minCenterCoords;
  d(i) = (pnts.x - loc.x)^2 + (pnts.y - loc.y)^2;
end
n = 1;
while true
  dmin = d(1);
  k = 1;
  for i = 2:length(d)
    if dmin > d(i)
      dmin = d(i);
      k = i;
    end
  end
  if dmin == inf
    iNodes = iNodes(selection(1:n));
    return;
  end
  d(k) = inf;
  selection(n) = k;
  n = n + 1;
  if n == 3
    iNodes = iNodes(selection);
    return;
  end
end
```

```
end
```

Find Closest 4 Nodes

Determines, from a set of nodes the set of 4 nodes that are the closest.

```
function [oNodes,Interp] = findClosest4(loc,Body)
  % Find distance to all nodes
  % Find the members of the body who's material matches the phase of the
  % body material.
  iNodes = Body.Nodes;
  Phase = Body.matl.Phase;
  include = true(size(iNodes));
  for i = 1:length(iNodes)
    if ~isvalid(iNodes(i))
      include(i) = false;
      continue;
    end
    if isfield(iNodes(i).data,'matl') && iNodes(i).data.matl.Phase ~= Phase
      include(i) = false;
      continue;
    end
  end
  iNodes = iNodes(include);
  if isempty(iNodes)
    oNodes = [];
    Interp = [];
    return;
  end
  dist2 = zeros(length(iNodes),1);
  i = 1;
  for Nd = iNodes
    NodeCenter = Nd.minCenterCoords;
    dist2(i) = (NodeCenter.x-loc.x)^2+(NodeCenter.y-loc.y)^2;
    if dist2(i) == 0
      oNodes = Nd.index;
      Interp = 1;
      return;
    end
    i = i + 1;
  end

  % Sort the dist and node array
  tNodes = Node.empty;
  if length(iNodes) > 3
    limit = 4;
  else
    limit = 2;
  end
  if ~isempty(iNodes)
    notdone = true;
    while notdone
      d1 = min(dist2);
      if d1 == Inf || length(tNodes) == limit
        [Interp, tNodes] = interpCoefficients(loc,tNodes);
        oNodes = zeros(1,length(tNodes));
        for i = 1:length(tNodes)
          oNodes(i) = tNodes(i).index;
        end
        return;
      end
      MinNodes = iNodes(dist2==d1);
      maxlen = min(length(MinNodes),limit - length(tNodes));
      tNodes(end+1:end+maxlen) = MinNodes(1:maxlen);
      dist2(dist2==d1) = Inf;
    end
  end
```

```
  Interp = [];
end
```

Find String In Cell

Finds, in a cell vector, a particular string and returns the index.

```
function [index] = FindStringInCell(iCell,iString)
index = 0;
for i = 1:length(iCell)
  if strcmp(iCell{i},iString)
    index = i;
    break;
  end
end
end
```

Func 2 Lookup

Unused: in favor of vectorized anonymous functions. This function takes a function, a range of values and a tolerance and computes an adaptive lookup table that covers the prescribed range of inputs.

```
function [x,v] = Func2Lookup(Func,xmin,xmax,vTol)
tic;
N = 200; n = 3;
xs = zeros(N,1); vs = xs; edges = xs; active = xs;
xs(1) = xmin; vs(1) = Func(xmin); edges(1) = 2; active(1) = true;
xs(2) = xmax; vs(2) = Func(xmax); edges(2) = 0; %active(2) = false;
while(any(active))
  for i = 1:n-1
    if active(i)
      % Test 5 points
      dx = (xs(edges(i))-xs(i))/6;
      m = (vs(edges(i))-vs(i))/(xs(edges(i))-xs(i));
      xs(n) = xs(i) + 3*dx;
      vs(n) = Func(xs(n));
      if abs(vs(n) - ((xs(n) - xs(i))*m + vs(i))) > vTol
        edges(n) = edges(i);
        edges(i) = n;
        active(n) = true;
        n = n + 1;
        break;
      else
        xs(n) = xs(i) + 2*dx;
        vs(n) = Func(xs(n));
        if abs(vs(n) - ((xs(n) - xs(i))*m + vs(i))) > vTol
          edges(n) = edges(i);
          edges(i) = n;
          active(n) = true;
          n = n + 1;
          break;
        else
          xs(n) = xs(i) + 4*dx;
          vs(n) = Func(xs(n));
          if abs(vs(n) - ((xs(n) - xs(i))*m + vs(i))) > vTol
            edges(n) = edges(i);
            edges(i) = n;
            active(n) = true;
```

```
            n = n + 1;
            break;
          else
            xs(n) = xs(i) + dx;
            vs(n) = Func(xs(n));
            if abs(vs(n) - ((xs(n) - xs(i))*m + vs(i))) > vTol
              edges(n) = edges(i);
              edges(i) = n;
              active(n) = true;
              n = n + 1;
              break;
            else
              xs(n) = xs(i) + 5*dx;
              vs(n) = Func(xs(n));
              if abs(vs(n) - ((xs(n) - xs(i))*m + vs(i))) > vTol
                edges(n) = edges(i);
                edges(i) = n;
                active(n) = true;
                n = n + 1;
                break;
              else
                active(i) = false;
              end
            end
          end
        end
      end
    end
    if n > N
      break;
    end
  end
  if n > N
    break;
  end
end
x = zeros(n-1,1);
v = zeros(n-1,1);
x(1) = xs(1);
v(1) = vs(1);
next = edges(1);
for i = 2:n-1
  x(i) = xs(next);
  v(i) = vs(next);
  next = edges(next);
end
plot(x,v,'o',xmin:0.01:xmax,Func(xmin:0.01:xmax));
toc;
end
```

Function Table

Unused: in favor of vectorized anonymous functions. Determines the set of unique functions and calculates a set length lookup table.

```
function [Indexes, Lookups] = Function_Table(...
  Tol, min_x, max_x, Functions, N)
LEN = length(Functions);
Lookups = zeros(LEN,N,2);
Indexes = zeros(LEN,1);
isUnique = false(size(Indexes));
n = 1;
for i = 1:LEN
  if ~isempty(Functions{i}) && Indexes(i) == 0
    isUnique(i) = true;
```

```
    Indexes(i) = n;
    for j = i+1:LEN
      if ~isempty(Functions{j}) && Indexes(j) == 0
        if Indexes(j) == 0 && Functions{i}(0.5) == Functions{j}(0.5) && Functions{i}(1) ==
Functions{j}(1)
          Indexes(j) = n;
        end
      end
    end
    n = n + 1;
  end
end

for i = 1:LEN
  f = Functions{i};
  if ~isempty(f)
    if isUnique(i)
      n = Indexes(i);
      entry = 2;
      delta = 1;
      Lookups(n,1,1) = min_x;
      Lookups(n,1,2) = f(min_x);
      x2 = 1e-8;
      y2 = Lookups(n,1,2);
      while x2 < max_x && entry <= N
        % Use the Tolerance to construct a lookup table from the function
        x1 = x2;
        y1 = y2;
        max_delta = inf;
        min_delta = 1e-8;
        delta = delta * 1.1;
        locating = true;
        Tries = 1;
        while locating && Tries < 10
          x2 = Lookups(n,entry-1,1) + delta;
          y2 = f(x2);
          if delta == min_delta || delta == max_delta
            locating = false;
          else
            ymid = f((x1 + x2)/2);
            err = ((y1 + y2) - 2*ymid)/ymid;
            if abs(err) > Tol
              factor = 0.99*sqrt(Tol/abs(err));
              max_delta = delta*(1 + factor)/2;
              delta = max(min_delta,delta*factor);
            elseif abs(err) < Tol*0.9
              factor = sqrt(Tol/abs(err));
              min_delta = delta*(1 + factor)/2;
              delta = min(max_delta,delta*factor);
            else
              locating = false;
            end
            Tries = Tries + 1;
          end
        end
        if Tries == 10
          x2 = (min_delta + max_delta)/2;
          y2 = f(x2);
        end
        Lookups(n,entry,1) = x2;
        Lookups(n,entry,2) = y2;
        entry = entry + 1;
      end
    end
  end
end
if n < LEN
  Lookups = Lookups(1:n,:,:);
end
end
```

Get Any Fc Loop of Size

Used in debugging, found loops of size 2 which were subsequently fixed.

```
function [success, visited] = getAnyFcLoopOfSize(visited, target, start, max_length)
  success = false;
  for fc = start.Faces
    if visited(end) ~= fc && (fc.Type == enumFType.Gas || ...
        fc.Type == enumFType.MatrixTransition)
      % Make sure the face is traversible
      if fc.Nodes(1) == start; i = 2; else; i = 1; end
      % Test for completion
      if fc.Nodes(i) == target
        success = true; visited = [visited fc]; return;
      else
        % Length Check
        if length(visited) + 1 == max_length
          success = false; return;
        else
          % Continue Searching
          for fci = fc.Nodes(i).Faces
            [success, new_visited] = getAnyFcLoopOfSize(...
              [visited fc], target, fc.Nodes(i), max_length);
            if success
              visited = new_visited;
              return;
            end
          end
        end
      end
    end
  end
end
```

Get Area Percent Horizontal

Calculates the percentage that an offset circle of offset “x” and diameter “d” covers a centered ring of inner radius “r1” and outer radius “r2”.

```
function [ area_perc ] = GetAreaPercentHorizontal( x, r1, r2, d )
%GETAREAPERCENTHORIZONTAL Summary of this function goes here
%   Calculates the percentage that an offset circle covers a ring between
%   r1 and r2
x = abs(x);
if d == 0 || x - d/2 > r2 || x + d/2 < r1; area_perc = 0; return; end
if x-d/2 < -r2 && x+d/2 > r2; area_perc = 1; return; end

c_r1 = max([x-d/2 r1]);
c_r2 = min([x+d/2 r2]);

N = 100;
r = linspace(c_r1,c_r2,N);
r = (r(1:end-1)+r(2:end))/2; % Center the radius's
dr = (c_r2-c_r1)/(N-1);
area = 0;

if x > d/2
  for ri = r
    % Center is outside of circle, angle can never be larger than pi/2
    area = area + 2*dr*ri*acos((ri^2+x^2-(d/2)^2)/(2*ri*x));
```

```
  end
else
  for ri = r
    if d/2 >= ri + x
      % Full Circle
      area = area + 2*dr*ri*pi;
    else
      % Center is insie of circle
      area = area + 2*dr*ri*acos((ri^2+x^2-(d/2)^2)/(2*ri*x));
    end
  end
end
area_perc = area/(pi*(r2^2-r1^2));
end
```

Get Area Percent Mix

Calculates the percentage that a circle of vertical offset “x” and diameter “d” covers the side of a thin annular shell of radius “r” and extents “y1” and “y2”.

```
function [ PercArea ] = GetAreaPercentMix(r, x, y1, y2, d )
%GETAREAPERCENTMIX Summary of this function goes here
%   Calculates the percentage that an circle at x of diameter d covers a
%   strip between y1 and y2
Total_Area = 2*pi*r*(y2-y1);
c_y1 = max([x-d/2 y1]);
c_y2 = min([x+d/2 y2]);
if c_y1 >= c_y2; PercArea = 0; return; end
N = max([2 floor(100*(c_y2-c_y1)/d)]);
y = linspace(c_y1,c_y2,N);
y = (y(1:end-1)+y(2:end))/2;
dy = (c_y2-c_y1)/(N-1);
area = 0;
for yi = y
  area = area + 2*dy*min([r sqrt((d/2)^2-(x-yi)^2)]);
end
PercArea = area/Total_Area;
end
```

Get Center of Overlap Region

From 2 overlaps find and return the center of overlapping segment.

```
function [c] = getCenterOfOverlapRegion(min1,min2,max1,max2)
if isscalar(min1)
  if isscalar(min2)
    temp1 = max(min1,min2);
  else
    temp1 = max([min1(ones(size(min2))); min2]);
  end
else
  if isscalar(min2)
    temp1 = max([min2(ones(size(min1))); min1]);
  else
    temp1 = max([min1; min2]);
  end
end
if isscalar(max1)
  if isscalar(max2)
    temp2 = min(max1,max2);
  else
```

```
    temp2 = min([max1(ones(size(max2))); max2]);
  end
else
  if isscalar(max2)
    temp2 = min([max2(ones(size(max1))); max1]);
  else
    temp2 = min([max1; max2]);
  end
end
c = (temp1 + temp2)/2;
end
```

Get Face Type

From two nodes of types “Type1” and “Type2”, get the face type that would be produced.

```
function NType = getFaceType(Type1,Type2)
  if Type1 ~= Type2
    NType = enumFType.Mix;
  else
    NType = Type1;
  end
end
```

Get First Derivative

Get first derivative with respect to angle, given a vector that is assumed to cover the entire set of angles.

