Predicting polymer drag reduction in turbulent pipe flows from rheological characteristics

by

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Abstract

Predicting polymer drag reduction from polymer solution rheology can be potentially achieved by developing a model between friction factor and rheological characteristics. The model's foundation depends on establishing a correlation between these parameters, and its robustness depends on the size of the data utilized. To establish this relation for hydrocarbon-based polymer solutions, the present work demonstrates friction factor tests with water-based polymer solution as preliminary results and parallelly presents the design, fabrication and commissioning of a flow facility that can operate with diesel fuel as the flow medium. The water-based polymer solution analysis includes extensive pipe flow tests for three different pipe sizes (1-inch, 1.5-inch, and 2-inch inner diameter) and several drag reduction percentages, to gather pressure drop data from the pipe flow facility to further calculate the skin friction coefficient (C_f). For each pressure drop, a fluid sample from the pipe flow setup is tested for shear viscosity and extensional viscosity measurements. The shear viscosity (μ) measurements, along with the known fluid density (ρ), flow velocity (V) and pipe inner diameter (D) were utilized to calculate the Reynold's number (Re) of the flow through the relation $Re = (\rho\, V\, D)\, /\mu$ and the extensional viscosity data provides the relaxation time (t_r) of the sample which was utilized along with the shear rate (γ) to calculate the Weissenberg number (Wi), given by $Wi = t_r \cdot \gamma$. These values of C_f, Re and Wi for each sample point when projected together, exhibit good correlation, and presents strong clues towards understanding the dependence of C_f on Wi and Re. The extensive data for water-based polymer

solution test and its analysis are presented. This will be used as foundational work for similar pipe flow tests planned with diesel-based polymer solution, to be conducted in a separate flow facility for diesel.

Based on the concept of the water flow loop, the diesel flow facility with a 1-inch pipe size was designed with consideration on safety and ventilation around the loop. The detailed component level design is presented, and the fabrication and commissioning of the loop was completed. Similar to the water-based tests, three preliminary tests with diesel fuel were conducted at six different Re values (5000, 10000, 15000, 20000, 25000, and 30000) to confirm the alignment with the Newtonian friction factor values. The results showed close and consistent alignment with the Newtonian $C_f - Re$ curve, confirming the diesel flow loop's readiness for polymer solution tests.

Preface

For the water-based tests, all the pressure drop measurements and shear viscosity measurements were taken by me. The extensional viscosity measurement was a collaborative work, with the dripping test setup's design and commissioning completed by Lucas Warwaruk and Joel Fenske, and all subsequent relaxation time measurements performed by me.

I solely worked on the design of the new diesel flow loop under guidance of Dr. Sina Ghaemi and Lucas Warwaruk. The component level fabrication was a collaboration between the machine shop and a third-party welding company for certified welding for pressurized components for use with diesel. Post fabrication, the assembly and commissioning of the diesel flow loop was a collaborative effort between me, the machine shop, and the electrical department under the machine shop.

Acknowledgement

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Nomenclature

A	Cross section area	n	Rate index
D	Pipe inner diameter	t_r	Relaxation time
D_l	Minimum diameter at start of elastic regime	t_f	Time scale of the flow
		t_{dg}	Degradation time
D_{min}	Minimum diameter of the filament	τ	Shear stress
D_0	Nozzle diameter	τ_w	Shear stress at the wall
L	Characteristic length	γ	Wall shear rate
V	Velocity	γ_b	Bulk shear rate
Q	Volumetric flow rate	σ	Surface tension
C_f	Skin friction coefficient	ΔP	Pressure drop
De	Deborah number	μ	Viscosity
T_r	Trouton ration	μ_s	Viscosity (polymer solution)
Wi	Weissenberg number (wall shear rate)	μ_0	Zero rate viscosity
Wi_c	Weissenberg number (bulk shear rate)	μ_∞	Infinite rate viscosity
V_b	Bulk velocity	λ	Extensional viscosity
m	Slope	ϵ	Strain rate
b	Intercept (vertical axis)	ε	Pipe roughness (absolute)
c	Consistency	ρ	Density
f	Friction factor	ρ_w	Density (water)
f_s	Friction factor (smooth pipes)	ρ_s	Density (polymer solution)
f_r	Friction factor (rough pipes)	η_p	Polymer contribution to viscosity
k	Relative pipe roughness		

List of abbreviations

DR   -   Drag reduction.

MDR   -   Maximum drag reduction.

RPM   -   Rotation per minute.

PIV   -   Particle image velocimetry.

DNS   -   Direct numerical simulations.

VFD   -   Variable frequency drive.

ID   -   Inner diameter.

PID   -   Proportional integral derivative.

Chapter 1

Introduction

1.1 Motivation

Frictional losses in pipe flow play a crucial role in various engineering applications, such as fluid transport, pipeline design and energy distribution. Understanding the factors influencing friction in pipe flow and minimizing these frictional losses is essential for optimizing system performance and minimizing energy consumption. In hydrocarbon pipelines, the fluid is transported over very long distances at high flow rates, this implies turbulent flow and thus higher frictional losses causing a significant decrease in throughput, requiring increased energy consumption and higher operating costs.

Drag reduction (DR) through the addition of small amounts of high molecular weight polymers is a well-known phenomenon, first observed by Toms (1948). It has proven to be an effective method in minimizing flow turbulence and increasing throughput. This was successfully demonstrated for crude oil pipelines by Lescarboura et al. (1971) in both laboratory and field testing and was first commercially implemented in the Trans Alaskan pipeline system in 1979 (Burger et al., 1982).

Quantifying this drag reduction requires extensive testing of the polymer solution in a pipe flow system, which becomes impractical for a large-scale oil transport operation. The present work aims

to understand the relationship between the DR percentage and the rheological properties of water-based polymer solution by testing these parameters for three different pipe sizes, each with five different Reynold's number flow for 6-8 different DR percentages and utilizing these 30-40 data points for each pipe diameter to understand the trend and develop a robust model to predict the DR percentage using polymer solution rheology. The current work was focused on the water-based polymer solutions because a functioning water flow facility was already available to start testing immediately and results from these tests can be utilized as a proof of concept, but to provide a scalable prediction model for hydrocarbons, similar work was required to be done with diesel-based polymer solution, because the drag reducing polymers used for hydrocarbons are different from the one used for water in terms of molecular weight, solubility and drag reducing capabilities, this requires a separate diesel flow facility. To address this requirement, the design and commissioning of a diesel flow loop is scoped in this work, and successful commissioning and baseline tests are presented, confirming the loop readiness for future polymer-solution tests. The choice of using diesel was based on the facts that, firstly, diesel has a higher flash point (> 52 ºC) and low volatility, making it safer to handle at room temperature compared to other easily available hydrocarbons like gasoline and kerosine, and secondly, it has a much lower viscosity than crude oil, making the flow loop design simpler, manageable pump requirements and easier drainage of the loop for repeating tests.

1.2 Thesis overview

This report starts with a discussion on the background work and fundamental concepts related to this field to set the stage, followed by the detailed account of the water-based polymer solution

tests. It then goes over the rheological analysis for water-based solutions and discusses the results and observations from these tests. The discussion then pivots to the details of the diesel flow facility, followed by its preliminary testing, results and observations. Conclusion and future work are discussed henceforth. Below is a chapter wise breakdown of this overview.

Chapter 2 provides the background and current state of research in this field, and dives into a few conceptual topics that are used as framework for this study.

Chapter 3 discusses the pipe flow facility for water-polymer test and details the test procedures, followed by the calculations of C_f. Furthermore, it details the shear viscosity and extensional viscosity measurement setup and data processing to calculate Re and Wi, concluding with a section for the analysis of uncertainty in the measurements for C_f, Re and Wi.

Chapter 4 examines the results for the water-based polymer solution tests and talks about the observations.

Chapter 5 discusses the pipe flow facility for diesel-polymer test and details the baseline test procedures and discusses the preliminary results.

Chapter 6 summarizes the findings of water-polymer test and provides details on the future work.

Chapter 2

Literature review

This chapter will first discuss two fundamental properties of fluid, shear viscosity and extensional viscosity, understanding of which is important in laying the foundation for discussing the next topics like friction in pipe flow and polymer drag reduction that are key in understanding the background work, the current state of research in this field and the current work presented.

2.1 Shear viscosity

The shear viscosity of a fluid is a fundamental property which is governed by the strength of the intermolecular cohesive forces of the fluid and characterizes its resistance to flow. To understand it better, consider a fluid flow over a flat surface. In this flow condition, due to high intermolecular attraction between the fluid and the solid surface molecules, the fluid layer in contact with the surface gets stuck to it, leading to zero velocity (no slip condition) and as this resistance is transferred to the fluid layers adjacent to this contact layer, the flow velocity progressively decreases near the solid surface, this result in a typical velocity profile as shown in figure 1(a). This relative velocities between fluid layers leads to the development of shear stress (τ) acting coplanar, between two adjacent layers. For Newtonian fluids, at constant temperature and pressure

conditions the magnitude of shear stress (τ) is directly proportional to the gradient of the velocity profile (dV/dy). Here, y is the vertical axis described in figure 1 and dV/dy can also be equated to shear rate (γ). As shown in figure 1(a), towards the free stream the difference in velocity between layers is very small (Slope-1), resulting in lower shear stress and as we go closer to the surface the velocity changes much more rapidly (Slope-2), causing higher shear stress. This relation is called the newton's law of viscosity,

$$\tau = \mu \cdot \left(\frac{dV}{dy}\right) \tag{1}$$

or

$$\tau = \mu \cdot \gamma, \tag{1.1}$$

where the fluid's viscosity (μ) is the proportionality constant. The higher the intermolecular cohesion in a fluid, higher will be the shear stress developed for a given shear rate and thus higher will be the value of viscosity for that fluid.
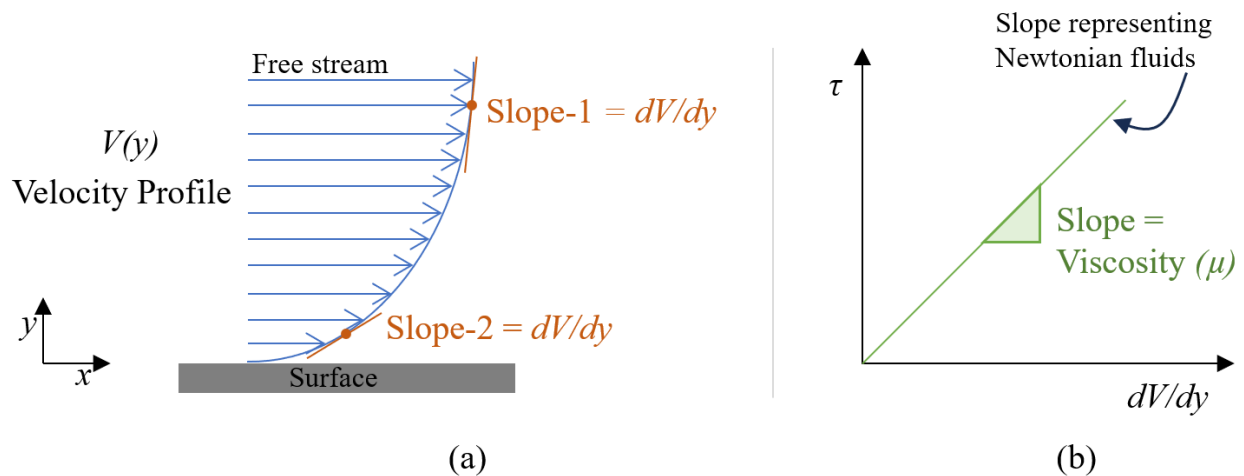
Figure 1: (a) Velocity profile of fluid flow over a surface. (b) Shear Stress (τ) versus gradient of velocity profile (dV/dy) plot showing the slope which represents the viscosity.