```
function [Var] = getFirstDer(Pos)
  Var(length(Pos)) = (Pos(2)-Pos(end-1));
  Var(2:end-1) = (Pos(3:end)-Pos(1:end-2));
  Var(1) = Var(end);
  denominator = (4*pi/(Frame.NTheta-1));
  Var = (Var/denominator)';
end
```

Get Proper Name

Opens up a generic userform that requires a name, and validates this name.

```
function [ answer ] = getProperName( ObjectName )
answer{1} = '/';
trial = 0;
while regexp(answer{1},'[/\*:?"<>|]', 'once')
  if trial > 0
    msgbox(['You cannot have any of the following ' ...
      'characters [/\*:?"<>|] in a file name']);
  end
  trial = trial + 1;
  answer = inputdlg(['Enter a descriptive name for the ' ObjectName],...
    'Name(filename,title,etc...):',[1 50]);
  if isempty(answer{1})
    answer = '';
    return;
  end
```

```
end
answer = answer{1};
end
```

Get Second Derivative

Get second derivative with respect to angle, given a vector that is assumed to cover the entire set of angles.

```
function [Var] = getSecondDer(Pos)
  Var(length(Pos)) = (Pos(2)-2*Pos(end)+Pos(end-1));
  Var(2:end-1) = (Pos(3:end)-2*Pos(2:end-1)+Pos(1:end-2));
  Var(1) = Var(end);
  denominator = ((2*pi)/(Frame.NTheta-1))^2;
  Var = (Var/denominator)';
end
```

Get Triad

Get the triad associated with node n1.

```
function [ Triad ] = GetTriad( n1 )
%GETTRIAD Summary of this function goes here
%   Detailed explanation goes here
Triad = cell(0);
count = 1;
for f1 = n1.Faces
  if isGasFace(f1)
    if f1.Nodes(1) == n1; n2 = f1.Nodes(2); else; n2 = f1.Nodes(1); end
    for f2 = n2.Faces
      if isGasFace(f2) && f2 ~= f1
        if f2.Nodes(1) == n2; n3 = f2.Nodes(2); else; n3 = f2.Nodes(1); end
        if n1 == n3; continue; end
        for f3 = n3.Faces
          if isGasFace(f3) && f3 ~= f2 && f2 ~= f1
            if f3.Nodes(1) == n1 || f3.Nodes(2) == n1
              Triad{count} = [f1 f2 f3];
              count = count + 1;
              break;
            end
          end
        end
      end
    end
  end
end
end

function isit = isGasFace(fc)
  isit = fc.Type == enumFType.Gas || fc.Type == enumFType.MatrixTransition;
end
```

Holder (shell class)

Unused class that holds a value type object such that it can be referenced via just the pointer without copying.

```
classdef Holder < handle
  %HOLDER Summary of this class goes here
  %   Detailed explanation goes here

  properties
    vars cell;
  end

  methods
    function obj = Holder(ivars)
      obj.vars = ivars;
    end
  end
end
```

iif

Inline if condition.

```
function out = iif(cond,a,b)
%IIF implements a ternary operator

% pre-assign out
out = repmat(b,size(cond));

out(cond) = a;
end
```

Interp Coefficients

Provides the interpolation coefficients given a set of (at most) 4 nodes to calculate the value of a property at a location. This can pair down the set to 1 or 2 nodes as well.

```
function [ Interp, iNodes ] = interpCoefficients(loc, iNodes)
%INTERPCOEFFICIENTS Summary of this function goes here
%   Detailed explanation goes here

% Given 4 or less nodes
notdone = true;
while notdone
  switch length(iNodes)
    case 0
      fprintf('ERR: No nodes provided for interpolation into interpCoefficients.m');
      Interp = [];
      iNodes = Node.empty;
      notdone = false;
    case 3
      fprintf('ERR: Invalid number of nodes provided for interpolation into
interpCoefficients.m');
      Interp = [];
      iNodes = Node.empty;
      notdone = false;
    case 1
      Interp = 1;
      notdone = false;
    case 2
      % Ratio of distances
      NC1 = iNodes(1).minCenterCoords;
      NC2 = iNodes(2).minCenterCoords;
      if iNodes(1).xmin == 0; NC1.x = 0; end
      if iNodes(2).xmin == 0; NC2.x = 0; end
      vec = Pnt2D(NC2.x-NC1.x,NC2.y-NC1.y);
```

```
  mag = sqrt(vec.x^2+vec.y^2);
  vec.x = vec.x/mag;
  vec.y = vec.y/mag;
  pnt = Pnt2D(loc.x-NC1.x,loc.y-NC1.y);
  dot = pnt.x*vec.x + pnt.y*vec.y;
  d1 = dot; % Distance to NC1
  d2 = mag - dot; % Distance to NC2
  Interp(2) = d1/(d1+d2);
  Interp(1) = d2/(d1+d2);
  notdone = false;
case 4
  % Bilinear Interpolation
  % Determine if it is between any two points and pick the pair with the
  % lowest collective distance
  pairs = zeros(3,6);
  P(4) = iNodes(4).minCenterCoords;
  P(1) = iNodes(1).minCenterCoords;
  P(2) = iNodes(2).minCenterCoords;
  P(3) = iNodes(3).minCenterCoords;
  if iNodes(1).xmin == 0; P(1).x = 0; end
  if iNodes(2).xmin == 0; P(2).x = 0; end
  if iNodes(3).xmin == 0; P(3).x = 0; end
  if iNodes(4).xmin == 0; P(4).x = 0; end
  isvertical = true;
  x = P(1).x;
  for i = 2:4
     if P(i).x ~= x
         isvertical = false;
         break;
     end
  end

  % If they are all vertical then pick one on either side
  if isvertical

      % They are all vertically aligned, pick 2
      % Find the closest that is greater than
      greaterthan = 0;
      d = inf;
      for i = 1:4
         if loc.y <= P(i).y
            if P(i).y - loc.y < d
                d = P(i).y - loc.y;
                greaterthan = i;
            end
         end
      end

      % Find the closest that is less than
      lessthan = 0;
      d = inf;
      for i = 1:4
          if loc.y >= P(i).y
             if loc.y - P(i).y < d
                 d = loc.y - P(i).y;
                 lessthan = i;
             end
          end
      end

      % Fill in the gaps with a next closest
      if lessthan ~= 0 && greaterthan ~= 0
          [ Interp, iNodes ] = interpCoefficients(loc, iNodes([lessthan; greaterthan]));
      else
          if lessthan == 0
              greaterthan2 = 0;
              d = inf;
              for i = 1:4
                  if i ~= greaterthan
                      if loc.y <= P(i).y
                        if P(i).y - loc.y < d
```

```
                                d = P(i).y - loc.y;
                                greaterthan2 = i;
                            end
                        end
                    end
                end

                [ Interp, iNodes ] = interpCoefficients(loc, iNodes([greaterthan2;
greaterthan]));
            else
                lessthan2 = 0;
                d = inf;
                for i = 1:4
                    if i ~= lessthan
                        if loc.y >= P(i).y
                          if loc.y - P(i).y < d
                              d = loc.y - P(i).y;
                              lessthan2 = i;
                          end
                        end
                    end
                end
                [ Interp, iNodes ] = interpCoefficients(loc, iNodes([lessthan2; lessthan]));
            end
         end
      else
         ishorizontal = true;
         y = P(1).y;
         for i = 2:4
            if P(i).y ~= y
                ishorizontal = false;
                break;
            end
         end
         if ishorizontal
              % They are all horizontally aligned, pick 2

              % They are all vertically aligned, pick 2
              % Find the closest that is greater than
              greaterthan = 0;
              d = inf;
              for i = 1:4
                 if loc.x <= P(i).x
                    if P(i).x - loc.x < d
                        d = P(i).x - loc.x;
                        greaterthan = i;
                    end
                 end
              end

              % Find the closest that is less than
              lessthan = 0;
              d = inf;
              for i = 1:4
                  if loc.x >= P(i).x
                     if loc.x - P(i).x < d
                         d = loc.x - P(i).x;
                         lessthan = i;
                     end
                  end
              end

              % Fill in the gaps with a next closest
              if lessthan ~= 0 && greaterthan ~= 0
                  [ Interp, iNodes ] = interpCoefficients(loc, iNodes([lessthan; greaterthan]));
              else
                  if lessthan == 0
                      greaterthan2 = 0;
                      d = inf;
                      for i = 1:4
                          if i ~= greaterthan
```

```
                            if loc.x <= P(i).x
                              if P(i).x - loc.x < d
                                  d = P(i).x - loc.x;
                                  greaterthan2 = i;
                              end
                            end
                        end
                    end
                    [ Interp, iNodes ] = interpCoefficients(loc, iNodes([greaterthan2;
greaterthan]));
                else
                    lessthan2 = 0;
                    d = inf;
                    for i = 1:4
                        if i ~= lessthan
                            if loc.x >= P(i).x
                              if loc.x - P(i).x < d
                                  d = loc.x - P(i).x;
                                  lessthan2 = i;
                              end
                            end
                        end
                    end
                    [ Interp, iNodes ] = interpCoefficients(loc, iNodes([lessthan2;
lessthan]));
                end
            end
        else
           % Linear Interpolate/extrapolate between all 4
           Interp = zeros(1,4);
           %
https://en.wikipedia.org/wiki/Bilinear_interpolation#:~:text=In%20mathematics%2C%20bilinear%20int
erpolation%20is,again%20in%20the%20other%20direction.
           x1 = min([P(1).x P(2).x P(3).x P(4).x]);
           x2 = max([P(1).x P(2).x P(3).x P(4).x]);
           y1 = min([P(1).y P(2).y P(3).y P(4).y]);
           y2 = max([P(1).y P(2).y P(3).y P(4).y]);
           Qs = 1:4;
           for i = 1:4
              if P(i).x == x1 && P(i).y == y1; Qs = take(1, i, Qs); break; end
           end
           for i = 1:4
              if P(i).x == x1 && P(i).y == y2; Qs = take(2, i, Qs); break; end
           end
           for i = 1:4
              if P(i).x == x2 && P(i).y == y1; Qs = take(3, i, Qs); break; end
           end
           factor = (1/((x2-x1)*(y2-y1)));
           Interp(Qs(1)) = factor * (x2 - loc.x) * (y2 - loc.y);
           Interp(Qs(2)) = factor * (x2 - loc.x) * (loc.y - y1);
           Interp(Qs(3)) = factor * (loc.x - x1) * (y2 - loc.y);
           Interp(Qs(4)) = factor * (loc.x - x1) * (loc.y - y1);
        end
     end
     notdone = false;

  end
end
end

function [input] = swap(index1, index2, input)
    temp = input(index1);
    input(index1) = input(index2);
    input(index2) = temp;
end

function [input] = take(value, index, input)
    for i = 1:length(input)
        if input(i) == value
           input = swap(i, index, input);
           return;
```

```
        end
    end
end
```

Is String Numeric

Test whether the provided string is numerical, applied for all user forms that require a numerical input.

```
function [isit] = isStrNumeric(str)
%ISSTRNUMERIC Summary of this function goes here
%   Detailed explanation goes here
isit = all(ismember(str, '0123456789+-.eEdD'));
end
```

Linear Conduction

Calculates the conductance in the axial direction, through a node.

```
function [U] = LinearConduction(Node,r1,r2,matl)
  %ANNULARCONDUCTION(Length,inner_Radius,outer_Radius,Material_Ref)
  L = Node.ymax(1) - Node.ymin(1);
  U = (2*pi*(r2*r2-r1*r1)*matl.ThermalConductivity)/L;
end
```

Power From PV

Calculate the power using the pressure and volume data for a single cycle.

```
function [Work] = PowerFromPV(P,V)
Pavg = (P(1:end-1)+P(2:end));
dVol = (V(2:end)-V(1:end-1));
Work = 0.5*sum(Pavg.*dVol);
end
```

Process Triad

Take a triad and based on a threshold close the prescribed face.

```
function [ ] = processTriad( Triad, derefinement_factor, index_to_close)
target = Triad(index_to_close);
others = Triad(Triad ~= target);
modification = sqrt(derefinement_factor);
threshold = 0.1/modification;
count = Frame.NTheta-1;

canCloseTarget = canClose(target);

if ~canCloseTarget; return; end

for i = 1:Frame.NTheta-1
  At = getArea(target,i);
  if At == 0; count = count - 1; continue; end
  A1 = getArea(others(1),i);
  if A1 == 0; count = count - 1; continue; end
  A2 = getArea(others(2),i);
```

```
  if A2 == 0; count = count - 1; continue; end
  r = At/min(A1,A2);
  if r < threshold
    setArea(target,i,0);
  else
    count = count - 1;
  end
end

fprintf(['Edited ' num2str(count) ' Increments\n']);
end
```

Propegate Active Faces

Recursive function designed to find all the independent faces of a region.

```
function [ k,Array,Visited ] = PropegateActiveFaces(Nd,Visited,k,Array)
Visited(Nd.index) = true;
if k == length(Array)
  return;
end
for Fc = Nd.Faces
  if Fc.Nodes(1).index <= length(Visited) && ...
      Fc.Nodes(2).index <= length(Visited) && ...
      isfield(Fc.data,'dx') && all(Fc.data.Area > 0)
    if ~Visited(Fc.Nodes(1).index)
      k = k + 1;
      Array(k) = Fc.index;
      [k,Array,Visited] = PropegateActiveFaces(Fc.Nodes(1),Visited,k,Array);
    elseif ~Visited(Fc.Nodes(2).index)
      k = k + 1;
      Array(k) = Fc.index;
      [k,Array,Visited] = PropegateActiveFaces(Fc.Nodes(2),Visited,k,Array);
    end
  end
end
end
```

Propegate Region

Recursive function designed to find all the nodes in a region.

```
function [region] = PropegateRegion(Nd,region,n)
  if region(Nd.index) == 0
    region(Nd.index) = n;
    for Fc = Nd.Faces
      % Test if it is a gas face that does not close off
      if isfield(Fc.data,'dx') && all(Fc.data.Area > 0)
        if Fc.Nodes(1) == Nd
          Nd2 = Fc.Nodes(2);
        else
          Nd2 = Fc.Nodes(1);
        end
        if Nd2.index <= length(region)
          region = PropegateRegion(Nd2,region,n);
        end
      end
    end
  end
end
```

Rotation Matrix

Calculates the rotation matrix in 2D.

```
function [ R ] = RotMatrix( THETA )
%ROTMATRIX Defines the rotation matrix for a vector by the angle THETA
R = [cos(THETA) -sin(THETA); sin(THETA) cos(THETA)];
end
```

Shift Vector

Shift a vector, which is assumed to cover all the angular increments, by a phase. The vector can be shifted by any fractional amount by linear interpolation of the resulting vector.

```
function [ vector ] = shiftVector( vector, Phase )
N = length(vector);
temp = N*(Phase/(2*pi));
n1 = floor(temp);
frac = temp-n1;
n2 = ceil(temp);
v1 = circshift(vector,-n1);
v2 = circshift(vector,-n2);
vector = (1-frac)*v1 + frac*v2;
end
```

Progress Bar

Created by Steve Hoelzer. Included here for completeness. Simple popup interface that allows for simple updates on the progress.

```
function progressbar(varargin)
% Description:
%   progressbar() provides an indication of the progress of some task using
% graphics and text. Calling progressbar repeatedly will update the figure and
% automatically estimate the amount of time remaining.
%   This implementation of progressbar is intended to be extremely simple to use
% while providing a high quality user experience.
%
% Features:
%   - Can add progressbar to existing m-files with a single line of code.
%   - Supports multiple bars in one figure to show progress of nested loops.
%   - Optional labels on bars.
%   - Figure closes automatically when task is complete.
%   - Only one figure can exist so old figures don't clutter the desktop.
%   - Remaining time estimate is accurate even if the figure gets closed.
%   - Minimal execution time. Won't slow down code.
%   - Randomized color. When a programmer gets bored...
%
% Example Function Calls For Single Bar Usage:
%   progressbar               % Initialize/reset
%   progressbar(0)            % Initialize/reset
%   progressbar('Label')      % Initialize/reset and label the bar
%   progressbar(0.5)          % Update
%   progressbar(1)            % Close
%
% Example Function Calls For Multi Bar Usage:
%   progressbar(0, 0)         % Initialize/reset two bars
%   progressbar('A', '')      % Initialize/reset two bars with one label
%   progressbar('', 'B')      % Initialize/reset two bars with one label
```

```
%   progressbar('A', 'B')     % Initialize/reset two bars with two labels
%   progressbar(0.3)          % Update 1st bar
%   progressbar(0.3, [])      % Update 1st bar
%   progressbar([], 0.3)      % Update 2nd bar
%   progressbar(0.7, 0.9)     % Update both bars
%   progressbar(1)            % Close
%   progressbar(1, [])        % Close
%   progressbar(1, 0.4)       % Close
%
% Notes:
%   For best results, call progressbar with all zero (or all string) inputs
% before any processing. This sets the proper starting time reference to
% calculate time remaining.
%   Bar color is choosen randomly when the figure is created or reset. Clicking
% the bar will cause a random color change.
%
% Demos:
%     % Single bar
%     m = 500;
%     progressbar % Init single bar
%     for i = 1:m
%       pause(0.01) % Do something important
%       progressbar(i/m) % Update progress bar
%     end
%
%     % Simple multi bar (update one bar at a time)
%     m = 4;
%     n = 3;
%     p = 100;
%     progressbar(0,0,0) % Init 3 bars
%     for i = 1:m
%         progressbar([],0) % Reset 2nd bar
%         for j = 1:n
%             progressbar([],[],0) % Reset 3rd bar
%             for k = 1:p
%                 pause(0.01) % Do something important
%                 progressbar([],[],k/p) % Update 3rd bar
%             end
%             progressbar([],j/n) % Update 2nd bar
%         end
%         progressbar(i/m) % Update 1st bar
%     end
%
%     % Fancy multi bar (use labels and update all bars at once)
%     m = 4;
%     n = 3;
%     p = 100;
%     progressbar('Monte Carlo Trials','Simulation','Component') % Init 3 bars
%     for i = 1:m
%         for j = 1:n
%             for k = 1:p
%                 pause(0.01) % Do something important
%                 % Update all bars
%                 frac3 = k/p;
%                 frac2 = ((j-1) + frac3) / n;
%                 frac1 = ((i-1) + frac2) / m;
%                 progressbar(frac1, frac2, frac3)
%             end
%         end
%     end
%
% Author:
%   Steve Hoelzer
%
% Revisions:
% 2002-Feb-27   Created function
% 2002-Mar-19   Updated title text order
% 2002-Apr-11   Use floor instead of round for percentdone
% 2002-Jun-06   Updated for speed using patch (Thanks to waitbar.m)
% 2002-Jun-19   Choose random patch color when a new figure is created
% 2002-Jun-24   Click on bar or axes to choose new random color
```

```
% 2002-Jun-27   Calc time left, reset progress bar when fractiondone == 0
% 2002-Jun-28   Remove extraText var, add position var
% 2002-Jul-18   fractiondone input is optional
% 2002-Jul-19   Allow position to specify screen coordinates
% 2002-Jul-22   Clear vars used in color change callback routine
% 2002-Jul-29   Position input is always specified in pixels
% 2002-Sep-09   Change order of title bar text
% 2003-Jun-13   Change 'min' to 'm' because of built in function 'min'
% 2003-Sep-08   Use callback for changing color instead of string
% 2003-Sep-10   Use persistent vars for speed, modify titlebarstr
% 2003-Sep-25   Correct titlebarstr for 0% case
% 2003-Nov-25   Clear all persistent vars when percentdone = 100
% 2004-Jan-22   Cleaner reset process, don't create figure if percentdone = 100
% 2004-Jan-27   Handle incorrect position input
% 2004-Feb-16   Minimum time interval between updates
% 2004-Apr-01   Cleaner process of enforcing minimum time interval
% 2004-Oct-08   Seperate function for timeleftstr, expand to include days
% 2004-Oct-20   Efficient if-else structure for sec2timestr
% 2006-Sep-11   Width is a multiple of height (don't stretch on widescreens)
% 2010-Sep-21   Major overhaul to support multiple bars and add labels
%
persistent progfig progdata lastupdate
% Get inputs
if nargin > 0
    input = varargin;
    ninput = nargin;
else
    % If no inputs, init with a single bar
    input = {0};
    ninput = 1;
end
% If task completed, close figure and clear vars, then exit
if input{1} == 1
    if ishandle(progfig)
        delete(progfig) % Close progress bar
    end
    clear progfig progdata lastupdate % Clear persistent vars
    drawnow
    return
end
% Init reset flag
resetflag = false;
% Set reset flag if first input is a string
if ischar(input{1})
    resetflag = true;
end
% Set reset flag if all inputs are zero
if input{1} == 0
    % If the quick check above passes, need to check all inputs
    if all([input{:}] == 0) && (length([input{:}]) == ninput)
        resetflag = true;
    end
end
% Set reset flag if more inputs than bars
if ninput > length(progdata)
    resetflag = true;
end
% If reset needed, close figure and forget old data
if resetflag
    if ishandle(progfig)
        delete(progfig) % Close progress bar
    end
    progfig = [];
    progdata = []; % Forget obsolete data
end
% Create new progress bar if needed
if ishandle(progfig)
else % This strange if-else works when progfig is empty (~ishandle() does not)

    % Define figure size and axes padding for the single bar case
    height = 0.03;
```

```
width = height * 8;
hpad = 0.02;
vpad = 0.25;

% Figure out how many bars to draw
nbars = max(ninput, length(progdata));

% Adjust figure size and axes padding for number of bars
heightfactor = (1 - vpad) * nbars + vpad;
height = height * heightfactor;
vpad = vpad / heightfactor;

% Initialize progress bar figure
left = (1 - width) / 2;
bottom = (1 - height) / 2;
progfig = figure(...
    'Units', 'normalized',...
    'Position', [left bottom width height],...
    'NumberTitle', 'off',...
    'Resize', 'off',...
    'MenuBar', 'none' );

% Initialize axes, patch, and text for each bar
left = hpad;
width = 1 - 2*hpad;
vpadtotal = vpad * (nbars + 1);
height = (1 - vpadtotal) / nbars;
for ndx = 1:nbars
    % Create axes, patch, and text
    bottom = vpad + (vpad + height) * (nbars - ndx);
    progdata(ndx).progaxes = axes( ...
        'Position', [left bottom width height], ...
        'XLim', [0 1], ...
        'YLim', [0 1], ...
        'Box', 'on', ...
        'ytick', [], ...
        'xtick', [] );
    progdata(ndx).progpatch = patch( ...
        'XData', [0 0 0 0], ...
        'YData', [0 0 1 1] );
    progdata(ndx).progtext = text(0.99, 0.5, '', ...
        'HorizontalAlignment', 'Right', ...
        'FontUnits', 'Normalized', ...
        'FontSize', 0.7 );
    progdata(ndx).proglabel = text(0.01, 0.5, '', ...
        'HorizontalAlignment', 'Left', ...
        'FontUnits', 'Normalized', ...
        'FontSize', 0.7 );
    if ischar(input{ndx})
        set(progdata(ndx).proglabel, 'String', input{ndx})
        input{ndx} = 0;
    end

    % Set callbacks to change color on mouse click
    set(progdata(ndx).progaxes, 'ButtonDownFcn', {@changecolor, progdata(ndx).progpatch})
    set(progdata(ndx).progpatch, 'ButtonDownFcn', {@changecolor, progdata(ndx).progpatch})
    set(progdata(ndx).progtext, 'ButtonDownFcn', {@changecolor, progdata(ndx).progpatch})
    set(progdata(ndx).proglabel, 'ButtonDownFcn', {@changecolor, progdata(ndx).progpatch})

    % Pick a random color for this patch
    changecolor([], [], progdata(ndx).progpatch)

    % Set starting time reference
    if ~isfield(progdata(ndx), 'starttime') || isempty(progdata(ndx).starttime)
        progdata(ndx).starttime = clock;
    end
end

% Set time of last update to ensure a redraw
lastupdate = clock - 1;
```

```
end
% Process inputs and update state of progdata
for ndx = 1:ninput
    if ~isempty(input{ndx})
        progdata(ndx).fractiondone = input{ndx};
        progdata(ndx).clock = clock;
    end
end
% Enforce a minimum time interval between graphics updates
myclock = clock;
if abs(myclock(6) - lastupdate(6)) < 0.01 % Could use etime() but this is faster
    return
end
% Update progress patch
for ndx = 1:length(progdata)
    set(progdata(ndx).progpatch, 'XData', ...
        [0, progdata(ndx).fractiondone, progdata(ndx).fractiondone, 0])
end
% Update progress text if there is more than one bar
if length(progdata) > 1
    for ndx = 1:length(progdata)
        set(progdata(ndx).progtext, 'String', ...
            sprintf('%1d%%', floor(100*progdata(ndx).fractiondone)))
    end
end
% Update progress figure title bar
if progdata(1).fractiondone > 0
    runtime = etime(progdata(1).clock, progdata(1).starttime);
    timeleft = runtime / progdata(1).fractiondone - runtime;
    timeleftstr = sec2timestr(timeleft);
    titlebarstr = sprintf('%2d%%    %s remaining', ...
        floor(100*progdata(1).fractiondone), timeleftstr);
else
    titlebarstr = ' 0%';
end
set(progfig, 'Name', titlebarstr)
% Force redraw to show changes
drawnow
% Record time of this update
lastupdate = clock;
% ------------------------------------------------------------------------------
function changecolor(h, e, progpatch) %#ok<INUSL>
% Change the color of the progress bar patch
% Prevent color from being too dark or too light
colormin = 1.5;
colormax = 2.8;
thiscolor = rand(1, 3);
while (sum(thiscolor) < colormin) || (sum(thiscolor) > colormax)
    thiscolor = rand(1, 3);
end
set(progpatch, 'FaceColor', thiscolor)
% ------------------------------------------------------------------------------
function timestr = sec2timestr(sec)
% Convert a time measurement from seconds into a human readable string.
% Convert seconds to other units
w = floor(sec/604800); % Weeks
sec = sec - w*604800;
d = floor(sec/86400); % Days
sec = sec - d*86400;
h = floor(sec/3600); % Hours
sec = sec - h*3600;
m = floor(sec/60); % Minutes
sec = sec - m*60;
s = floor(sec); % Seconds
% Create time string
if w > 0
    if w > 9
        timestr = sprintf('%d week', w);
    else
        timestr = sprintf('%d week, %d day', w, d);
    end
```

```
elseif d > 0
    if d > 9
        timestr = sprintf('%d day', d);
    else
        timestr = sprintf('%d day, %d hr', d, h);
    end
elseif h > 0
    if h > 9
        timestr = sprintf('%d hr', h);
    else
        timestr = sprintf('%d hr, %d min', h, m);
    end
elseif m > 0
    if m > 9
        timestr = sprintf('%d min', m);
    else
        timestr = sprintf('%d min, %d sec', m, s);
    end
else
    timestr = sprintf('%d sec', s);
end
```

Symbolic Math

Takes a string of mathematical algebra and returns the calculated answer, used in enhancing input boxes with math functionality.