Viscosity is highly dependent on the temperature; it decreases with the increase in temperature. As the temperature of the fluid increases, its molecules attain a higher energy level, making it easier to overcome the cohesive forces between them and thus reducing the shear stresses for a given shear rate, resulting in lower viscosity. When the temperature is reduced, the intermolecular cohesive forces dominate again, causing viscosity to increase. The effect of pressure on viscosity is opposite, viscosity increases with the increase in pressure. This effect is comparatively much smaller and is usually neglected.

It can be summarized that for Newtonian fluids the relation between τ and γ at constant temperature and pressure is linear and the τ-γ curve crosses through zero. There is a class of fluids that does not follow either or both of the above two conditions, these fluids are categorized as non-Newtonian fluids. In general, these fluids can be sub categorized as detailed in figure 2 (Chhabra et al., 2010).
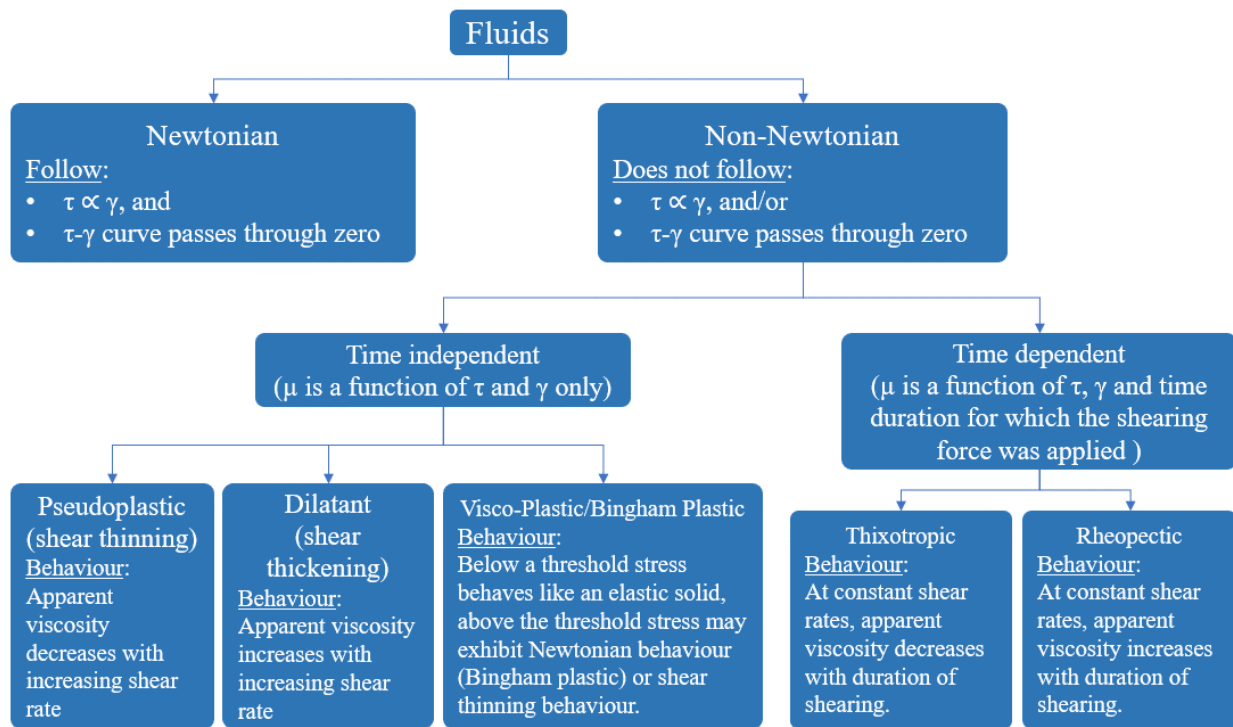
Figure 2: Fluid categories showing Newtonian and non-Newtonian properties and expanding on the further categorization of non-Newtonian fluids with their behavioral properties.

We will further elaborate on the pseudoplastic (shear thinning) fluids which is among the most common non-Newtonian fluids and represents the dilute polymer solutions that we will study extensively in the report. In shear thinning fluids the apparent viscosity decreases with the increase in shear rate. Specifically, for polymer solutions, at very low shear rates ($< 10^{-2}$ 1/s) the apparent viscosity approaches a constant value and becomes independent of shear rates, exhibiting Newtonian behaviour, this is termed as zero-rate viscosity (μ_0). Similarly, at very high shear rates the apparent viscosity plateaus towards a constant value of infinite-rate viscosity (μ_∞).

There have been many mathematical models and experimental fits proposed to approximate this behaviour for polymer solutions, the two most notable are elaborated below (Chhabra et al., 2010).

1. The power law model (Ostwald de Waele equation):

   This model is represented as

$$\mu = c\,(\gamma)^{n-1} \,, \tag{2}$$

   where, c is the consistency, and n is the power law rate index. For a positive value of n, less than one, this relation characterizes the shear thinning behaviour of the fluid for a range of shear rate. This relation, however, fails to predict the apparent viscosity plateaus for very low and very high shear rates, i.e. μ_0 and μ_∞.

2. The Cross-power law model (Cross, 1965):

   The equation

$$\mu = \mu_\infty + \left(\frac{(\mu_0 - \mu_\infty)}{1 + (c \cdot \gamma)^n} \right) \,, \tag{3}$$

is a more widely accepted model that overcomes the deficiencies of the simpler Ostwald

de Waele equation and correctly predicts μ_0 and μ_∞ for the two extreme shear rate cases.

2.2 Extensional viscosity

Extensional viscosity is a rheological property of fluids that quantifies their resistance to deformation under conditions of extension or stretching. It is more prominently studied in viscoelastic materials like polymer melts and dilute polymer solutions. This property was first studied by Trouton (1906) when he coined the term "coefficient of viscous traction (λ)". Trouton experimented with pitch (a viscoelastic polymer) and studied its extensional behaviour through a series of different experimental methods, he reported similar values of λ, repeatably achieved through the different methods tested. In his paper, he established the relation (experimentally) between shear viscosity (μ) and the coefficient of viscous traction or extensional viscosity (λ) as

$$\mu = \frac{1}{3}\lambda \ , \tag{4}$$

which was later theoretically derived by Burgers (1935). The relation, λ/μ is referred to as the Trouton ratio (T_r). While this ratio holds true for Newtonian fluids under steady and spatially uniform flows, these steady and uniform flows are almost never the case in practical applications like fiber turning, ink jet printing, blow molding etc., where extensional viscosity plays an important role. This makes modeling extensional flows and measuring extensional viscosity much more complicated than the simpler shear viscosity measurements.

For unsteady flow conditions, the concept of transient extensional viscosity $\lambda(t)$ was introduced (Barnes et al., 1989), in which λ is a function of both time (t) and strain rate (ε). But its use should be dealt with caution, as expressed by Petrie (2006), stating the inapplicability of the Trouton ratio in correctly describing non-Newtonian (viscoelastic) extensional flows, which requires specific constitutive equations for each type.

In terms of spatial flow fields, extensional flows are of three types (Petrie, 2006):

1. Uniaxial: Refers to elongation in a single axial direction (x) with thinning in the remaining two orthogonal directions (y and z). This flow represents the steady and spatially uniform extension that conforms with the Trouton ratio: $\lambda = 3\mu$ for Newtonian fluids.

2. Biaxial: Refers to extensional flow in two orthogonal directions (x and y) simultaneously with a corresponding decrease in thickness along the third direction (z). Like stretching a balloon. For this type of flow, $\lambda = 6\mu$ in Newtonian fluids.

3. Planar: Refers to extensional flow in one direction (x) with a constant width along the planar orthogonal direction (y) and a thickness contraction in the third direction (z). For this type of Newtonian flows, $\lambda = 4\mu$.

When the Trouton ration ($T_r = \lambda/\mu$) is applied to non-Newtonian fluids, a conceptual ambiguity arises because shear viscosity (μ) is a function of shear rate (γ), $\mu(\gamma)$ and extensional viscosity (λ) is a function of strain rate or the rate of elongation (ε), $\lambda(\varepsilon)$, and a relation between γ and ε is required to be established. This relation was proposed by Jones et al. (1987) for inelastic non-Newtonian fluids, equating $\gamma = \sqrt{3}\,\varepsilon$, and defining Trouton ration as

$$T_r = \frac{\lambda(\varepsilon)}{\mu(\sqrt{3}\varepsilon)} \ . \tag{5}$$

It was further shown by Jones et al. (1987) that for inelastic fluids the value of T_r is 3 for all values of ε, so therefore, viscoelastic fluids will represent all values of T_r apart from 3. This only helps in establishing viscoelastic behaviour of a fluid, but with the complex nature of such fluids, getting to a mathematical equation that correctly model this behaviour and predicts the extensional viscosity, required complex mathematical analysis.

Alternatively, the elastic property of these viscoelastic non-Newtonian fluids can be characterized by a parameter called relaxation time (t_r). It represents the time it takes for the fluid's mechanical response to return to equilibrium after being subjected to a deformation or disturbance. It is a measure of how quickly the fluid relaxes or returns to its original state once the applied force or deformation is removed.

In viscoelastic fluids, which exhibit both viscous (liquid-like) and elastic (solid-like) behavior, the relaxation time reflects the balance between these two aspects of the material's response to stress. When observed on a same time scale, a short relaxation time implies a quick return to equilibrium state after deformation indicating that the fluid behaves more like a viscous liquid and a long relaxation time implies that the fluid takes a significant amount of time to return to equilibrium after deformation. Such fluids exhibit more elastic behavior.

Here the mention of time sale is important as a fluid with short relaxation time can show elastic behavior if observed on a much shorter flow time scale and a fluid with a high relaxation time may still not show elastic dominance if observed on a longer flow time scale. This relationship between relaxation time (t_r) and time scale of the flow (t_f) is represented by a dimensionless parameter, Deborah number (De), shown as

$$De = \frac{t_r}{t_f} \ .$$
(6)

So, a smaller value of De represents more viscous behaviour and a higher value indicates more elastic behaviour of the fluid. An important thing to note here is that the time scale of the flow does not merely represent the observation time, instead it reflects the time scale of the deformation

(Poole, 2012), inherit to unsteady flows, implying that as the flow approached steady state, $t_f \rightarrow \infty$ and $De \rightarrow 0$.

For steady flows, another dimensionless parameter, the Weissenberg number (Wi) named after Karl Weissenberg, is often used. Wi is the ratio of the relaxation time of the fluid and the specific process time which is represented as the reciprocal of the shear rate for steady simple shear flows, given as

$$Wi = t_r \cdot \gamma \tag{7}$$

or

$$Wi = t_r \cdot \left(\frac{\partial V}{\partial y} \right). \tag{7.1}$$

As described by Poole (2012), the Weissenberg number assesses the extent of anisotropy or alignment produced by deformation and is suitable for characterizing flows with a consistent stretching history, like simple shear. Conversely, the Deborah number is better suited for characterizing flows with a variable stretching history and fundamentally quantifies the rate at which elastic energy is either stored or released.

2.3 Friction in pipe flow

Whenever a fluid is set in motion, either over an open surface or enclosed within a pipe or a duct, the liquid molecules face resistance to this motion due to friction between two fluid molecules or between the fluid molecules and the surface over which they are flowing. This surface is generally termed as the wall (the pipe's inner surface). There is an inertial resistance at play as well, but it is only experienced significantly during change in flow rates, it diminishes once a steady mass flow rate is reached.

Considering pipe flow, this resistance to the flow is what creates the pressure differential that is associated with the flow. As the energy from the pump is transferred from one fluid element to another, each fluid element experiences a cumulative resistance from all elements ahead of it in the flow direction, so the fluid element upstream experiences higher resistance compared to the fluid element downstream and thus the pressure at each cross-section drops as we go downstream of the flow.

This resistance is influenced by fluid density (ρ), fluid viscosity (μ), fluid velocity (V), pipe inner diameter (D) and absolute roughness of the pipe (ε). It can be quantified by a dimensionless parameter called friction factor (f) and through dimensional analysis (Benedict, 1980) can be shown to be a function of Reynold's number (Re) and relative roughness ($k = \varepsilon/D$) of the pipe. The pressure-drop (ΔP), associated with this resistance for a given length L of a circular pipe with diameter D can be characterized by the Darcy–Weisbach equation (Darcy and Weisbach, 1857)

$$\Delta P = f \cdot L \cdot \left(\frac{\rho}{2}\right) \cdot \left(\frac{V^2}{D}\right) , \tag{8}$$

this can be re-arranged to equate f as

$$f = \frac{D \cdot \left(\frac{\Delta P}{L}\right)}{\left(\frac{1}{2}\right) \cdot \rho \cdot V^2} . \tag{9}$$

The frictional resistance can also be represented by another dimensionless parameter called the mean skin friction coefficient (C_f) defined by Von Karman (1946), which is the ratio of shear stress at the wall (τ_w) and the dynamic pressure, expressed as

$$C_f = \frac{\tau_w}{\left(\frac{1}{2}\right) \cdot \rho \cdot V^2} , \tag{10}$$

Or

$$C_f = \frac{\left(\frac{D}{4}\right) \cdot \left(\frac{\Delta P}{L}\right)}{\left(\frac{1}{2}\right) \cdot \rho \cdot V^2} . \tag{10.1}$$

From (9) and (10.1) it can be shown that

$$f = 4\, C_f , \tag{11}$$

the representation of f and C_f requires ΔP to be known, and this can only be achieved through direct measurements on a pipe flow setup. But as discussed earlier in this section, f being a function of Re and k, there was a lot of interest and therefore work done to derive an expression to calculate the value of f directly from the known Re and k.

For Laminar flows, the work of Hagen and Poiseuille (1839) provided the exact solution to the Navier-Stokes equation

$$\Delta P = \frac{128 \cdot \mu \cdot Q \cdot L}{\pi D^4} , \qquad (12)$$

here Q is the volumetric flow rate. A corresponding equation for f can be achieved by equating (12) in (9), obtaining

$$f = \frac{64}{Re} , \qquad (13)$$

this clearly shows the independence of friction factor from the pipe roughness for the laminar flow regime. For Turbulent flows, since there is no exact solution for the Navier-Stokes equation, arriving to an equation was not that straight forward. During the first half of the 20th century, research was focused on both experimental and analytical evaluation of turbulent flow in smooth and rough pipes, and it will soon be evident that pipe roughness plays an important role in predicting the frictional losses.

Towards the experimental side, the most notable work was from Nikuradse (1933), where he conducted an extensive study on artificially roughened pipes for a wide range of materials and surface roughness to systematically understand the impact of pipe roughness on frictional losses. His work provided key contributions in our understanding of fluid flow in rough pipes and provided a relative roughness scale (Nikuradse sand scale) based on the sand roughness used for artificial roughness.

At the same time, Prandtl (1933), advancing on the analytical work of Blasius (1911) for smooth pipes, developed the theoretical law of friction in smooth pipes for Newtonian fluids, showing the relation between friction factor (f_s) and Re (Virk et al., 1970; Virk, 1971) as

$$\frac{1}{\sqrt{f_s}} = 4\, log\left(Re\,\sqrt{f_s}\right) - 0.4 \; , \tag{14}$$

here, f_s represents the Fanning friction factor which equated to the Darcy friction factor (f) as $f_s = (1/4) \cdot f$, and considering equation 11, $f_s = C_f$. Equation 14 showed good agreement with the experimental data from Nikuradse (1932) for smooth pipes.

Utilizing the valuable experimental data from Nikuradse for rough pipes, Von Karman proposed an expression for friction factor (f_r) for fully rough pipes (Benedict, 1980)

$$\frac{1}{\sqrt{f_r}} = 2\, log\left(\frac{Re}{\varepsilon}\right) + 1.74 \; . \tag{15}$$

With these developments a family of friction factor – Re curve were now available for smooth and fully rough region with different relative roughness, but there was an intermediate 'transition region' that was still unresolved.

Colebrook and White (1937) proposed an expression for this transition region and later combined it with the expression for the smooth pipe (14) and fully rough region (15) proposing a common solution for both smooth and rough pipes, expressed as

$$\frac{1}{\sqrt{f}} = -2\, Log\left[\frac{\varepsilon}{3.7\, D} + \frac{2.51}{Re\,\sqrt{f}}\right] , \tag{16}$$

an implicit equation that can be solved numerically. This completed the picture for mapping the friction factor curves for all flow regimes and pipe roughness. But this data was still scattered and based on the artificially roughened pipes. It took the work of Moody (1944) to combine the laminar, the turbulent smooth pipe, the turbulent transition, and fully rough region into one single

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plot that is famously known as the '*The Moody plot*' (figure 3). Moody's work also provided the

effective roughness for different commercial pipes on the Nikuradse sand scale, that allowed the

use of this plot for more practical applications since the empirical solutions through which this

plot was derived was based on the Nikuradse scale. The moody plot is still widely used in

commercial applications where a quick approximate estimation of the friction factor is desired
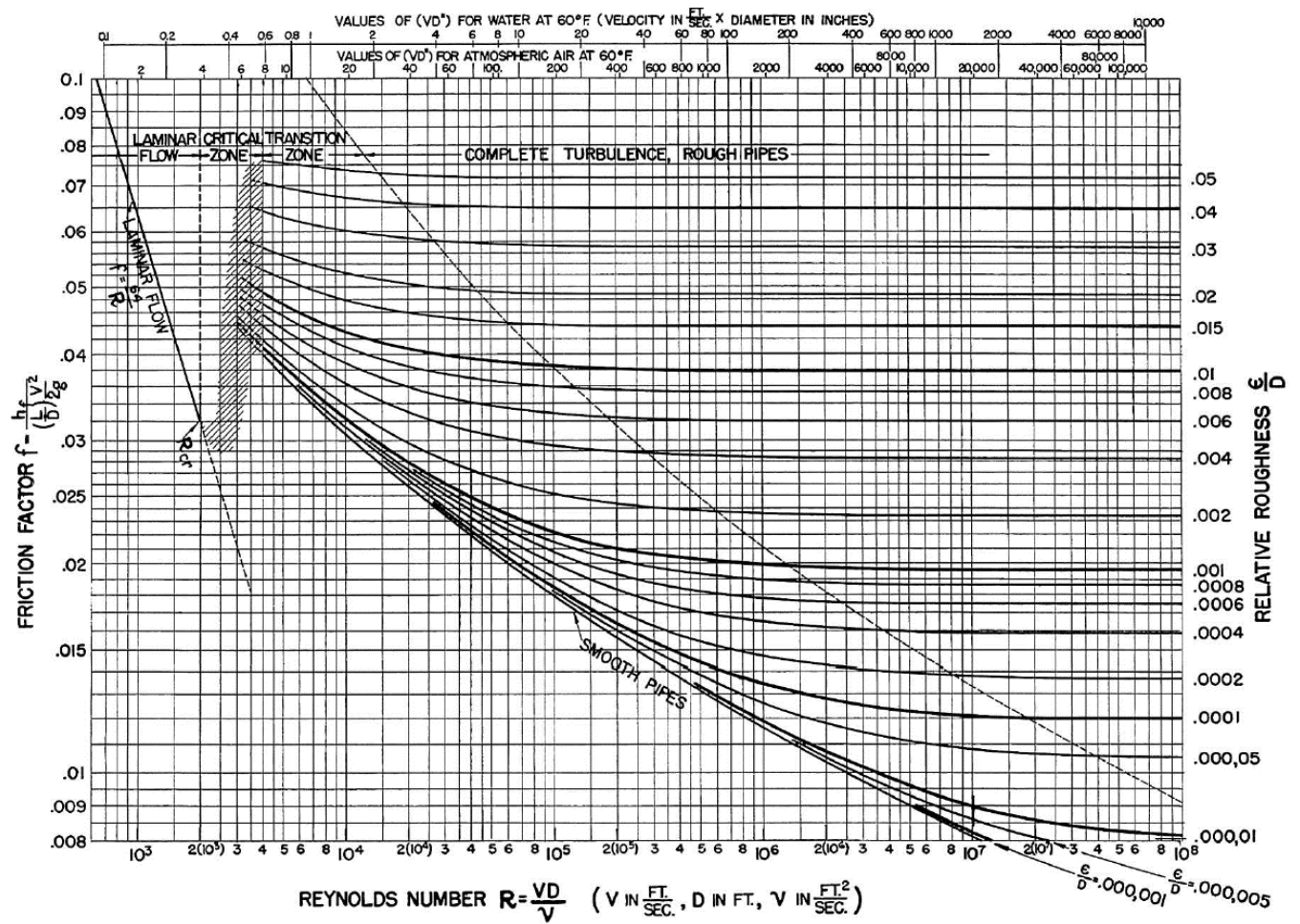
over an accurate one.

Figure 3: The 'Moody plot' (Moody, 1944) presenting the Darcy friction factor (*f*) versus *Re* curves for laminar, transition and fully rough region, specific to different material roughness. With permission from the American Society of Mechanical Engineers (ASME).

2.4 Polymer drag reduction

Polymer drag reduction is a phenomenon of reduction in frictional losses in turbulent flows by the addition of a small quantity of high molecular weight polymers. Since the discovery in the late 1940s (Toms, 1948), polymer drag reduction in fluid flow has been studied extensively to understand the physics behind the phenomenon, as well as to optimizing the mechanism for various practical applications including fluid pipeline transport, firefighting, water distribution, marine transport, aviation, agriculture etc.

Various types of polymers have been studied for their drag-reducing properties. polyacrylamides (PAM), polyethylene oxide (PEO), and xanthan gum are among the commonly investigated polymers. PAM, with its long-chain structure, flexibility and water solubility is particularly well-known for its effectiveness in reducing drag.

The mechanism behind polymer drag reduction can be attributed to the elastic properties of the polymer molecules (Tabor and de Gennes, 1986). As the fluid moves through the pipeline, the polymer molecules align themselves along the flow direction and the turbulent flow of the fluid stretches these polymer molecules, dissipating some of the turbulent energies (small eddies) in the process and reducing the overall turbulence and vortex shedding within the fluid. This leads to a more streamlined flow profile, resulting in a reduction of losses due to viscous friction, which translates into reduced pressure drop and enhanced flow efficiency. This simplistic explanation does not account for the lack of detailed mathematical correlation available at present between the near wall turbulence and friction factor that can be used to precisely predict DR, leaving a small gap in our understanding, that requires further experimental and analytical work.