```
function [NumberOutput] = SymbolicMath(StringInput)
% Initialize
StringInput(StringInput==' ') = [];
Intermediates = zeros(3,1);
collapsed = false(size(StringInput));
count = 1;

% Brackets & Basic Numbers
level = 0; basic_number_start = 0;
for i = 1:length(StringInput)
    if strcmp(StringInput(i),'(')
        if level == 0
            start = i;
        end
        level = level + 1;
    elseif strcmp(StringInput(i),')')
        level = level - 1;
        if level == 0
            Intermediates(1,count) = start;
            Intermediates(2,count) = i;
            Intermediates(3,count) = SymbolicMath(StringInput((start+1):(i-1)));
            collapsed(start:i) = true;
            count = count + 1;
        end
    end
    if level == 0 && ismember(StringInput(i), '0123456789.eE')
        if basic_number_start == 0
            basic_number_start = i;
        end
        if i == length(StringInput)
            Intermediates(1,count) = basic_number_start;
            Intermediates(2,count) = i;
            Intermediates(3,count) = ...
                str2double(StringInput(basic_number_start:i));
            collapsed(basic_number_start:i) = true;
            basic_number_start = 0;
            count = count + 1;
        end
```

```
    else
        if basic_number_start ~= 0
            Intermediates(1,count) = basic_number_start;
            Intermediates(2,count) = i - 1;
            Intermediates(3,count) = ...
                str2double(StringInput(basic_number_start:(i-1)));
            collapsed(basic_number_start:(i-1)) = true;
            basic_number_start = 0;
            count = count + 1;
        end
    end
end
if level ~= 0
    NumberOutput = NaN;
    return;
end

% Exponents
if strcmp(StringInput(1),'^') || strcmp(StringInput(end),'^')
    NumberOutput = NaN;
    return;
end
for i = 2:(length(StringInput)-1)
    if ~collapsed(i)
        if strcmp(StringInput(i),'^')
            % Find the intermediate before and after and merge them
            before = 0;
            after = 0;
            for ind = 1:(count-1)
                if Intermediates(2,ind) == i-1
                    before = ind;
                elseif Intermediates(1,ind) == i+1
                    after = ind;
                end
            end
            if before > 0 && after > 0
                Intermediates(3,before) = Intermediates(3,before) ^ ...
                    Intermediates(3,after);
                Intermediates(2,before) = Intermediates(2,after);
                Intermediates(1,after) = -1;
                Intermediates(2,after) = -1;
            else
                NumberOutput = NaN;
                return;
            end
            collapsed(i) = true;
        end
    end
end

% Division
if strcmp(StringInput(1),'/') || strcmp(StringInput(end),'/')
    NumberOutput = NaN;
    return;
end
for i = 2:(length(StringInput)-1)
    if ~collapsed(i)
        if strcmp(StringInput(i),'/')
            % Find the intermediate before and after and merge them
            before = 0;
            after = 0;
            for ind = 1:(count-1)
                if Intermediates(2,ind) == i-1
                    before = ind;
                elseif Intermediates(1,ind) == i+1
                    after = ind;
                end
            end
            if before > 0 && after > 0
                Intermediates(3,before) = Intermediates(3,before) / ...
```

```
                    Intermediates(3,after);
                Intermediates(2,before) = Intermediates(2,after);
                Intermediates(1,after) = -1;
                Intermediates(2,after) = -1;
            else
                NumberOutput = NaN;
                return;
            end
            collapsed(i) = true;
        end
    end
end

% Multiplication
if strcmp(StringInput(1),'*') || strcmp(StringInput(end),'*')
    NumberOutput = NaN;
    return;
end
for i = 2:(length(StringInput)-1)
    if ~collapsed(i)
        if strcmp(StringInput(i),'*')
            % Find the intermediate before and after and merge them
            before = 0;
            after = 0;
            for ind = 1:(count-1)
                if Intermediates(2,ind) == i-1
                    before = ind;
                elseif Intermediates(1,ind) == i+1
                    after = ind;
                end
            end
            if before > 0 && after > 0
                Intermediates(3,before) = Intermediates(3,before) * ...
                    Intermediates(3,after);
                Intermediates(2,before) = Intermediates(2,after);
                Intermediates(1,after) = -1;
                Intermediates(2,after) = -1;
            else
                NumberOutput = NaN;
                return;
            end
            collapsed(i) = true;
        end
    end
end

% Addition
if strcmp(StringInput(end),'+')
    NumberOutput = NaN;
    return;
end
for i = 1:(length(StringInput)-1)
    if ~collapsed(i)
        if strcmp(StringInput(i),'+')
            % Find the intermediate before and after and merge them
            before = 0;
            after = 0;
            for ind = 1:(count-1)
                if Intermediates(2,ind) == i-1
                    before = ind;
                elseif Intermediates(1,ind) == i+1
                    after = ind;
                end
            end
            if after > 0
                if before > 0
                    Intermediates(3,before) = Intermediates(3,before) + ...
                        Intermediates(3,after);
                    Intermediates(2,before) = Intermediates(2,after);
                    Intermediates(1,after) = -1;
```

```
                    Intermediates(2,after) = -1;
                else
                    % Intermediates(3,after) = Intermediates(3,after);
                    Intermediates(1,after) = i;
                end
            else
                NumberOutput = NaN;
                return;
            end
            collapsed(i) = true;
        end
    end
end

% Subtraction
if strcmp(StringInput(end),'-')
    NumberOutput = NaN;
    return;
end
for i = 1:(length(StringInput)-1)
    if ~collapsed(i)
        if strcmp(StringInput(i),'-')
            % Find the intermediate before and after and merge them
            before = 0;
            after = 0;
            for ind = 1:(count-1)
                if Intermediates(2,ind) == i-1
                    before = ind;
                elseif Intermediates(1,ind) == i+1
                    after = ind;
                end
            end
            if after > 0
                if before > 0
                    Intermediates(3,before) = Intermediates(3,before) - Intermediates(3,after);
                    Intermediates(2,before) = Intermediates(2,after);
                    Intermediates(1,after) = -1;
                    Intermediates(2,after) = -1;
                else
                    Intermediates(3,after) = - Intermediates(3,after);
                    Intermediates(1,after) = i;
                end
            else
                NumberOutput = NaN;
                return;
            end
            collapsed(i) = true;
        end
    end
end

% Assess conclusion
if ~all(collapsed)
    NumberOutput = NaN;
    return;
end
for i = 1:count-1
    if Intermediates(1,i) ~= -1
        NumberOutput = Intermediates(3,i);
        return;
    end
end
end
```

Is Function

Determines if a particular object of unknown type is a function. Usually this is for differentiating between an error and a correctly assigned function.

```
function [TF, ID] = isfunction(FUN)
% ISFUNCTION - true for valid matlab functions
%
%   TF = ISFUNCTION(FUN) returns 1 if FUN is a valid matlab function, and 0
%   otherwise. Matlab functions can be strings or function handles.
%
%   [TF, ID] = ISFUNCTION(FUN) also returns an identier ID. ID can take the
%   following values:
%      1  : FUN is a function string
%      2  : FUN is a function handle
%      0  : FUN is not a function, but no further specification
%     -1  : FUN is not a function but a script
%     -2  : FUN is not a valid function m-file (e.g., a matfile)
%     -3  : FUN does not exist (as a function)
%     -4  : FUN is not a function but something else (a variable)
%
%   FUN can be a cell array, TF and ID will then be arrays, the same size
%   as FUN
%
%   Examples:
%     tf = isfunction('lookfor')
%        % tf = 1
%     [tf, id] = isfunction({@isfunction, 'sin','qrqtwrxxy',1:4, @clown.jpg})
%        % -> tf = [ 1  1  0  0  0 ]
%        %    id = [ 2  1 -2 -4 -3 ]
%
%   See also FUNCTION, SCRIPT, EXIST,
%            ISA, WHICH, NARGIN, FUNCTION_HANDLE

% version 3.2 (apr 2018)
% (c) Jos van der Geest
% Matlab File Exchange Author ID: 10584
% email: samelinoa@gmail.com
%
% History:
% 1.0 (dec 2011) created for strings only
% 2.0 (apr 2013) accepts cell arrays
% 3.0 (feb 2014) implemented identier based on catched error
% 3.1 (feb 2014) added lots of help and documentation, inspired to post on
%                FEX by a recent Question/Answer thread
% 3.2 (apr 2018) spell check and contact info

if ~iscell(FUN)
    % we use cellfun, so convert to cells
    FUN = {FUN} ;
end
ID = cellfun(@local_isfunction,FUN) ; % get the identifier for each "function"
TF = ID > 0 ; % valid matlab functions have a positive identifier

% = = = = = = = = = = = = = = = = = = = = = =

function ID = local_isfunction(FUNNAME)
try
    nargin(FUNNAME) ; % nargin errors when FUNNAME is not a function
    ID = 1  + isa(FUNNAME, 'function_handle') ; % 1 for m-file, 2 for handle
catch ME
    % catch the error of nargin
    switch (ME.identifier)
        case 'MATLAB:nargin:isScript'
            ID = -1 ; % script
        case 'MATLAB:narginout:notValidMfile'
            ID = -2 ; % probably another type of file, or it does not exist
        case 'MATLAB:narginout:functionDoesnotExist'
            ID = -3 ; % probably a handle, but not to a function
        case 'MATLAB:narginout:BadInput'
```

```
            ID = -4 ; % probably a variable or an array
        otherwise
            ID = 0 ; % unknown cause for error
    end
end
```

G.2. Other Functions

Wall Smart Discretize

Takes a body, a mesher (set of discretize options) and an orientation over which the discretization is taking place and returns the set of boundary positions which will divide the body. This function looks at whether or not each surface of the body is exposed to a gas body, in which case it will generate the surface nodes. The rest of the body is either the maximum thickness or growing from the surface nodes.