The earlier work for understanding the mechanism responsible for drag reduction involved experimental measurements of mean velocity profile, notably, using the laser-Doppler flowmeter by Goldstein et al. (1969), Rudd (1971, 1972) and Kumor et al. (1973), specifically studying the turbulent boundary layer. Many velocity profile models were proposed because of these investigations, of which the three-layer model reported by Virk et al. (1970) and Virk (1971), with a viscous sublayer, an elastic sublayer, and a turbulent core, was in most agreement with the then available experimental results.

Recent advancement in experimental techniques like particle image velocimetry (PIV) and computational capabilities have expanded and refined our understanding of this phenomenon. White and Mungal (2008) had meticulously summarized the progress in this field so far. Their work highlights the two main explanations for the onset of DR, viscous effects, and elastic effects.

Viscous effects, advocated by Lumley (1969), L'vov et al. (2004), and Ryskin (1987), propose that polymer stretching in turbulent flow increases effective viscosity. Polymers stretch just beyond the viscous sublayer, called the buffer layer, boosting elongational viscosity. This elevated viscosity reduces turbulence, enlarges the buffer layer, and lowers wall friction.

Recent work by L'vov et al. (2004) and supported by Benzi et al. (2006) suggests another view. They propose that polymer stretching leads to a linearly increasing space-dependent effective viscosity from the wall.

Tabor and de Gennes (1986) introduce the elastic theory. It argues that partially stretched polymers store elastic energy, becoming significant for DR. This theory predicts DR onset when cumulative elastic energy equals kinetic energy within the buffer layer, disrupting the energy cascade,

thickening the buffer layer, and inducing DR. Experimental data supports the merit of both theories.

There are various factors that contribute towards the degree of drag reduction achieved for a particular polymer solution. Polymer concentration, being one of the factors, has a significant effect on drag reduction. Generally, as the polymer concentration is increased, the drag reduction increases due to the reduction in Reynolds shear stress, which accounts for most of the turbulence in the fluid. However, over a certain concentration the Reynolds shear stresses becomes zero and any further increase in the polymer concentration does not translate to further drag reduction. On the contrary, this further increase in polymer concentration increases the shear viscosity of the solution, thus in fact increasing turbulent friction. This region of the flow regime was studied by Virk (Virk et al., 1970; Virk, 1971) and was termed as 'maximum drag reduction (MDR)', and since DR being independent of the polymeric parameters, he proposed a universal Fanning friction factor relationship for MDR, expressed as

$$\frac{1}{\sqrt{f_s}} = 19.0 \, log\left(R_e \cdot \sqrt{f_s}\right) - 32.4 \ . \tag{17}$$

One application where the concept of polymer drag reduction has been utilized to a greater extent, is the transport of hydrocarbons fluids in pipeline over very large distances. The oil extracted from oil rigs in offshore and remote areas is required to be transported to the refining facilities which are generally near big cities and sometimes refined oil products are also transported from one location to another through these pipelines. Pumping these large volumes of fluid over such large spans at high flow rates has its incentives but it also implies overcoming the extensive hydrodynamic losses due to turbulent flow in the pipeline, and thus requires a great deal in

pumping power. The idea of reducing turbulence using polymer additives sparked great interest, which translated equally to the research and development that followed.

Lescarboura et al. (1971) conducted a comparative polymer drag reduction test in an 8-inch and 12-inch crude oil pipeline running 28 miles and 32 miles long respectively, using a drag reducer code named CDR and few grades of polyisobutylene. He reported around 50% maximum drag reduction with CDR for the case of 1150 ppm polymer concentration. His results also aligned with his 1-inch pipe lab tests when scaled up using flow velocity instead of pipe diameter. He also highlights that the reason for initial slow progress in this field was due to the limited availability of drag reducers in aliphatic hydrocarbons, leading to insufficient research base for companies to implement it on a large scale. The first commercial large-scale use of polymer drag reduction was for the Trans Alaskan Pipeline System (TAPS) during 1979 (Burger et al., 1982). They utilized the same drag reducer CDR as reported by Lescarboura and reported an increase in throughput of around 200,000 barrels per day (approximately 15% increase).

The lack of mathematical understanding of these complex turbulent flows has not slowed down progress on the experimental front. Nadolink and Haigh (1995) have meticulously summarized this progress with over 2500 references up to 1995, followed by Graham (2004), expanding on the progress in computational simulations of these flows, specifically through direct numerical simulations (DNS), that allowed analysis of the near-wall coherent structures, that are observed to be significantly modified by viscoelasticity.

Specific experimental work for modeling drag reduction through polymer solution rheology is presented by Owolabi et al. (2017), studying the drag reduction with polyacrylamide (PAM) solution in water at different concentrations in circular pipe and duct flows in a flow loop setup. Their work also presents shear viscosity and relaxation time measurements for samples collected

at different time periods during the flow tests and were able to relate the %DR to Wi with the data from both pipe and duct flow, converging to the relation %DR $= 2C_1[1/(1+e^{Wicr - Wi}) - Wi_{cr}]$, where C_1 is the limiting value of %DR as $Wi \rightarrow \infty$, reported to be 64 and Wi_{cr} represents the critical Wi for the onset of DR, reported as $Wi_{cr} = 0.5$. Additionally, $Wi \geq 5$ was reported for MDR.

The current work in this area is focused towards understanding the effect of molecular weight, solubility, macromolecular size, and polymer elastic properties on the drag reducing ability along with improvement in techniques to optimize and synthesize these polymers (Nesyn et al. 2018).

Chapter 3

Measurements in water-based polymer solutions

This chapter provides a detailed description of the pipe flow facility used for the water-based polymer solution test, it discusses the main component used to run the facility and how each component contribute towards obtaining the friction factor data from the pipe flow test. The details of all the test procedures, measurement analysis and calculations used are presented here. This is followed by the discussion on the shear viscosity and extensional viscosity measurements conducted on the polymer solution collected from the pipe flow test and how these measurements are used in relation to each other. Finally discussing the uncertainty in the measurements of C_f, Re and Wi.

3.1 Details of the pipe flow facility

The experimental setup for the water-based polymer solution test utilizes a 2-inch inner diameter (ID), horizontal pipe loop system, comprising of a vertical tank connected to a centrifugal pump

inlet. The pump outlet connects to the pipe loop with a total length of 22 m (including a 6.25 m long straight test section), the loop runs back into the tank and pump inlet, as shown in figure 4.
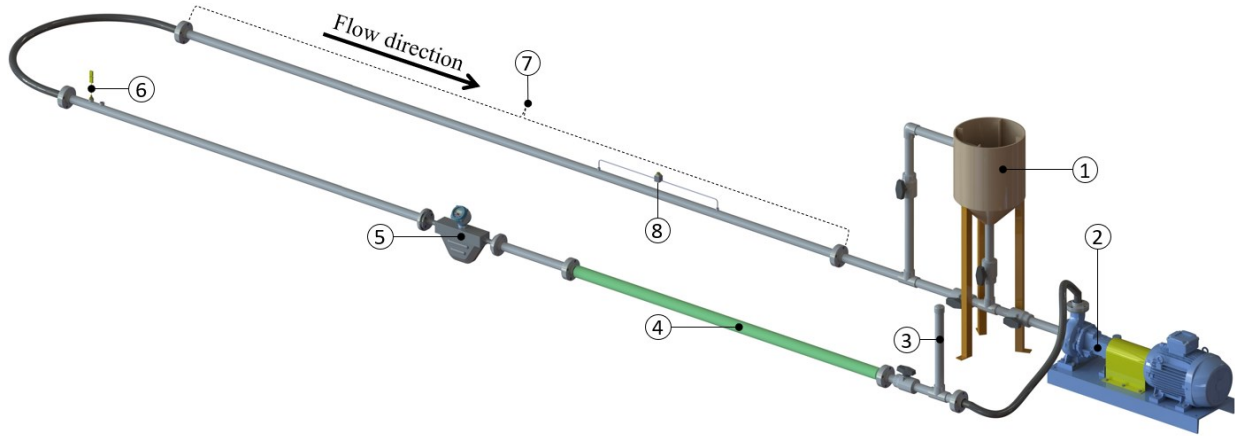

Figure 4: Overview of the pipe flow setup used for water-based tests, highlighting each component unit and flow direction.

The flow can be executed in an open loop configuration, where the flow runs through the tank with an open surface, or in a closed loop configuration, where the flow runs directly back into the pump inlet, bypassing the tank (refer to figure 5).

	Open Loop		Closed Loop	
V1	Open	V1	Closed
V2	Closed	V2	Open
V3	Open	V3	Open
V4	Open	V4	Open
V5	Open	V5	Open

Figure 5: Valve configuration details for pipe flow setup used for water-based test, providing configuration for open and closed loop system.

This flow loop allows controlling the flow rates and temperature of the fluid, while measuring the pressure drop for the fully developed turbulent flow in the test section. Figure 4 shows the flow loop system with the key components highlighted, which are detailed as follows:

1. Tank: 200 liters vertical plastic tank with a 2-inch outlet and inlet.

2. Pump: Georgia Iron Works 2X3LCC slurry pump powered by a TECO Westinghouse 40 HP motor.

3. Pulsation dampener: In-house fabricated air column dampener to stabilize the flow.

4. Heat exchanger: In-house fabricated, concentric tube design, with a 4-inch tube jacketing the 2-inch flow pipe, with inlet and outlet ports on the 4-inch pipe to run cold/hot water to regulate the temperature.

5. Coriolis flow meter: Micro motion 2-inch F-Series Coriolis flow meter (F200S418C2BAEZZZZ) with a 2700 series field mount transmitter (2700R12BBAEZZZ) for mass flow readings.

6. Thermocouple: K-type thermocouple from Omega for temperature readings.

7. Test section: The test section is a 6.25 m long straight stainless-steel pipe with an upstream pressure port at 3.75 m from the upstream edge and the distance between the upstream and downstream port (L) = 1.75 m. Three different test sections are used with 1-inch, 1.5-inch, and 2-inch inner pipe diameter.
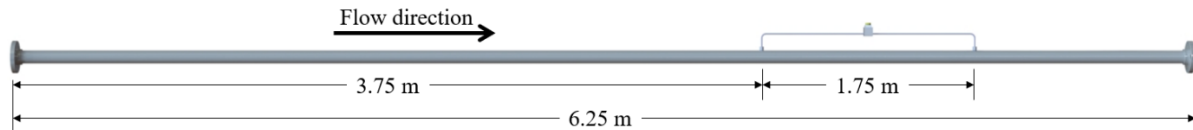
Figure 6: Details of the test section used for water-based test with measurements of the development region, distance between the pressure ports and overall test section length.

8. Pressure transducer: A valydine DP-15 pressure transducer was used, connected to the pressure port on the test section through 1/8-inch double-ferrule stainless-steel tube fittings. The diaphragm numbers used in the pressure transducer are: 3-22 ($\pm$ 0.20 psi) for 2-inch pipe size, 3-24 ($\pm$ 0.32 psi) for 1.5-inch pipe size and 3-30 ($\pm$ 1.25 psi) for 1-inch pipe size.