```
function [x] = Wall_Smart_Discretize(Body,Mesher,Orient)
  %UNTITLED2 Summary of this function goes here
  %   Detailed explanation goes here
  material = Body.matl;
  if Body.matl.Phase == enumMaterial.Gas
    % Gas Body
    N_entrance = Mesher.Gas_Entrance_Exit_N;
    maximum_growth = Mesher.maximum_growth;
    maximum_thickness = Mesher.Gas_Maximum_Size;
    minimum_thickness = Mesher.Gas_Minimum_Size;
    % Derived Values
    shifti = [];
    switch Orient
      case enumOrient.Vertical
        [~,~,inside_dim, outside_dim] = Body.limits(Orient);
      case enumOrient.Horizontal
        [inside_dim,outside_dim,~,~] = Body.limits(Orient);
        if ~isscalar(inside_dim)
          shifti = inside_dim - inside_dim(1);
          inside_dim = inside_dim(1);
        end
        if ~isscalar(outside_dim)
          %shifto = outside_dim - outside_dim(1);
          outside_dim = outside_dim(1);
        end
    end
    Distance = outside_dim - inside_dim;
    Transition_Distance = Distance * 0.15;
    x = inside_dim;
    thickness = Transition_Distance / double(N_entrance);
    if thickness > maximum_thickness
      N = ceil(Distance/maximum_thickness);
      x = linspace(inside_dim,outside_dim,N+1);
    else
      while thickness < minimum_thickness && N_entrance > 1
        N_entrance = N_entrance - 1;
        thickness = Transition_Distance / double(N_entrance);
      end
      if N_entrance == 1
          thickness = min(minimum_thickness, Distance/2);
          if Distance/2 - thickness < thickness
              x = [inside_dim (inside_dim + outside_dim)/2 outside_dim];
          else
              x = [inside_dim inside_dim + thickness];
              marker = 2;
              while (x(end) < Distance/2 + inside_dim)
                thickness = min(maximum_thickness, maximum_growth * thickness);
                x(end+1) = x(end) + thickness;
              end
              % Adjust it at the end
              Current_Distance = x(end) - x(marker);
              Expected_Distance = Distance/2 + inside_dim - x(marker);
```

```
            x((marker+1):end) = (x((marker+1):end) - x(marker))*...
              (Expected_Distance/Current_Distance) + x(marker);
            % Flip it
            x = [x outside_dim-(flip(x(1:end-1))-inside_dim)];
        end
    else
        for i = 1:N_entrance
          x(end+1) = x(end) + thickness;
        end
        marker = length(x);
        while (x(end) < Distance/2 + inside_dim)
          thickness = min(maximum_thickness, maximum_growth * thickness);
          x(end+1) = x(end) + thickness;
        end
        % Adjust it at the end
        Current_Distance = x(end) - x(marker);
        Expected_Distance = Distance/2 + inside_dim - x(marker);
        x((marker+1):end) = (x((marker+1):end) - x(marker))*...
          (Expected_Distance/Current_Distance) + x(marker);
        % Flip it
        x = [x outside_dim-(flip(x(1:end-1))-inside_dim)];
    end
  end
else
  % Solid Body
  min_ang_frequency = Body.Group.Model.engineSpeed;
  oscillation_depth_N = Mesher.oscillation_depth_N;
  maximum_thickness = Mesher.maximum_thickness;
  maximum_growth = Mesher.maximum_growth;
  shifti = [];
  switch Orient
    case enumOrient.Vertical
      [~,~,inside_dim, outside_dim] = Body.limits(Orient);
      inside_exp = Mesher.isInsideRadiiExposed(Body);
      outside_exp = Mesher.isOutsideRadiiExposed(Body);
    case enumOrient.Horizontal
      [inside_dim,outside_dim,~,~] = Body.limits(Orient);
      inside_exp = Mesher.isBottomExposed(Body);
      outside_exp = Mesher.isTopExposed(Body);
      if ~isscalar(inside_dim)
        shifti = inside_dim - inside_dim(1);
        inside_dim = inside_dim(1);
      end
      if ~isscalar(outside_dim)
        %shifto = outside_dim - outside_dim(1);
        outside_dim = outside_dim(1);
      end
  end
  if Body.matl.dT_du == -1
    alpha = 1000000;
  else
    % output requirements, x must have the min and maximum point
    alpha = material.thermaldiffusivity;
  end

  % Using the 5% amplitude condition
  xdepth = 3*sqrt(2*alpha/min_ang_frequency);
  xtotal = outside_dim - inside_dim;
  if inside_exp
    if outside_exp
      if xtotal < 2*xdepth
        % Discretize the entire depth to the near wall standards
        N = ceil(xtotal/(xdepth/double(oscillation_depth_N)));
        x = linspace(inside_dim,outside_dim,N+1);
      else
        % Grow from both ends (calc with half then mirror)
        N_max = ceil(0.5*xtotal/(xdepth/double(oscillation_depth_N)));
        x = [linspace(inside_dim,inside_dim + xdepth,oscillation_depth_N+1) ...
          zeros(1,N_max-oscillation_depth_N)];
        i = oscillation_depth_N+1;
        while x(i) < inside_dim + xtotal/2
```

```
          i = i + 1;
          x(i) = x(i-1) + min([maximum_growth*(x(i-1)-x(i-2)) ...
            maximum_thickness]);
        end
        x(i) = inside_dim + xtotal/2;
        x(i+1:2*i-1) = outside_dim - (flip(x(1:i-1))-inside_dim);
        if length(x) > 2*i - 1
          x(2*i:end) = [];
        end
      end
    else
      if xtotal < xdepth
        % Discretize the entire depth to the near wall standards
        N = ceil(xtotal/(xdepth/double(oscillation_depth_N)));
        x = linspace(inside_dim,outside_dim,N+1);
      else
        % Grow from inside end
        N_max = ceil(xtotal/(xdepth/double(oscillation_depth_N)));
        x = [linspace(inside_dim,inside_dim + xdepth,oscillation_depth_N+1) ...
          zeros(1,N_max-oscillation_depth_N)];
        i = oscillation_depth_N+1;
        while x(i) < outside_dim
          i = i + 1;
          x(i) = x(i-1) + min([maximum_growth*(x(i-1)-x(i-2)) ...
            maximum_thickness]);
        end
        x(i) = outside_dim;
        if length(x) > i
          x(i+1:end) = [];
        end
      end
    end
  else
    if outside_exp
      if xtotal < xdepth
        % Discretize the entire depth to the near wall standards
        N = ceil(xtotal/(xdepth/double(oscillation_depth_N)));
        x = linspace(inside_dim,outside_dim,N+1);
      else
        % Grow from outside end, use mathematics from the other
        % direction, then flip afterwards
        N_max = ceil(xtotal/(xdepth/double(oscillation_depth_N)));
        x = [linspace(inside_dim,inside_dim + xdepth,oscillation_depth_N+1) ...
          zeros(1,N_max-oscillation_depth_N)];
        i = oscillation_depth_N+1;
        while x(i) < outside_dim
          i = i + 1;
          x(i) = x(i-1) + min([maximum_growth*(x(i-1)-x(i-2)) ...
            maximum_thickness]);
        end
        x(i) = outside_dim;
        if length(x) > i
          x(i+1:end) = [];
        end
        % Flip
        x = inside_dim + (outside_dim - x);
      end
    else
      % Discretize the entire depth to the minimum stardards
      N = ceil(xtotal/maximum_thickness);
      x = linspace(inside_dim,outside_dim,N+1);
    end
  end
end
if isempty(shifti)
  x = transpose(x);
else
  temp = transpose(x);
  x = zeros(length(x),length(shifti));
  for r = 1:length(temp)
    x(r,:) = shifti(:);
```

```
    end
    for c = 1:length(shifti)
      x(:,c) = x(:,c) + temp;
    end
  end
end
```

Tube Bank Friction

Determining the constant coefficient for friction across a staggered tube bank.

```
function [ Cf ] = TubeBankFriction( Xt,Xl,do )
%TUBEBANKFRICTION 300 -> Re -> 15,000
%   f = Cf*Re^-0.18
Xt_Xl = Xt/Xl;
Xl_do = Xl/do;
a = -0.108*Xt_Xl^2+0.3137*Xt_Xl-0.2335;
b = 0.7298*Xt_Xl^2-1.296*Xt_Xl+1.0343;
c = -0.2129*Xt_Xl^2+0.5613*Xt_Xl-0.7471;
Cf = a*Xl_do^2+b*Xl_do+c;
end
```

Aligned Tube Bank Conduction

Unused, defines the constant and exponent of a function for calculating convection for flow over a set of bare, aligned tubes.

```
function [ Const, Exponent ] = AlignedTubeBankConduction( Xt,Xl,do )
%ALIGNEDTUBEBANKCONDUCTION Const * Re ^ Exponent = Nst*Npr^(2/3)
Xt_Xl = Xt/Xl;
Xt_do = Xt/do;
Xl_do = Xl/do;
Const = (0.118*Xt_Xl+0.252);
Exponent = (-0.0125*Xt_Xl-0.433*Xl+0.0765*Xt-0.0892);
end
```

Tube Bank Convection Constant

Defines the constant and exponent of a function for calculating convection for flow over a set of bare, staggered tubes.

```
function [ Ch ] = TubeBankConvectiveConstant(Xt,Xl,do,Nr)
%TUBEBANKNUSSELT Nst*NPr^0.667 = [Ch]*NRe^-0.4
Xt_Xl = Xt/Xl;
Xt_do = Xt/do;
a = -0.1548*Xt_Xl+0.0591;
b = 0.5437*Xt_Xl-0.0373;
c = -1.9244*Xt_Xl^3+0.68562*Xt_Xl^2-7.9841*Xt_Xl+2.772;
Ch = a*Xt_do^2 + b*Xt_do + c;
if nargin > 3
  Ch = Ch*(1-1/(Nr^1.112+0.918353));
end
end
```

G.3. Relationships

Enum Relation

```
classdef enumRelation
   enumeration
      Constant,...
      StackedShift,... % Unused
      Fixed,... % Unuseable
```

```
      AreaConstant,...
      Scaled,...
      LowestScaled,...
      Stroke,...
      Piston,...
      Width
   end
end
```

Relation

```
classdef Relation < handle
    % Relation - Class
    % ... -> name - String
    % ... -> mode - enumRelation
    % ... -> con1 - Connection
    % ... -> con2 - Connection
    % ... -> frame - Frame, associated with a mechanism with stroke

    properties
        name;
        mode enumRelation;
        con1 Connection;
        con2 Connection;
        frame Frame;
        manager RelationManager;
    end

    methods
        function this = Relation(manager,name,mode,con1,con2,frame)
            this.manager = manager;
            this.name = name;
            this.mode = mode;
            this.con1 = con1;
            this.con2 = con2;
            if nargin > 5
                this.frame = frame;
            end
        end
        function deReference(this)
            for i = length(this.manager.Relations):-1:1
                if this.manager.Relations(i).con1 == this.con1 && ...
                    this.manager.Relations(i).con2 == this.con2
                    this.manager.Relations(i) = [];
                end
            end
            this.manager.isChanged = true;
        end
        function Item = get(this,PropertyName)
            switch PropertyName
                case 'Name'
                    Item = this.name;
                case 'Connection1'
                    Item = this.con1;
                case 'Connection2'
                    Item = this.con2;
                case 'Frame'
                    Item = this.frame;
                otherwise
                    fprintf(['XXX Relation GET Inteface for ' PropertyName ...
                        ' is not found XXX\n']);
            end
        end
        function set(this,PropertyName,Item)
            switch PropertyName
                case 'Name'
                    this.name = Item;
                otherwise
```

```
                    fprintf(['XXX Relation SET Inteface for ' PropertyName ...
                        ' is not found XXX\n']);
            end
        end
    end
end
```

RelationManager

Manages Geometric Relationships

```
classdef RelationManager < handle

  properties
    Group Group; % Group that this relation grid refers to
    Orient enumOrient;
    Relations Relation;
    Grid logical = [];
    Grid_modes cell;

    isChanged logical = false;
  end

  properties (Dependent)
    name;
  end

  methods
    %% Relation - Class
    % ... -> name - String
    % ... -> mode - enumRelation
    % ... -> con1 - Connection
    % ... -> con2 - Connection
    % ... -> frame - Frame, associated with a mechanism with stroke

    %% Grid Construction
    function this = RelationManager(Group, Orient)
      if nargin > 1
        this.Group = Group;
        this.Orient = Orient;
      end
    end
    function Item = get(this,PropertyName)
      switch PropertyName
        case 'Name'
          Item = this.name;
        case 'Relations'
          Item = this.Relations;
        otherwise
          fprintf(['XXX Group GET Inteface for ' PropertyName ...
            ' is not found XXX\n']);
      end
    end
    function set(this,PropertyName,Item) %#ok<INUSD,INUSL>
      switch PropertyName
        otherwise
          fprintf(['XXX Group SET Inteface for ' PropertyName ...
            ' is not found XXX\n']);
      end
    end
    function name = get.name(this)
      switch this.Orient
        case enumOrient.Horizontal
          name = 'Rel. Man. handling horizontal connections';
        case enumOrient.Vertical
          name = 'Rel. Man. handling vertical connections';
```

```
  end
end

function update(this)
  this.isChanged = false;
  % In essence, recreate the grid from the number of connections
  % ... in group, then append each relation one by one into the
  % ... grid
  this.Grid = false(1,length(this.Group.Connections));
  this.Grid_modes = cell(0);
  keep = true(size(this.Relations));
  for i = 1:length(this.Relations)
    if keep(i)
      for j = i+1:length(this.Relations)
        if keep(j)
          if this.Relations(i).con1 == ...
              this.Relations(j).con1 && ...
              this.Relations(i).con2 == ...
              this.Relations(j).con2
            keep(j) = false;
          end
        end
      end
    end
  end
  this.Relations(~keep) = [];
  for relation = this.Relations
    this.appendGrid(relation);
  end
end

function appendGrid(this, new_relation)
  % this.Relations(end+1) = new_relation;
  % So to make it here, there are no invalidities.
  ind1 = new_relation.con1.index;
  ind2 = new_relation.con2.index;