3.2 Preparation of the polymer solution

The solution studied is a 50 ppm (50 mg/l) solution of polyacrylamide (PAM) in water. PAM is a water soluble, high molecular weight polymer with a chemical structure -($-CH_2CHCONH_2$-)-$_n$. For a total test volume of 115 liters, 5.75 g of PAM is used to get 50 ppm concentration. A batch of 15 liters of water (at room temperature) is mixed with 5.75 g of PAM in a small tank, using an overhead mixer with a 3-inch impeller diameter, running at a very low RPM of about 20-30 to avoid any mechanical degradation of the polymer. The solution is mixed for 2 hours, and after that the mixing is stopped, and the impeller is lifted out of the solution to allow the residual polymer on the impeller to drip down into the solution. The solution is then allowed to sit for 24 hours, to facilitate the escape of microbubbles and homogenization of the solution. This 15-liter batch will subsequently be mixed with the remaining 100 liters of water in the pipe flow loop, before the test.

3.3 Test preparation and procedures

This section details the preparations done before the test and all test procedures used for the water-based testing. A total of three test sections (1-inch, 1.5-inch, and 2-inch inner pipe diameter) are tested separately. Each following the same procedure as described in the following sections.

3.3.1 Calculation of mass flow rates

A total of five averaged ΔP readings were collected per test by setting five mass flow rates ($\dot{M}$) corresponding to Re: 60000, 70000, 80000, 90000 and 100000 as a baseline. These calculations were based on the viscosity of water ($\mu = 0.0010023$ kg/m-s) at 20±0.5 ºC. These mass flow rates are calculated using the relation

$$\dot{M} = \frac{\pi \cdot D \cdot Re \cdot \mu}{4} \; , \tag{18}$$

and are presented in table 1 corresponding to each Re value and for each pipe size.

Pipe size = 1-inch $D = 0.0267$ m		Pipe size = 1.5-inch $D = 0.0413$ m		Pipe size = 2-inch $D = 0.0525$ m	
Re	$\dot{M}$ (kg/s)	Re	$\dot{M}$ (kg/s)	Re	$\dot{M}$ (kg/s)
60000	1.261	60000	1.932	60000	2.480
70000	1.471	70000	2.253	70000	2.893
80000	1.681	80000	2.575	80000	3.306
90000	1.891	90000	2.897	90000	3.720
100000	2.101	100000	3.219	100000	4.133

Table 1: Mass flow rate calculation listed for each pipe size with the measured inner diameter (D) per column, showing the mass flow rate required to achieve the corresponding Re for pipe flow test with water.

3.3.2 Pressure transducer calibration

The pressure transducer is calibrated using Omega DPI 610 pressure calibrator. Three consecutive calibrations are conducted for each diaphragm, with the transducer adjusted through the demodulator to output 0-10 volts corresponding to 0-max psi rated for that diaphragm. For each calibration, ten equally spaced pressure values are taken covering the full pressure range of the diaphragm and voltage output from transducer is recorded for each pressure point for both up and down pressure sweep. The voltage versus pressure is plotted to confirm the linearity of the curve and good overlap between up and down sweep which indicates no hysteresis loss.

3.3.3 De-airing and transducer bleeding procedure

When the loop is first filled with water, there are many air pockets all around the loop at locations like pipe joints, pipe bends and transducer tubing. These pockets, if not removed, can mix with the flow stream, and negatively impact the measurements. So, to ensure the removal of all air pockets and micro bubbles, a systematic process is followed to get the same level of flow quality every time. This process is explained step by step as follows:

Step 1: Ater water is introduced into the loop, set open loop valve configuration.

Step 2: Open transducer bypass valve and then close both the pressure transducer valves.

Step 3: Run the pump at 600 RPM for 5 minutes to allow bigger air bubbles to escape from the open surface in the tank.

Step 4: Stop the pump and switch to close loop configuration with tank outlet open.

Step 5: Slowly ramp up the RPM from 0 to 800 for 30 seconds, this will dislodge smaller air bubbles trapped in the pipe joints. These bubbles will now be visible in the flow stream.

Step 6: Gradually reduce the RPM from 800 to 400 and run for 5 minutes. This will allow the dislodged bubbles to escape through the tank inlet and outlet columns.

Step 7: Repeat step 5 and 6 two more times.

Step 8: Stop the pump and allow the fluid to rest for 10 minutes. This will allow the micro bubbles in the stream to rise and accumulate to form larger bubbles.

Step 9: Repeat step 5 and 6 two more times.

Step 10: Continue running the pump at 400 RPM for 10-15 minutes, use this run time to regulate the fluid temperature to achieve 20 $\pm$0.5 ºC.

Step 11: Stop the pump, close the tank outlet valve, and with the pressure transducer bypass valve open, open both bleed valves.

Step 12: Very slowly open both pressure port valves, allowing water into the transducer. This will start the bleeding. Let the bleeding continue for 3-4 minutes.

Step 13: Close both bleed valves and open the tank outlet valve.

Step 14: With the transducer bypass valve open, run the pump at 600 RPM for 2 minutes. This will push out any air bubbles in the transducer tubing, through the bypass line into the main pipe, which can then be escaped out.

Step 15: Stop the pump and close the transducer bypass valve.

Step 16: Verify that the fluid temperature is within 20±0.5 ºC, if not, run the pump at 400 RPM with the heat exchanger running till the correct temperature is achieved.

The system will now be ready for the test to begin.

3.3.4 Test procedure for baseline water test

For each test section, three independent tests with water are conducted to confirm alignment with the Newtonian C_f- Re curve (14) and repeatability of the results. Before the test, the tank is filled with 100 liters of water which is introduced into the loop, the loop de-airing and transducer bleeding process is then executed as detailed in section 3.3.3. The test is run using the LabVIEW software with a PID controller, and since a centrifugal pump is utilized here, the operator can either control the pump RPM in manual-mode or set the mass flow rates in auto-mode, which automatically adjusts the pump RPM to get the set mass flow rate. Table 1 breaks down the test procedure steps to run the baseline water test for the five mass flow values (refer to section 3.3.1) for each pipe size, aligning each step with the data log time and providing actions and set values against each step, while maintaining the flow temperature within 20±0.5 ºC

Step	Log time stamp	Action	For 1-inch pipe size	For 1.5-inch pipe size	For 2-inch pipe size	Temperature condition
1	-	Once transducer is calibrated, loop is filled and de-aired and transducer bleeding is completed, set closed loop configuration, and close the tank outlet valve.				20±0.5 ºC
2	-	Turn ON VFD, flow meter and transducer demodulator, verify pump is at zero RPM.				
3		Open pressure port valves and close the transducer bypass valve.				
4	0	Start data log.				
5	120	In manual mode, gradually increase pump RPM to 600.				
6	420	Set auto mode, then set $\dot{M}$ (kg/s) to →	1.261	1.932	2.480	
7	780	In auto mode, set $\dot{M}$ (kg/s) to →	1.471	2.253	2.893	
8	1140	In auto mode, set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
9	1500	In auto mode, set $\dot{M}$ (kg/s) to →	1.891	2.897	3.720	
10	1860	In auto mode, set $\dot{M}$ (kg/s) to →	2.101	3.219	4.133	
11	2220	Switch to manual mode and gradually reduce pump RPM to zero.				-
12	2340	Stop data log.				-
13	-	Open the transducer bypass valve and then close both pressure port valves.				-
14	-	Turn OFF VFD, flow meter and transducer demodulator				-
15	-	Drain the loop.				-

Table 2: Step-by-step test procedure aligning with the LabVIEW log time stamp, for baseline water pipe flow test for all three pipe sizes.

3.3.5 Polymer degradation test

The 50 ppm polymer solution was expected to result in 65-75% DR compared to the water data. So, to get more data points on the C_f-Re plot, lower concentrations were required to be tested. A way to simulate lower concentration is to intentionally degrade the polymer solution by means of mechanical degradation, which breaks down the long chain molecules and can lower the %DR. This was achieved by designing a polymer degradation test that runs a 50 ppm solution and progressively degrades it by running the pump at high RPMs for a close-to-exponential increments in time, for example: time intervals of $1 - 2 - 4 - 8 - 12 - 16 - 20$ minutes was used, and after each degradation step, dropping the mass flow to a known value that was tested for water to obtain the %DR after each degradation. This data was then used to plot %DR versus degradation time (t_{dg}) which was then used to derive a mathematical model to calculate t_{dg} required to get an evenly spaced %DR, to populate the C_f-Re plot evenly.

For this test, polymer solution was prepared using the process detailed in section 3.2. The tank is filled with 70 liters of tap water at room temperature. Water is then introduced in the loop and 'de-airing and transducer bleeding process' is followed as detailed in section 3.3.3. Next, the tank outlet valve is closed, and the 15 liters batch of polymer solution is poured into the tank. The same container is rinsed with 15 liters of water twice, and added to the tank, to extract any residual polymer stuck to the container wall. This completes the 115 liters of polymer solution in the pipe flow system. The tank outlet valve is then slowly opened, and the system is allowed to rest for 10 minutes so any new air bubble introduced due to pouring can escape. After that the below test procedure is followed for the degradation test.

Note: Since the high RPM degradation will require isolating the pressure transducer to protect it from over-pressurizing, the below two terms are used frequently, as defined, in the test procedure.

1. Isolate pressure transducer = Open the transducer bypass valve, then close both pressure port valves.
2. Reconnect pressure transducer = Open both pressure port valves, then close the transducer bypass valve

Step	Log time stamp	Action				Temperature condition
1	-	Once transducer is calibrated, loop is filled and de-aired, transducer bleeding is completed and polymer batch is added to the tank, set open loop configuration.				
2	-	Turn ON VFD, flow meter and transducer demodulator, verify pump is at zero RPM.				
3	-	Open pressure port valves and close the transducer bypass valve.				
4	0	Start data log.				
5	120	In manual mode, gradually increase pump RPM to 600. This will mix the polymer solution evenly.				
6	410	Switch to closed loop configuration and close tank outlet.				
			For 1-inch pipe size	For 1.5-inch pipe size	For 2-inch pipe size	20±0.5 ºC
7	420	Set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
8	770	Isolate pressure transducer				
9	780	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
10	810	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
11	820	Reconnect pressure transducer				
12	1160	Isolate pressure transducer				
13	1170	set manual mode, gradually increase pump RPM to →	1300	1300	1400	

14	1230	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
15	1240	Reconnect pressure transducer				
16	1580	Isolate pressure transducer				
17	1590	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
18	1710	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
19	1720	Reconnect pressure transducer				
20	2060	Isolate pressure transducer				
21	2070	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
22	2310	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
23	2320	Reconnect pressure transducer				
24	2660	Isolate pressure transducer				
25	2670	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
26	3150	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	20±0.5 ºC
27	3160	Reconnect pressure transducer				
28	3500	Isolate pressure transducer				
29	3510	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
30	4230	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
31	4240	Reconnect pressure transducer				
32	4580	Isolate pressure transducer				
33	4590	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
34	5550	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
35	5560	Reconnect pressure transducer				
36	5900	Isolate pressure transducer				
37	5910	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
38	7110	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	

39	7120	Reconnect pressure transducer				
40	7460	Isolate pressure transducer				
41	7470	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
42	8910	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
43	8920	Reconnect pressure transducer				
44	9440	Isolate pressure transducer				
45	9450	set manual mode, gradually increase pump RPM to →	1300	1300	1400	20±0.5 ºC
46	11130	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
47	11140	Reconnect pressure transducer				
48	11480	Isolate pressure transducer				
49	11490	set manual mode, gradually increase pump RPM to →	1300	1300	1400	
50	13410	set auto mode, then set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
51	13420	Reconnect pressure transducer				
52	13770	Switch to manual mode and gradually reduce pump RPM to zero.				-
53	13890	Stop data log.				-
54	-	Isolate pressure transducer				-
55	-	Turn OFF: VFD, flow meter and transducer demodulator				-
56	-	Drain the loop and rinse it with water twice.				-

Table 3: Step-by-step test procedure aligning with the LabVIEW log time stamp, for water-based polymer solution degradation test, for all three pipe sizes.