  % Adding to each other's groups
  group1 = find(this.Grid(:,ind1)==true);
  group2 = find(this.Grid(:,ind2)==true);
  allready = false;
  previous = 0;
  for i = 1:length(group2)
    group1(end+1) = group2(i);
  end
  if ~isempty(group1)
    for i = group1
      if this.Grid_modes{i} == new_relation.mode
        if allready
          this.merge_rows(i,previous);
          return;
        end
        % Simply append ind2 to this group
        this.Grid(i,ind1) = true;
        this.Grid(i,ind2) = true;
        allready = true;
        previous = i;
      end
    end
    if allready; return; end
  end

  % Forming new groups
  % To make it here, both entities are not part of a group that
  % ... has the same mode, thus, it forms a new group
  row = this.get_new_group_row();
  this.Grid(row,ind1) = true;
  this.Grid(row,ind2) = true;
  this.Grid_modes{row} = new_relation.mode;
end
```

```
function merge_rows(this,row1,row2)
  for i = 1:size(this.Grid,2)
    this.Grid(row1,i) = this.Grid(row1,i) || ...
      this.Grid(row2,i);
  end
  this.Grid(row2,:) = false;
  this.Grid_modes{row2} = enumRelation.empty;
end

function index = get_new_group_row(this)
  % See if there is an empty row
  for i = 1:size(this.Grid,1)
    if all(this.Grid(i,:)==false)
      index = i;
      return;
    end
  end
  % else make a new row
  index = size(this.Grid,1) + 1;
end

%% Relationship Adding
function yesno = isNewRelationValid(this, ind1, ind2)
  yesno = true;
  % Make sure that grid is actually large enough
  if ~(size(this.Grid,2) >= ind1 && size(this.Grid,2) >= ind2)
    this.update();
  end
  % If one of the connections does not have any existing
  % ... relations then it is an automatic pass
  if ~any(this.Grid(:,ind1)); yesno = true; return; end
  if ~any(this.Grid(:,ind2)); yesno = true; return; end
  % If we got to this point then we have to find if the two
  % ... indexes are connected in some way
  groups1 = find(this.Grid(:,ind1)==true);
  groups2 = find(this.Grid(:,ind2)==true);
  for i = groups1
    for j = groups2
      % Test to see if "i" is patheable to "j"
      target = j;
      start = i;
      [found, ~] = are_rows_connected(...
        this.Grid,target,start,false(size(this.Grid,1),1));
      if found
        yesno = false; return;
      end
    end
  end
end

function success = addRelation(this, name, mode, con1, con2, frame)
  success = false;
  if this.isChanged; this.update(); end
  if this.Orient ~= con1.Orient; return; end
  if con1.Orient ~= con2.Orient; return; end
  % There cannot be an existing thing between con1 and con2
  if ~this.isNewRelationValid(con1.index, con2.index)
    return;
  end
  if nargin > 5
    newRelation = Relation(this,name,mode,con1,con2,frame);
  else
    newRelation = Relation(this,name,mode,con1,con2);
  end
  this.Relations(end+1) = newRelation;
  this.update();
  success = true;
end

%% Relationship Editing
function [success, visitedgroups, shifts, data] = Edit(...
```

```
  this, con, shift, visitedgroups, shifts, data)
if this.isChanged; this.update(); end
%% Get all the shifts that happened due to this edit
if isa(con,'Connection')
  ind = con.index;
else
  ind = con;
end
if isempty(this.Grid)
  this.update();
end
if nargin < 4
  visitedgroups = false(size(this.Grid,1),1);
  shifts = zeros(size(this.Group.Connections));
  shifts(ind) = shift;
  data = struct();
end
groups = find(this.Grid(:,ind)==true);
for i = groups'
  if ~visitedgroups(i)
    cons = find(this.Grid(i,:)==true);
    [var, data] = this.getShifts(cons, i, ind, shift, data);
    if isempty(var); success = false; return; end
    shifts(cons) = var;
    visitedgroups(i) = true;
    for j = cons
      if shifts(j) ~= 0
        [success, visitedgroups, shifts, data] = ...
          this.Edit(j,shifts(j),visitedgroups,...
          shifts, data);
        if ~success; return; end
      end
    end
  end
end
success = true;

%% Apply all those shifts and test each body
if nargin < 4
  for i = 1:length(this.Group.Connections)
    this.Group.Connections(i).x = ...
      this.Group.Connections(i).x + shifts(i);
  end
  if isfield(data,'frames') && isfield(data,'frameshift')
    for i = 1:length(data.frames)
      for iLRM = this.Group.Model.Converters
        for RefFrame = iLRM.Frames
          if RefFrame == data.frames(i)
            Mech = RefFrame.Mechanism;
            Mech.dont_propegate = true;
            Mech.set('Stroke',...
              Mech.get('Stroke')+data.frameshift(i));
          end
        end
      end
    end
  end
  for iBody = this.Group.Bodies; iBody.update(); end
  for iBody = this.Group.Bodies
    if ~iBody.isValid
      for i = 1:length(this.Group.Connections)
        this.Group.Connections(i).x = ...
          this.Group.Connections(i).x - shifts(i);
      end
      if isfield(data,'frames') && isfield(data,'frameshift')
        for i = 1:length(data.frames)
          for iLRM = this.Group.Model.Converters
            for RefFrame = iLRM.Frames
              if RefFrame == data.frames(i)
                Mech = RefFrame.Mechanism;
                Mech.dont_propegate = true;
```

```
                Mech.set('Stroke',Mech.get('Stroke')-data.frameshift(i));
              end
            end
          end
        end
      end
      for iBody2 = this.Group.Bodies
        iBody2.update();
      end
      fprintf(['XXX Connection shift failed because ' ...
        'it caused overlaping bodies XXX\n']);
      success = false;
      return;
    end
  end
end

function [shifts, data] = getShifts(this, cons, group, root, shift, data)
  shifts = zeros(size(cons));
  if isnan(shift); return; end
  shifts(cons==root) = shift;
  if shift == 0; return; end
  if this.Group.Model.RelationOn
    switch this.Grid_modes{group}
      case enumRelation.Constant
        % Since we are not comming from the mechanism, these
        % ... behave as if they were constant
        shifts = shift * ones(size(cons));
      case enumRelation.StackedShift
        for i = length(cons):-1:1
          if this.Group.Connections(cons(i)).x > ...
              this.Group.Connections(root).x
            shifts(i) = shift;
          else
            shifts(i) = 0;
          end
        end
      case enumRelation.Fixed
        shifts = [];
      case enumRelation.AreaConstant
        if this.Orient == enumOrient.Vertical
          for i = length(cons):-1:1
            C1o = this.Group.Connections(root).x;
            C2o = this.Group.Connections(cons(i)).x;
            shifts(i) = ...
              sqrt(C2o^2 + ...
              shift * (2*C1o + shift)) - C2o;
          end
        else
          % Behaves as if it were constant
          shifts = shift * ones(size(cons));
        end
      case enumRelation.Scaled
        if this.Group.Connections(root).x == 0
          C1o = this.Group.Connections(root).x + shift/2;
          for i = length(cons):-1:1
            C2o = this.Group.Connections(cons(i)).x;
            shifts(i) = shift * C2o / C1o;
          end
        else
          C1o = this.Group.Connections(root).x;
          for i = length(cons):-1:1
            C2o = this.Group.Connections(cons(i)).x;
            shifts(i) = shift * C2o / C1o;
          end
        end
      case enumRelation.LowestScaled, ...
          enumRelation.Stroke, ...
          enumRelation.Piston
        curmin = inf;
```

```
  baseind = root;
  for i = length(cons):-1:1
    if this.Group.Connections(cons(i)).x < curmin
      curmin = this.Group.Connections(cons(i)).x;
      baseind = i;
    end
  end
  if baseind == root
    % Compacts to the other side
    curmax = -inf;
    for i = length(cons):-1:1
      if this.Group.Connections(cons(i)).x > curmax
        curmax = this.Group.Connections(cons(i)).x;
      end
    end
    for i = length(cons):-1:1
      C1o = this.Group.Connections(root).x;
      C2o = this.Group.Connections(cons(i)).x;
      shifts(i) = shift * ...
        (curmax - C2o)/(curmax - C1o);
    end
  else
    % Scale everything relative to the base
    for i = length(cons):-1:1
      C1o = this.Group.Connections(root).x;
      C2o = this.Group.Connections(cons(i)).x;
      shifts(i) = shift * ...
        (C2o - curmin) / (C1o - curmin);
    end
  end
  switch this.Grid_modes{group}
    case enumRelation.LowestScaled
      return;
    case enumRelation.Stroke
      % Get largest shift and edit the value of the
      % ... stroke in the same direction
      sgn = 1;
    case enumRelation.Piston
      % Get largest shift and edit the value of the
      % ... stroke in the opposite direction
      sgn = -1;
  end
  curmax = max(shifts);
  for rel = this.Relations
    if rel.mode == enumRelation.Stroke || ...
        any(cons == rel.con1.index) || ...
        any(cons == rel.con2.index)
      if isfield(data,'frame')
        data.frame(end+1) = rel.frame;
        data.frameshift(end+1) = sgn * curmax;
      else
        data.frame = rel.frame;
        data.frameshift = sgn * curmax;
      end
    end
  end
case enumRelation.Width
  switch length(cons)
    case 4
      xvals = zeros(4,1);
      for i = 1:4
        xvals(i) = ...
          this.Group.Connections(cons(i)).x;
      end
      % Determine order translation
      % location of first connection
      try
        indexes = zeros(4,1);
        temp = min(xvals);
        indexes(1) = find(xvals==temp);
        temp = min(xvals(xvals>temp));
```

```
    indexes(2) = find(xvals==temp);
    temp = min(xvals(xvals>temp));
    indexes(3) = find(xvals==temp);
    temp = max(xvals);
    indexes(4) = find(xvals==temp);
    if root == cons(indexes(1))
      % Middle should remain the same but shift up or
      % ... down
      shifts(indexes(1)) = shift;
      shifts(indexes(2)) = shift/2;
      shifts(indexes(3)) = shift/2;
      shifts(indexes(4)) = 0;
    elseif root == cons(indexes(2))
      % Boundaries should remain the same, but the
      % center should stretch
      shifts(indexes(1)) = 0;
      shifts(indexes(2)) = shift;
      shifts(indexes(3)) = -shift;
      shifts(indexes(4)) = 0;
    elseif root == cons(indexes(3))
      % Boundaries should remain the same, but the
      % center should stretch
      shifts(indexes(1)) = 0;
      shifts(indexes(2)) = -shift;
      shifts(indexes(3)) = shift;
      shifts(indexes(4)) = 0;
    else
      % Middle should remain the same but shift up or
      % ... down
      shifts(indexes(1)) = 0;
      shifts(indexes(2)) = shift/2;
      shifts(indexes(3)) = shift/2;
      shifts(indexes(4)) = shift;
    end
  catch
    fprintf('err');
  end
case 6
  xvals = zeros(6,1);
  for i = 1:6
    xvals(i) = ...
      this.Group.Connections(cons(i)).x;
  end
  % Determine order translation
  % location of first connection
  indexes = zeros(6,1);
  temp = min(xvals);
  indexes(1) = find(xvals==temp);
  temp = min(xvals(xvals>temp));
  indexes(2) = find(xvals==temp);
  temp = min(xvals(xvals>temp));
  indexes(3) = find(xvals==temp);
  temp = min(xvals(xvals>temp));
  indexes(4) = find(xvals==temp);
  temp = min(xvals(xvals>temp));
  indexes(5) = find(xvals==temp);
  temp = max(xvals);
  indexes(6) = find(xvals==temp);
  if root == cons(indexes(1))
    shifts(indexes(1)) = shift;
    shifts(indexes(2)) = shift/2;
    shifts(indexes(3)) = shift/2;
    shifts(indexes(4)) = shift/2;
    shifts(indexes(5)) = shift/2;
    shifts(indexes(6)) = 0;
  elseif root == cons(indexes(2))
    shifts(indexes(1)) = 0;
    shifts(indexes(2)) = shift;
    shifts(indexes(3)) = 0;
    shifts(indexes(4)) = 0;
    shifts(indexes(5)) = -shift;
```

```
            shifts(indexes(6)) = 0;
          elseif root == cons(indexes(3))
            shifts(indexes(1)) = 0;
            shifts(indexes(2)) = 0;
            shifts(indexes(3)) = shift;
            shifts(indexes(4)) = -shift;
            shifts(indexes(5)) = 0;
            shifts(indexes(6)) = 0;
          elseif root == cons(indexes(4))
            shifts(indexes(1)) = 0;
            shifts(indexes(2)) = 0;
            shifts(indexes(3)) = -shift;
            shifts(indexes(4)) = shift;
            shifts(indexes(5)) = 0;
            shifts(indexes(6)) = 0;
          elseif root == cons(indexes(5))
            shifts(indexes(1)) = 0;
            shifts(indexes(2)) = -shift;
            shifts(indexes(3)) = 0;
            shifts(indexes(4)) = 0;
            shifts(indexes(5)) = shift;
            shifts(indexes(6)) = 0;
          elseif root == cons(indexes(6))
            shifts(indexes(1)) = 0;
            shifts(indexes(2)) = shift/2;
            shifts(indexes(3)) = shift/2;
            shifts(indexes(4)) = shift/2;
            shifts(indexes(5)) = shift/2;
            shifts(indexes(6)) = shift;
          end
        otherwise
          fprintf(['XXX A width mate is not working ' ...
            'because it does not contain 4' ...
            'elements XXX\n']);
      end
    end
  end
  if any(isnan(shifts))
    fprintf('err');
  end
end

function color = getColor(this, index)
  if this.Group.isChanged; this.Group.update(); end
  count = 1;
  colors = ...
    [0.67, 0, 0; ...
    1, 0.33, 0.33; ...
    1, 0.67, 0; ...
    1, 1, 0.33; ...
    0, 0.67, 0; ...
    0.33, 1, 0.33; ...
    0.33, 1, 1; ...
    0, 0.67, 0.67; ...
    0, 0.67, 0; ...
    0.33, 0.33, 1; ...
    1, 0.33, 1; ...
    0.67, 0, 0.67; ...
    0.67, 0.67, 0.67; ...
    0.33, 0.33, 0.33];
  color = [0, 0, 0];
  for iGroup = this.Group.Model.Groups
    for RMan = iGroup.RelationManagers
      if RMan.isChanged; RMan.update(); end
      if RMan ~= this
        for i = 1:size(RMan.Grid,1)
          if any(RMan.Grid(i,:) == true)
            count = count + 1;
          end
        end
      else
```

```
            for i = 1:size(RMan.Grid,1)
              if i == index
                while (count > 14)
                  count = count - 14;
                end
                color = colors(count,:);
                return;
              end
              if any(RMan.Grid(i,:) == true)
                count = count + 1;
              end
            end
          end
        end
      end

      function Label = getLabel(this, mode, con1, con2)
        Label = '';
        for i = 1:length(this.Grid_modes)
          if this.Grid_modes{i} == mode
            % Find a relation that matches
            for Rel = this.Relations
              if Rel.mode == mode && (con1 == Rel.con1 || con1 == Rel.con2 || ...
                  con2 == Rel.con1 || con2 == Rel.con2)
                Label = Rel.name;
                return;
              end
            end
          end
        end
      end
    end
  end

function [yesno, checked] = are_rows_connected(grid,target,start,checked)
if target == start; yesno = true; return; end
yesno = false;
cols = find(grid(start,:)==true);
for i = cols
  rows = find(grid(:,i)==true);
  rows(checked(rows)) = [];
  for j = rows
    if j ~= start
      checked(j) = true;
      [yesno, checked] = are_rows_connected(grid,target,j,checked);
      if yesno; return; end
    end
  end
end
end

function [el] = custmink(array,k)
el = -inf;
for i = 1:k
  el = min(array(array>el));
end
end

function [el] = custmaxk(array,k)
el = +inf;
for i = 1:k
  el = max(array(array<el));
end
end
```

G.4. Optimization

Load Model

```
function Model = load_Model(name)
    newfile = [pwd '\Saved Files\' name];
    File = load(newfile,'Model');
    Model = File.Model;
    Model.AxisReference = gca;

    Model.showPressureAnimation = false;
    Model.recordPressure = false;
    Model.showTemperatureAnimation = false;
    Model.recordTemperature = false;
    Model.showVelocityAnimation = false;
    Model.recordVelocity = false;
    Model.showTurbulenceAnimation = false;
    Model.recordTurbulence = false;
    Model.recordOnlyLastCycle = true;
    Model.recordStatistics = true;
    Model.outputPath= '';
    Model.warmUpPhaseLength = 0;
    Model.animationFrameTime = 0.05;
end
```

Gradient Ascent

```
function [History] = GradientAscent(...
    Model, ...
    OptimizationSchemeID)
  History = [];
% Find the Folder "Test_Running" and allow the user to select a test set
% ... which generates the appropriate structure.
files = dir('Test_Running');
names = {files.name};
names(1:2) = [];
if ~iscell(names); names = {names}; end
for index = size(names,1):-1:1; names{index} = names{index}(1:end-2); end
index = listdlg('PromptString','Pick the test running conditions',...
    'ListString',names,...
    'SelectionMode','single',...
    'InitialValue',index);
if ~isempty(index)
    if strfind(names{index},'.m')
      func = str2func(names{index}(1:end-2));
    else
      func = str2func(names{index});
    end
    RunConditions = func();
else
    msgbox('A run condition struct is required to run the model.');
    return;
end

% Pick Optimizing Variable -> output: options
options = struct('OptimizedProperty','');
names = {
  'Max Power';
  'Max Thermo Power Per Unit Engine Volume';
  'Max Efficiency';
  'Max West Number'};
index = listdlg('ListString',names,...
  'SelectionMode','single',...
  'InitialValue',1);
```

```
if ~isempty(index)
  options.OptimizedProperty = names{index};
else
  msgbox('You must select a parameter to be optimized');
  return;
end
% RunConditions = struct that lays out the test conditions in the style of
% ... test set running.
if isfield(RunConditions,'PressureBounds')
    mod_pressure = ~isempty(RunConditions.PressureBounds);
    if length(RunConditions.PressureBounds) == 1
        options.MinPressure = 101325;
        options.MaxPressure = RunConditions.PressureBounds(2);
    elseif mod_pressure
        options.MinPressure = RunConditions.PressureBounds(1);
        options.MaxPressure = RunConditions.PressureBounds(2);
    end
else
  mod_pressure = false;
end
if isfield(RunConditions,'SpeedBounds')
    mod_speed = ~isempty(RunConditions.SpeedBounds);
    if length(RunConditions.SpeedBounds) == 1
        options.MinSpeed = 0.2;
        options.MaxSpeed = RunConditions.SpeedBounds(2);
    elseif mod_speed
        options.MinSpeed = RunConditions.SpeedBounds(1);
        options.MaxSpeed = RunConditions.SpeedBounds(2);
    end
else
  mod_speed = false;
end
originalname = replace(Model.name,' - Optimized','');
sets = RunConditions;
for optrial = 1:length(sets)
    RunConditions = sets(optrial);

    % Load the specificied model
    if isempty(RunConditions.title)
        Model.name = originalname;
        NewModel = [Model.name ' - Optimized'];
    else
        Model.name = RunConditions.title;
        NewModel = RunConditions.title;
    end

    RunConditions.title = NewModel;
    RunConditions.Model = NewModel;
    addpath('..\runs\');
    addpath(cd);

    found = false;
    for i = 1:length(Model.OptimizationSchemes)
        if Model.OptimizationSchemes(i).ID == OptimizationSchemeID
          Study = Model.OptimizationSchemes(i);
            Names = cell(1,length(Model.OptimizationSchemes(i).IDs));
            Objects = cell(1,length(Model.OptimizationSchemes(i).IDs));
            found = true;
            for k = 1:length(Model.OptimizationSchemes(i).IDs)
                Names{k} = Model.OptimizationSchemes(i).Names{k};
                switch Model.OptimizationSchemes(i).Classes{k}
                    case 'Connection'
                        for iGroup = Model.Groups
                            for iCon = iGroup.Connections
                                if iCon.ID == Model.OptimizationSchemes(i).IDs{k}
                                    Objects{k} = iCon;
                                    break;
                                end
                            end
                            if Objects{k} == iCon; break; end
                        end
```

```
                case 'LinRotMechanism'
                    for iLRM = Model.Converters
                        if iLRM.ID == Model.OptimizationSchemes(i).IDs{k}
                            Objects{k} = iLRM;
                            break;
                        end
                    end
            end
        end
        Fields = Model.OptimizationSchemes(i).Fields;
        break;
    end
end

if mod_pressure
    pressure_ind = length(Objects) + 1;
end
if mod_speed
    speed_ind = length(Objects) + mod_pressure + 1;
end

if ~found
    fprintf('XXX Model or Optimization Scheme is not found. XXX\b');
    return;
end

% Process the model
Model.name = NewModel;
% Open up memory, keeping only the last SnapShot
Model.SnapShots(1:end-1) = [];
% Recording Options
Model.showLivePV = false;
Model.showPressureAnimation = false;
Model.recordPressure = true;
Model.showTemperatureAnimation = false;
Model.recordTemperature = true;
Model.showVelocityAnimation = false;
Model.recordVelocity = false;
Model.showTurbulenceAnimation = false;
Model.recordTurbulence = true;
Model.showConductionAnimation = false;
Model.recordConductionFlux = false;
Model.showPressureDropAnimation = false;
Model.recordPressureDrop = false;
Model.recordOnlyLastCycle = true;
Model.recordStatistics = true;
Model.warmUpPhaseLength = 0;
Model.deRefinementFactorInput = 1;
Model.RelationOn = true;
save(Model.name,'Model');

% Initialize Recording
% ... Struct that provides the class-field names and value, as well as goal
h1 = figure();
h2 = figure();

% Adadelta parameters
extra = mod_pressure + mod_speed;
shifts = zeros(length(Objects) + extra,1);
take_a_break = false(length(shifts),1);
gradient = shifts;
% gamma = 0.6;
tol = 1e-6;
optimizing = true;
maxiterations = 30;
iteration = 1;
L = 0.001;
Scale = 1;
local_scale = 1;
%EPara2 = ones(size(shifts))*0.01;
%EGrad2 = ones(size(shifts));
```

```
    % Define History
    History = struct();
    [History.Score, success, ~, ~] = RunSubFunction(Model,RunConditions,options);
    if ~success
      fprintf('XXX Failed to run the first test, corrupted snapshot or unsolveable geometry
XXX\n');
      return;
    end
    History.Names = cell(size(Objects));
    History.IDs = zeros(size(Objects));
    for i = 1:length(Objects)
        History.Names{i} = Names{i};
        History.IDs(i) = Objects{i}.ID;
    end
    if mod_pressure
        History.Names{pressure_ind} = 'Pressure (Atm)';
    end
    if mod_speed
        History.Names{speed_ind} = 'Speed (Hz)';
    end
    History.data = zeros(length(Objects) + mod_pressure + mod_speed,0);
    if ~isempty(Study.History)
      iteration = iteration + 1;
      maxiterations = maxiterations + 1;
      for i = 1:length(History.Names)
        for j = 1:length(Study.History.Names)
          if strcmp(History.Names{i},Study.History.Names{j})
    %         EPara2(i) = Study.History.EPara2(j);
    %         EGrad2(i) = Study.History.EGrad2(j);
    %         gradient(i) = Study.History.gradient(j);
            break;
          end
        end
      end
      Scale = Study.History.Scale;
    end
    count = 1;
    for i = 1:length(Objects)
        History.data(i,count) = Objects{i}.get(Fields{i});
    end
    if mod_pressure
        History.data(pressure_ind,count) = RunConditions.EnginePressure/101325;
    end
    if mod_speed
        History.data(speed_ind,count) = RunConditions.rpm/60;
    end


    while optimizing && iteration < maxiterations
      iteration = iteration + 1;
        % Calculate local gradient - output shifts - using Adadelta
        for i = 1:length(Objects)
            if ~take_a_break(i)
                [gradient(i), History] = ...
                    getShiftObject(gradient(i),Objects{i},Fields{i},History,...
                    Model,RunConditions,options);
            end
        end
        if mod_pressure
            ind = pressure_ind;
            if ~take_a_break(ind)
                [gradient(ind), History, RunConditions] = getShiftRunCon(...
                    gradient(ind),History,Model,RunConditions,...
                    'EnginePressure',options.MinPressure,options.MaxPressure,options);
            end
        end
        if mod_speed
            ind = speed_ind;
            if ~take_a_break(ind)
                [gradient(ind), History, RunConditions] = getShiftRunCon(...
```