From the above test, the averaged ΔP value for the constant mass flow rate period after each degradation step is utilized along with the ΔP value from the baseline water test for the same mass flow rate to obtain the value of %DR after each degradation period as $(\Delta P_{water} - \Delta P_{polymer})/ \Delta P_{water} \times 100$. This %DR value is plotted against the degradation time duration up to each %DR point. The ΔP versus time plot for the whole test is shown in

figure 7 and the %DR versus Degradation time duration is presented in figure 8. These plots are for the 1.5-inch pipe size degradation test. The 1-inch and 2-inch tests showed similar plots.

The curve in figure 8 fits an exponential model: $(a \cdot e^{bx} + c \cdot e^{dx})$, with a, b, c, and d representing the coefficients and x representing the time. This was used to derive the required t_{dg} to achieve an evenly spaced %DR for the polymer solution test.
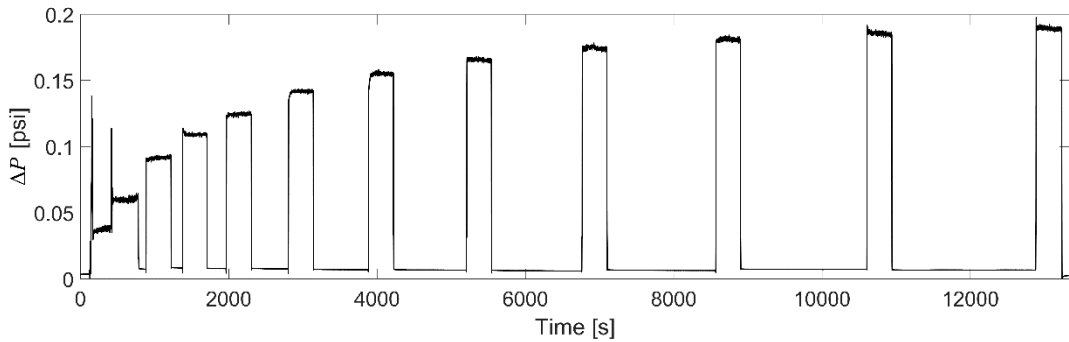
Figure 7: ΔP versus time plot for polymer degradation test detailed in table 3, this specific plot is from the 1.5-inch pipe size test, the test with other two pipe sizes exhibit similar plots.
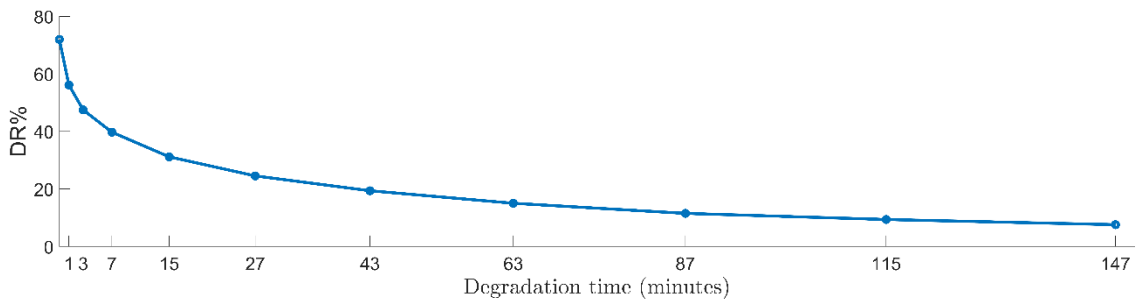
Figure 8: %DR versus degradation time plot for polymer degradation test in 1.5-inch pipe size, degradation was performed at 1300 pump PRM, the test with other two pipe sizes exhibit similar plots.

3.3.6 Polymer solution test

The preparation for the polymer test is the same as for the polymer degradation test. Polymer solution was prepared using the process detailed in section 3.2. The tank is filled with 70 liters of tap water at room temperature. Water is then introduced in the loop and 'de-airing and transducer bleeding process' is followed as detailed in section 3.3.3. At this stage, with water in the loop, the five mass flow rates mentioned in table-2 are run for 60 seconds each, to cross check the pressure drop readings with the baseline water test to ensure no deviation due to contamination or calibration shift. Next, the tank outlet valve is closed, and the 15 liters batch of polymer solution is poured into the tank. The same container is rinsed with 15 liters of water twice, and added to the tank, to extract any residual polymer stuck to the container wall. This completes the 115 liters of polymer solution in the pipe flow system. The tank outlet valve is then slowly opened, and the system is allowed to rest for 10 minutes so any new air bubble introduced due to pouring can escape. The below test procedure is followed for the polymer test.

Step	Log time stamp	Action	Temperature condition
1	-	Once transducer is calibrated, loop is filled and de-aired, transducer bleeding is completed and polymer batch is added to the tank, set open loop configuration.	20±0.5 ℃
2	-	Turn ON VFD, flow meter and transducer demodulator, verify pump is at zero RPM.	
3	-	Open pressure port valves and close the transducer bypass valve.	
4	0	Start data log.	
5	120	In manual mode, gradually increase RPM to 600. This will mix the polymer solution evenly.	
6	400	Isolate Pressure Transducer	
7	410	Switch to closed loop configuration and close tank outlet.	

			For 1-inch pipe size	For 1.5-inch pipe size	For 2-inch pipe size	
8	420	Set manual mode, gradually increase pump RPM to →	1300	1300	1400	
9	↑ + t_{dg}	Set auto mode, then set $\dot{M}$ (kg/s) to →	1.261	1.932	2.480	
10	↑ + 10	Reconnect Pressure Transducer				
11	↑ + 10	Collect baseline sample – 100 ml				
12	↑ + 160	Collect Re: 60000 sample – 100 ml				
13	↑ + 180	In auto mode, set $\dot{M}$ (kg/s) to →	1.471	2.253	2.893	
14	↑ + 180	Collect Re: 70000 sample – 100 ml				20±0.5 ℃
15	↑ + 180	In auto mode, set $\dot{M}$ (kg/s) to →	1.681	2.575	3.306	
16	↑ + 180	Collect Re: 80000 sample – 100 ml				
17	↑ + 180	In auto mode, set $\dot{M}$ (kg/s) to →	1.891	2.897	3.720	
18	↑ + 180	Collect Re: 90000 sample – 100 ml				
19	↑ + 180	In auto mode, set $\dot{M}$ (kg/s) to →	2.101	3.219	4.133	
20	↑ + 180	Collect Re: 100000 sample – 100 ml				
21	↑ + 180	Switch to manual mode and gradually reduce RPM to zero.				-
22	↑ + 120	Stop data log.				-
23	-	Isolate Pressure Transducer				-
24	-	Turn OFF: - VFD, flow meter and transducer demodulator				-
25	-	Drain the loop and rinse it with water twice.				-

Table 4: Step-by-step test procedure aligning with the LabVIEW log time stamp, for water-based polymer solution test, for all three pipe sizes.

In the above test procedure, log stamp 420 is the start of degradation period and ↑ + t_{dg} (indicating 420 + t_{dg}) gives the end time stamp for the degradation. t_{dg} value was adjusted based on the degradation test results to achieve different DR% which are evenly spaced out between MDR and the Newtonian values.

3.4 Calculation of skin-friction coefficient
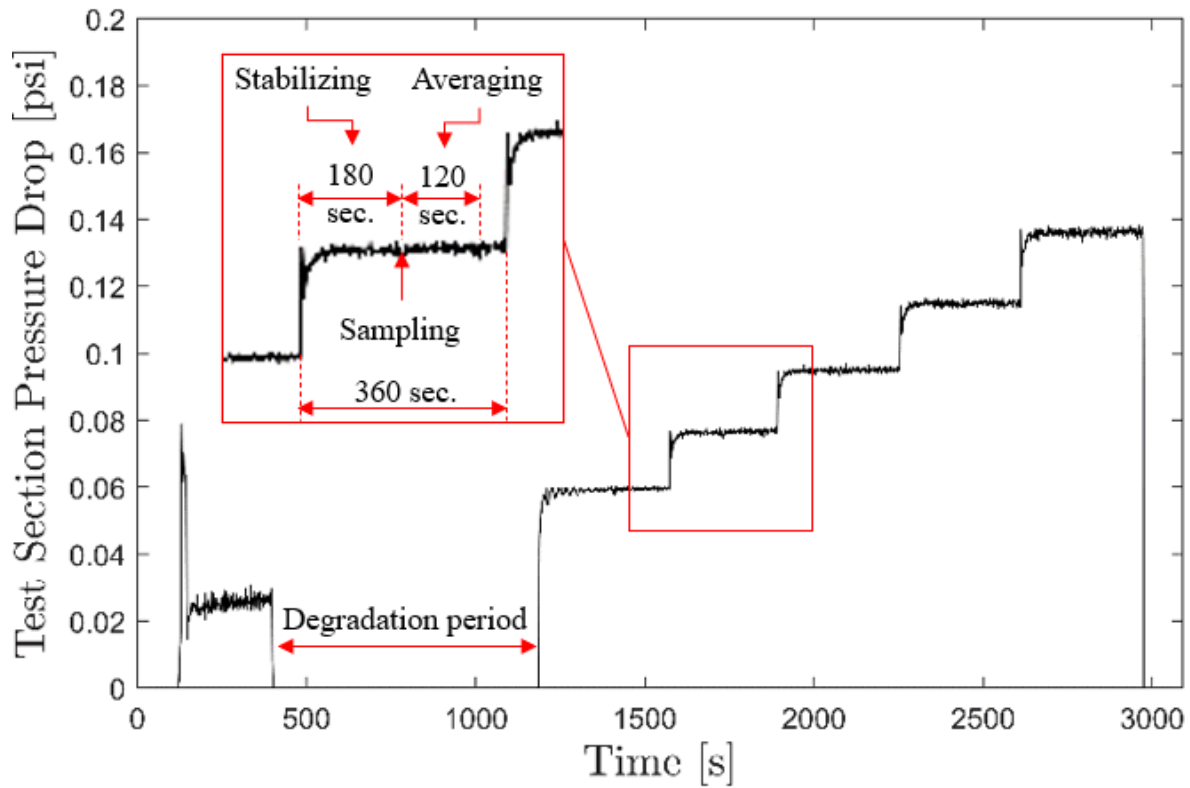
Figure 9: ΔP versus time plot example from the polymer solution pipe flow test, explaining the sampling and data averaging method used to obtain the five averaged ΔP values for each test.

As detailed in figure 9, each mass flow was run for 360 seconds, the first 180 seconds were kept for stabilizing the pressure value and the data for the next 120 seconds was used to average the ΔP

readings. At the start of each averaging, a sample was collected from the pipe flow loop which was tested for shear viscosity and extensional viscosity measurements (detailed in section 3.5 and 3.6 respectively) on the same day as the polymer solution test (refer to appendix B for ΔP versus t plots for each test).