```
            gradient(ind),History,Model,RunConditions,...
            'rpm',options.MinSpeed,options.MaxSpeed,options);
      end
    end

    if max(abs(gradient)) < tol
      optimizing = false;
    end

    % Adadelta algorithm - Shifts
    for i = 1:length(Objects)
%     shifts(i) = sqrt((EPara2(i) + 1e-8) / ...
%       (EGrad2(i) + 1e-8)) * gradient(i);
      shifts(i) = L*gradient(i);%/sqrt(EGrad2(i) + 1e-8);
    end
    if mod_pressure
%     shifts(i) = sqrt((EPara2(pressure_ind) + 1e-8) / ...
%       (EGrad2(pressure_ind) + 1e-8)) * gradient(pressure_ind);
      shifts(pressure_ind) = gradient(pressure_ind);%/sqrt(EGrad2(pressure_ind) + 1e-8);
    end
    if mod_speed
%     shifts(speed_ind) = sqrt((EPara2(speed_ind) + 1e-8) / ...
%       (EGrad2(speed_ind) + 1e-8)) * gradient(speed_ind);
      shifts(speed_ind) = gradient(speed_ind);%/sqrt(EGrad2(speed_ind) + 1e-8);
    end
    if max(abs(shifts)) > Scale*0.005
      shifts = Scale*shifts*0.005/max(abs(shifts));
    elseif max(abs(shifts)) < Scale*0.002
      shifts = Scale*shifts*0.002/max(abs(shifts));
    end

    for i = 1:length(shifts)
      fprintf([num2str(shifts(i)) ' ']);
      if i == length(shifts)
        fprintf('\n');
      end
    end

    power_backup = History.Score(end);
    increasing = true;
    stepcount = 1;
    trial = 1;
    fprintf('Starting Uphill Climb \n');
    while increasing
      % Make a step
      backup = zeros(1,length(Objects)+mod_pressure+mod_speed);
      for i = 1:length(Objects)
        fprintf(['Shifting Object: ' num2str(i) '\n']);
          backup(i) = Objects{i}.get(Fields{i});
          if ~take_a_break(i)
            newValue = Objects{i}.get(Fields{i}) + shifts(i);
            if isa(Objects{i},'Connection')
              for iBody = Objects{i}.Bodies
                for iCon = iBody.Connections
                  if iCon.Orient == Objects{i}.Orient && iCon ~= Objects{i}
                    if sign(iCon.x - Objects{i}.x) == sign(shifts(i))
                      if ~iCon.IsFixedTo(Objects{i})
                          shifts(i) = sign(shifts(i)).*min(abs(shifts(i)), ...
                            abs(0.33*(iCon.x - Objects{i}.x)));
                      end
                    end
                  end
                end
              end
            end
            try_ = 0;
            while Objects{i}.get(Fields{i}) ~= newValue
              Objects{i}.set(Fields{i},newValue);
              if Objects{i}.get(Fields{i}) ~= newValue
                shifts(i) = shifts(i) / 2;
                newValue = Objects{i}.get(Fields{i}) + local_scale * shifts(i);
```

```
                    try_ = try_ + 1;
                    if try_ > 3; shifts(i) = 0; break; end
                  else; break;
                  end
                end
                take_a_break(i) = (~take_a_break(i) && abs(local_scale * shifts(i)) < tol);
              end
            end
            if mod_pressure
              fprintf(['Shifting Pressure: ' num2str(i) '\n']);
              backup(pressure_ind) = RunConditions.EnginePressure;
              RunConditions.EnginePressure = min(options.MaxPressure,...
                max(options.MinPressure,RunConditions.EnginePressure + local_scale *
shifts(pressure_ind)));
            end
            if mod_speed
              fprintf(['Shifting Speed: ' num2str(i) '\n']);
              backup(speed_ind) = RunConditions.rpm;
              RunConditions.rpm = min(options.MaxSpeed,...
                max(options.MinSpeed,RunConditions.rpm + local_scale * shifts(speed_ind)));
            end

            % Discretize & Run using a single run
            [Power, success, ShaftPower, statistics] = RunSubFunction(Model,RunConditions,options);

            if ~success || isnan(Power)
              fprintf('Simulation Failed\n');
              for i = 1:length(Objects); Objects{i}.set(Fields{i},backup(i)); end
              if mod_pressure; RunConditions.EnginePressure = backup(pressure_ind); end
              if mod_speed; RunConditions.rpm = backup(speed_ind); end
              Power = power_backup;
              break;
            end
            if all(take_a_break(i))
              fprintf('Simulation Stalled\n');
              break;
            end

            % Test the step
            fprintf('Testing the Next Step \n');
            increasing = Power > power_backup*1.002;
            if increasing
              if local_scale == 1
                % Continue stepping
                power_backup = Power;
                stepcount = stepcount + 1;
              else
                increasing = false;
                local_scale = 1;
              end
            else
              % Undo the shift
              for i = 1:length(Objects); Objects{i}.set(Fields{i},backup(i)); end
              if mod_pressure; RunConditions.EnginePressure = backup(pressure_ind); end
              if mod_speed; RunConditions.rpm = backup(speed_ind); end
              Power = power_backup;
              save(Model.name,'Model');
              if stepcount == 1 && trial < 3
                % We overstepped this point, but the gradient is still valid
                % shifts = shifts;
                trial = trial + 1;
                increasing = true;
                local_scale = local_scale / 2;
              else
                local_scale = 1;
                stepcount = 1;
                increasing = false;
              end
            end
          end
```

```
    if ~isfield(History,'Score'); History.Score = []; end
    count = length(History.Score) + 1;

    History.Score(count) = Power;

    figure(h1);
    plot(History.Score);
    xlabel('Trial');
    switch options.OptimizedProperty
      case 'Max Power'
        ylabel('Power [W]');
        title('Trend in Power during gradient ascent');
      case 'Max Thermo Power Per Unit Engine Volume'
        ylabel('Thermo Power [W] per m^3');
        title('Trend in Power Density during gradient ascent');
      case 'Max Efficiency'
        ylabel('Efficiency [%]');
        title('Trend in Efficiency during gradient ascent');
      case 'Max West Number'
        ylabel('West Number');
        title('Trend in West Number during gradient ascent');
    end


    for i = 1:length(Objects)
        History.data(i,count) = Objects{i}.get(Fields{i});
    end
    if mod_pressure
        History.data(pressure_ind,count) = RunConditions.EnginePressure/101325;
    end
    if mod_speed
        History.data(speed_ind,count) = RunConditions.rpm/60;
    end

    figure(h2);
    xlabel('Trial');
    ylabel('Position (m)');
    for i = 1:size(History.data,1)
        plot(History.data(i,:));
        hold on;
    end
    legend(History.Names,'Location','northwest')
    hold off;
    if count > 1
      if History.Score(count) - History.Score(count-1) < 1e-2
        fprintf('Simulation Stalled\n');
        break;
      end
    end
end
% History.EPara2 = EPara2;
% History.EGrad2 = EGrad2;
History.Scale = Scale;
History.gradient = gradient;
Study.History = History;
save(Model.name,'Model');

% Record Matrix of Body Sizes
for iGroup = Model.Groups
    for iBody = iGroup.Bodies
        if iBody.matl.Phase == enumMaterial.Gas
            if isempty(iBody.customname); field = ['Body_' num2str(iBody.ID)];
            else; field = replace(iBody.customname,' ','_');
            end
            [~,~,x1,x2] = iBody.limits(enumOrient.Vertical);
            [~,~,y1,y2] = iBody.limits(enumOrient.Horizontal);
            sets(optrial).(field) = [pi*(x2^2-x1^2) y2(1)-y1(1)];
            sets(optrial).Score = Power;
        end
    end
end
```

```
    sets(optrial).Score = Power;
    sets(optrial).Converged = success;
    sets(optrial).statistics = statistics;
    sets(optrial).HistoryScore = History.Score;
    sets(optrial).HistoryDOF = History.data;
    sets(optrial).HistoryNames = History.Names;
    save(['Optimization_set_' replace(replace(date,' ','_'),':','-')], 'sets');
end
end

function [Parameter, success, ShaftPower, statistics] = RunSubFunction(Model, RunConditions,
options)
    [success] = Model.Run(RunConditions);
    addpath(['..\runs\' RunConditions.title]);
    load([RunConditions.title '_Statistics'],'statistics');
    ShaftPower = mean(statistics.Power);
    switch options.OptimizedProperty
      case 'Max Power'
        Parameter = ShaftPower;
      case 'Max Thermo Power Per Unit Engine Volume'
          ThermoPower = 0;
        for iPV = Model.PVoutputs
            ThermoPower = ThermoPower + iPV.Power;
        end
        Vol = mean(statistics.VMax);
        if ThermoPower < 0 % To prevent convergence on an incorrect sense of optimal
            Parameter = ThermoPower;
        else
            Parameter = ThermoPower/Vol;
        end
        statistics.Power = ThermoPower;
      case 'Max Efficiency'
        Q = -sum(statistics.To_Source);
        Parameter = ShaftPower/Q;
      case 'Max West Number'
        Wo = ShaftPower;
        P = RunConditions.EnginePressure;
        dV = statistics.VMax - statistics.VMin;
        V = mean(dV(dV~=0));
        f = RunConditions.rpm/60;
        TH = RunConditions.SourceTemp;
        TK = RunConditions.SinkTemp;
        Parameter = Wo/(P*V*f)*(TH + TK)/(TH - TK);
    end
    statistics.Power = mean(statistics.Power);
    statistics.Time = [];
    statistics.Angle = [];
    statistics.Omega = [];
    statistics.TotalPower = [];
    statistics.To_Environment = sum(statistics.To_Environment);
    statistics.To_Source = sum(statistics.To_Source);
    statistics.To_Sink = sum(statistics.To_Sink);
    statistics.Flow_Loss = sum(statistics.Flow_Loss);
    %{
    Power = 0;
    for PV = Model.PVoutputs
      str = [PV.name '_' Model.name];
      str = replace(str,':',' -');
      load(['..\runs\' RunConditions.title '\' str '.mat'], 'data');
      pV = zeros(size(data.DependentVariable,1)+1,1); pP = pV;
      for i = 1:size(data.DependentVariable,2)
        pV(1:end-1) = data.IndependentVariable(:,i);
        pV(end) = data.IndependentVariable(1,i);
        pP(1:end-1) = data.DependentVariable(:,i);
        pP(end) = data.DependentVariable(1,i);
        Power = Power + PowerFromPV(pP,pV);
      end
    end
    %}
end
```

```
function [grad, History] = getShiftObject(grad,obj,fld,History,...
                Model,RunConditions,options)
if grad < 0
  modshift = -0.001;
else
  modshift = 0.001;
end
grad = 0;
backup = obj.get(fld);
newValue = backup + modshift;
try_ = 0;
while obj.get(fld) ~= newValue
    obj.set(fld,newValue);
    if obj.get(fld) == newValue
        [Power, success, ~, ~] = RunSubFunction(Model,RunConditions,options);
        % Undo
        obj.set(fld,backup);
        if ~success
          modshift = -modshift / 2;
          newValue = backup + modshift;
          obj.set(fld,newValue);
          try_ = try_ + 1;
          if try_ > 8; break; end
        else
          grad = (Power - History.Score(end))/modshift;
          return;
        end
    else
        modshift = -modshift / 2;
        newValue = backup + modshift;
        obj.set(fld,newValue);
        try_ = try_ + 1;
        if try_ > 8; break; end
    end
end
if grad == 0
  fprintf('err');
end
end

function [grad, History, RunCon] = getShiftRunCon(grad,History,...
                Model,RunCon,Field,MinVal,MaxVal,options)
success = false;
backup = RunCon.(Field);
while ~success
  if strcmp(Field,'EnginePressure')
    modshift = 100;
  elseif strcmp(Field,'rpm')
    modshift = 0.1;
  end
  RunCon.(Field) = min(MaxVal,max(MinVal,backup + modshift));
  [Power, success, ~, ~] = RunSubFunction(Model,RunCon,options);
  if ~success
    modshift = modshift/2;
    RunCon.(Field) = backup;
  end
end
grad = (Power - History.Score(end))/modshift;
% if sign(grad) == sign(modshift)
%     % Take advantage of it
%     History.Score(end) = statistics.TotalPower(end);
% else
%     % Undo the small change
%     RunCon.(Field) = RunCon.(Field) - modshift;
% end
end
```

Optimization Scheme

```
classdef OptimizationScheme < handle

    properties
        Model;
        name;
        ID;
        Names;
        Classes;
        IDs;
        Fields;
        History;
    end

    methods
        function this = OptimizationScheme(Model)
            if nargin > 0
                this.name = getProperName('Optimization Study');
                this.Model = Model;
                this.ID = Model.getOptimizationStudyID();
            end
        end
        function AddObj(this, obj, field)
            len = length(this.Names)+1;
            this.Names{len} = getProperName('Degree of Freedom');
            if strcmp(this.Names{len},'')
                this.Names{len} = [...
                    class(obj) ' - ' num2str(obj.ID) ' - ' field];
            end
            this.Classes{len} = class(obj);
            this.IDs{len} = obj.ID;
            this.Fields{len} = field;
        end
        function Item = get(this,PropertyName)
            switch PropertyName
                case 'Name'
                    Item = this.name;
                case 'DOFs'
                    Item = this.Names;
                otherwise
                    fprintf(['XXX Optimization Study GET Inteface for ' PropertyName ...
                        ' is not found XXX\n']);
            end
        end
        function set(this,PropertyName,Item)
            switch PropertyName
                case 'Name'
                    this.name = Item;
                case 'DOFs'
                    for i = length(Item):-1:1
                        if Item(i)
                            this.Names(i) = [];
                            this.Classes(i) = [];
                            this.IDs(i) = [];
                            this.Fields(i) = [];
                        end
                    end
                otherwise
                    fprintf(['XXX Optimization Study SET Inteface for ' PropertyName ...
                        ' is not found XXX\n']);
            end
        end
    end
end
```