The pipe flow setup provided the data log of ΔP, $\dot{M}$ and temperature (T), these values are averaged as shown in figure 9, to get five values of ΔP corresponding to the five mass-flow rates ($\dot{M}$) and five temperature (T) readings. A temperature model (Cheng, 2008) was used to calculate the density of water (ρ_w), given as

$$\rho_s = 1000 \left(1 - \left| \frac{(T-4)}{622} \right|^{1.7} \right),$$

(19)

which was substituted for the polymer solution density (ρ_s) since the polymer concentration is very low (50 ppm). The bulk flow velocity (V_b) is calculated from the measured $\dot{M}$ and the calculated ρ_s values, as

$$V_b = \frac{\dot{M}}{A \cdot \rho_s} \; ; \quad A = \frac{\pi \cdot D^2}{4} \; .$$

(20)

With the value of ρ_s, V_b and ΔP known, C_f is calculated corresponding to all five ΔP, by the equation

$$C_f = \frac{\tau_w}{\left(\frac{1}{2}\right) \cdot \rho_s \cdot V_b{}^2} = \frac{\left(\frac{D}{4}\right) \cdot \left(\frac{\Delta P}{L}\right) \cdot (6894.76)}{\left(\frac{1}{2}\right) \cdot \rho_s \cdot V_b{}^2} ,$$

(21)

here 6894.76 is the conversion factor from PSI to Pascal.

3.5 Shear viscosity measurements

Discovery hybrid rheometer with a double gap concentric cylinder cups and rotor attachment (figure 10) was used to measure the shear viscosity (μ_s) for the five polymer solution samples from the pipe flow setup. This setup was also equipped with a Peltier cup attachment that was connected to a heat exchanger unit to regulate the test fluid temperature. Trios software was used to connect to the rheometer, setup measurement parameters and analyze the results.
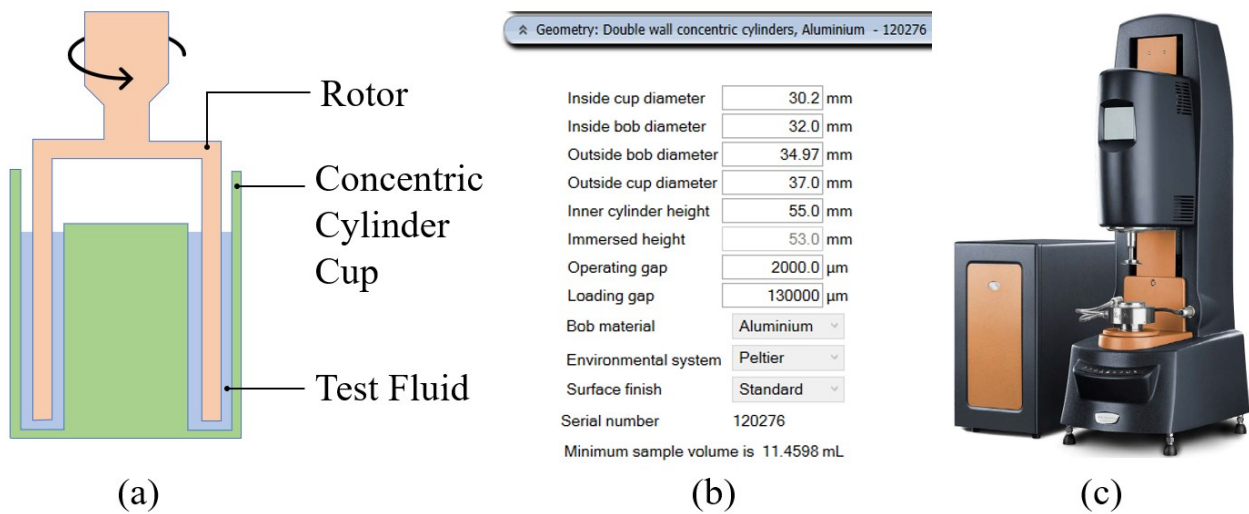
Figure 10: (a) Cross-section view of the double wall concentric cylinder cup and rotor attachment. (b) Geometry parameters for double wall concentric cylinder cup. (c) Image reference for the TA Discovery Hybrid Rheometer used for shear viscosity measurements.

For this measurement, a flow sweep test was conducted by setting a logarithmic shear rate sweep from 0.1 1/s to 1000 1/s, with ten points per decade, giving a total of 41 shear rates (γ_s) values, maintaining the Peltier cup at 20 °C. Each shear rate is maintained for 30 seconds, of which the initial 10 seconds is the equilibration time and the next 20 seconds is the averaging time. The sensor on the rotor registers the torque value corresponding to each shear rate, this torque value represents the shear stress (τ_w), which is divided by the shear rate (γ_s) to get the viscosity value. On

the viscosity versus shear rate plot (figure 11), the data for shear rate lower than 4 1/s was excluded, as that is closer to the lower limit of measurement for the rheometer and the viscosity readings shows high inconsistency in that region. Additionally, the data for shear rates above 200 1/s was also excluded as viscosity readings show a sharp increase due to the formation of Taylor vortices at these high shear rates.

The plot region between shear rate 4 1/s to 200 1/s was used, applying a cross fit model to generate the below four parameters (refer to appendix C for shear viscosity data for each test):

1. Zero-rate viscosity (μ_0): viscosity (Pa.s) at zero shear rate.

2. Infinite-rate viscosity (μ_∞): viscosity (Pa.s) at infinite shear rate.

3. Consistency (c): neutral time (s) at which the linear behavior changes to power law.

4. Rate index (n): flow index.
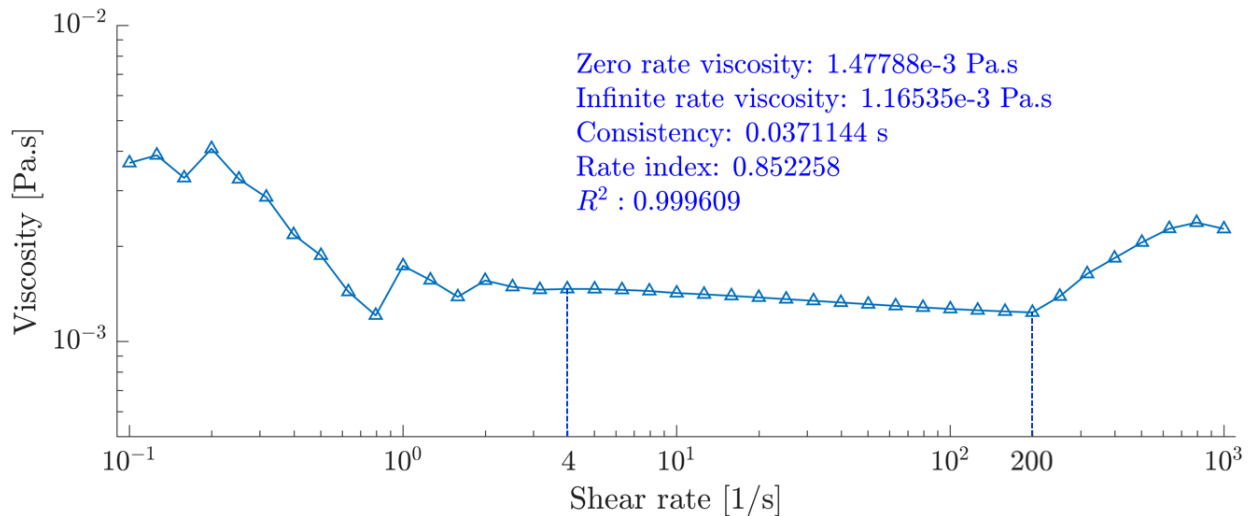
Figure 11: Viscosity versus shear rate plot example for water-based polymer solution, showing the portion of the reading used between the shear rate value 4 1/s and 200 1/s to obtain zero-rate viscosity (μ_0), infinite-rate viscosity (μ_∞), consistency (c), and rate index (n).

These four parameters were used to calculate the shear viscosity (μ_s) of the polymer solution samples using the cross-power law model (Cross, 1965), expressed as

$$\mu_s = \mu_\infty + \frac{(\mu_0 - \mu_\infty)}{1 + (c \cdot \gamma_s)^n} \ , \tag{22}$$

this can be re-arranged as

$$\mu_s = \frac{\tau_w}{\gamma_s} = \mu_\infty + \frac{(\mu_0 - \mu_\infty)}{1 + (c \cdot \gamma_s)^n} \ , \tag{22.1}$$

And

$$(\mu_\infty \cdot \gamma_s) + \frac{(\mu_0 - \mu_\infty) \cdot \gamma_s}{1 + (c \cdot \gamma_s)^n} - \tau_w = 0 \ . \tag{22.2}$$

Equation 22.2 was solved numerically in MATLAB, to obtain the value of γ_s, which is then substituted back in equation 22 to obtain μ_s. Now, with the value of μ_s known, Re can be calculated from the equation

$$Re = \frac{\rho_s \cdot V_b \cdot D}{\mu_s} \ . \tag{23}$$

With the value of C_f calculated from (21) and corresponding value of Re from (23) for each of the five sample points per test. All test data can be combined into a single C_f versus Re plot for each pipe size (detailed in section 4.1).

3.6 Extensional viscosity measurements

For the extensional viscosity measurements, a dripping setup (figure 12a) was devised, that consists of a syringe pump connected to a nozzle, set at a flow rate of 0.2 ml/min. At this rate each polymer solution drop takes about 5 seconds to extend down and detach from the nozzle, allowing enough time for the camera to detect and activate recording. As the drop starts to detach from the nozzle, it forms an extensional filament (figure 12b) that becomes thinner with time and eventually breaks off. A light source was placed behind the nozzle for illumination, and a Photron FASTCAM Nova S9 high speed camera was used to capture this filament evolution.

(a)   (b)
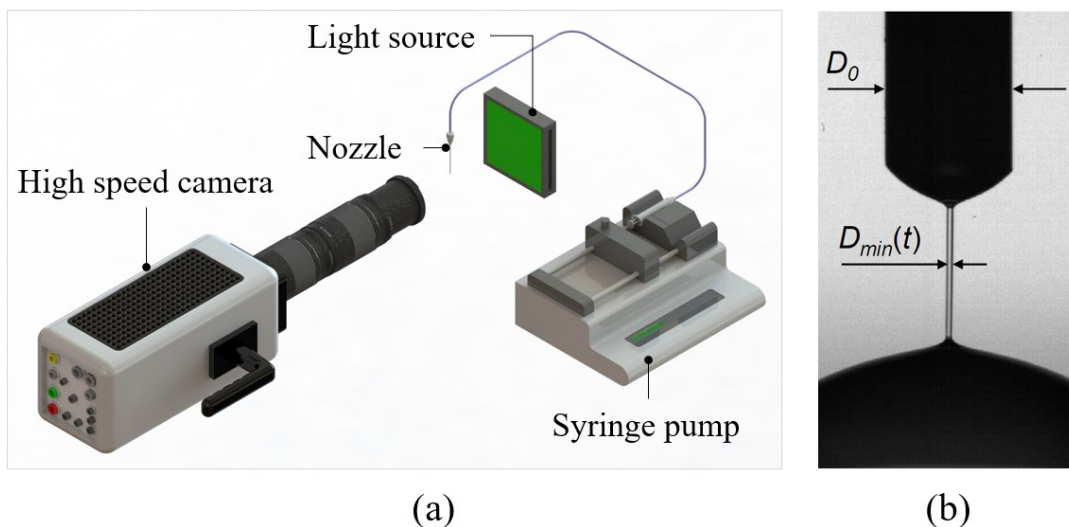
Figure 12: (a) CAD representation of the dripping setup used for extensional viscosity measurements. (b) An image frame from the high-speed camera showing the extensional filament as the fluid drop detaches from the nozzle, with $D_{min}(t)$ and D_0 measurements.

Here, D_0 represents the nozzle diameter and $D_{min}(t)$ is the time varying minimum diameter of the filament. This filament evolution was plotted on a semi log scale as the log of the normalized minimum diameter (D_{min} / D_0) versus time (t) (refer to appendix D for plots from each test). The filament evolution, as captured with the high-speed camera is demonstrates in figure 13, in this

figure the uneven time stamp gap should be noted, this is because the initial necking takes a longer time compared to the thinning towards the end.

t = 0.0 ms   t = 12.0 ms   t = 24.0 ms   t = 28.8 ms   t = 33.6 ms

t = 36.0 ms   t = 38.4 ms   t = 40.8 ms   t = 43.2 ms   t = 45.6 ms
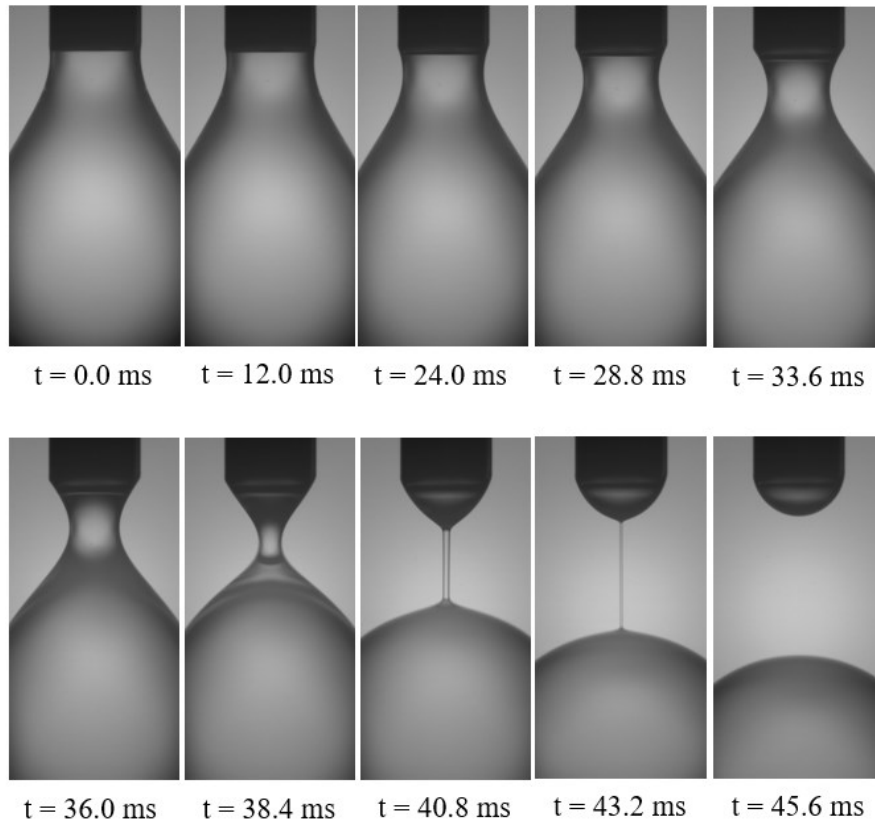
Figure 13: Evolution of a 50 ppm polymer solution filament is shown with respect to time (t), the first frame (0 ms) represents the start time when $D_{min} \approx D_0$.

Figure 14 shows the semi log plot for this evolution. Here, initial regime (A), which involves the major portion of the filament thinning, involves viscous effects that cannot be neglected. For the following portion of the thinning process (B) that demonstrates an exponential decrease of the minimum diameter, the viscous stresses become low enough to be neglected and only the elastic and capillary stresses dominate the balance of forces.
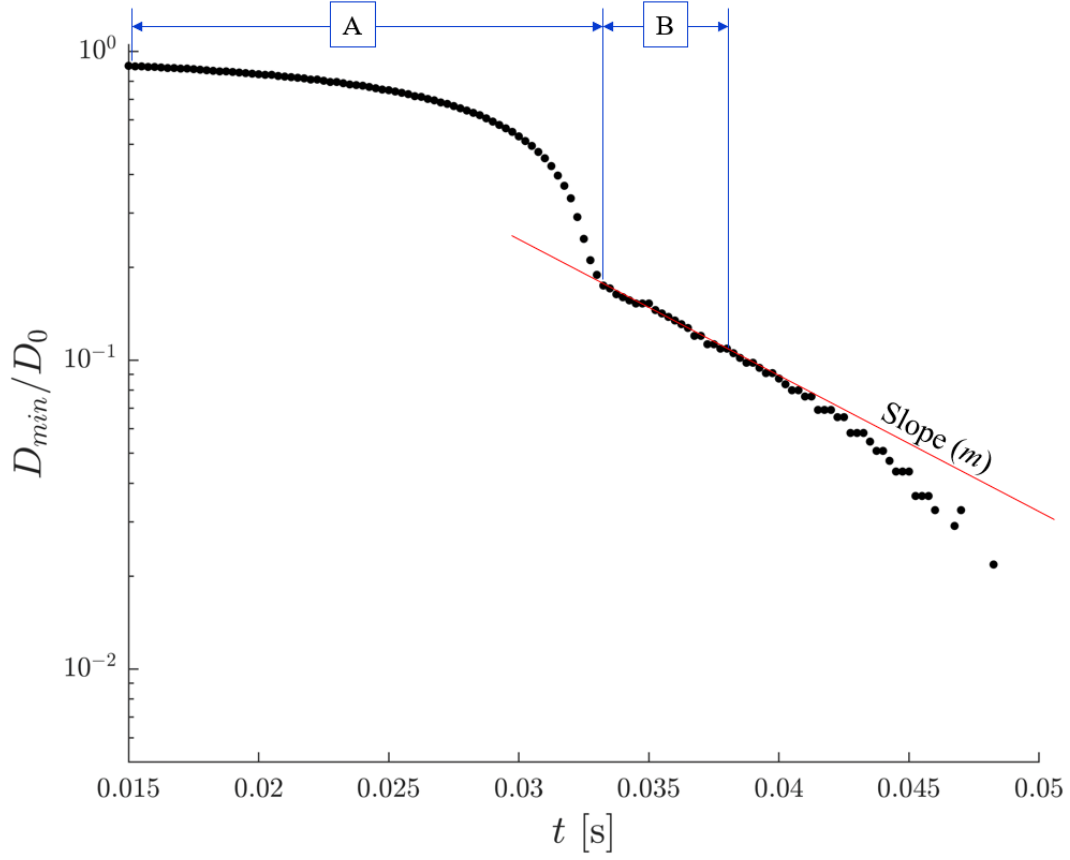
Figure 14: Log of the normalized minimum diameter (D_{min}/D_0) of the filament versus time (t) plot for a 50 ppm water-based polymer solution, highlighting the slope m, used for the calculation of the relaxation time t_r.

This region, showing an exponential decrease in filament minimum diameter, is expressed by Anna et al. (2001) as

$$D_{min}(t) = \left(\frac{\eta_p \cdot D_1{}^4}{2 \cdot t_r \cdot \sigma}\right)^{1/3} \cdot exp\left(-\frac{t}{3 \cdot t_r}\right),$$

(24)

where, η_p is the polymeric contribution to the viscosity, σ is the surface tension and D_1 is the minimum diameter at the start of the elastic regime in analysis, as considered by Anna et al., (2001). On dividing both side by D_0 and taking natural log of both side of equation 24, we obtain

$$\frac{D_{min}(t)}{D_0} = \frac{1}{D_0} \left(\frac{\eta_p \cdot D_1{}^4}{2 \cdot t_r \cdot \sigma} \right)^{1/3} \cdot exp\left(-\frac{t}{3 \cdot t_r} \right) , \qquad (24.1)$$

and

$$ln\left(\frac{D_{min}(t)}{D_0} \right) = ln\left[\frac{1}{D_0} \left(\frac{\eta_p \cdot D_1{}^4}{2 \cdot t_r \cdot \sigma} \right)^{1/3} \right] + \left(-\frac{t}{3 \cdot t_r} \right) . \qquad (24.2)$$

This expression represents the slope – intercept form for semi log plot: $ln\,(y) = mx + ln\,(b)$, with m and b representing slope and vertical intercept respectively. This, when represented in terms of the log of the normalized minimum diameter (D_{min}/D_0) versus time (t) gives

$$ln\left(\frac{D_{min}(t)}{D_0} \right) = ln(b) + (m.t) . \qquad (25)$$

By comparing 24.2 and 25, we get the relationship between the relaxation time (t_r) and slope (m) as

$$m = -\frac{1}{3 \cdot t_r} \; ; \quad or \quad t_r = -\frac{1}{3 \cdot m} . \qquad (26)$$

From the $ln\,(D_{min}/D_0)$ versus time (t) data, the portion of the exponential decrease of the minimum diameter was extracted and a linear fit is applied using MATLAB '*lmdivide*' function to solve for slope (m) and y-intercept (b). With this value of slope, the relaxation time (t_r) was calculated using equation 26 (refer to appendix D for relaxation time value of each sample point).

With the relaxation time (t_r) value from (26) and shear rate (γ_s) calculated from (22.2), The Weissenberg number (Wi) for each sample point is calculated using equation 7.

3.7 Uncertainty analysis for C_f, Re and Wi.

Here we estimate the uncertainty associated with the measurements of C_f, Re and Wi by identifying the measurements uncertainties for all the independent readings and measurements obtained from the flow loop, shear viscosity measurements and extensional viscosity measurements, and applying the propagation of uncertainties progressively to the indirect measurements and calculations, up to the equations for C_f, Re and Wi, to obtain their relative uncertainties.

The process used to calculate the relative uncertainty is briefly explained as follows. For a variable z, which is a function of variables p, q, and r ($z = F(p, q, r)$), the relative uncertainty of z (δ_z / z), for the absolute uncertainties of the independent variables p (δ_p), q (δ_q), and r (δ_r) is given by

$$\frac{\delta_z}{z} = \sqrt{\left[\left(\frac{\delta_p}{p} \right)^2 + \left(\frac{\delta_q}{q} \right)^2 + \left(\frac{\delta_r}{r} \right)^2 \right]}, \qquad (27)$$

To calculate the percentage uncertainty (relative uncertainty × 100) of C_f, Re and Wi, we need to first establish the absolute uncertainty of all the independent parameters that C_f, Re and Wi are a function of. These parameters are listed below with their absolute uncertainty calculations.

1. Temperature (T) in ºC: The resolution of the readings from the thermocouple is 0.1 ºC. So, the absolute uncertainty for this reading will be ±0.05 ºC.

2. Mass flow rate ($\dot{M}$) in kg/s: The resolution of the reading from the flow meter is 0.0001 kg/s. So, the absolute uncertainty for this reading will be ±0.00005 kg/s or ±5e-5 kg/s.

3. Pressure drop (ΔP) in psi: The resolution of the reading from the pressure transducer calibration is 0.001 psi. So, the absolute uncertainty for this reading will be ±0.0005 psi or ±5e-4 psi.

4. Pipe inner diameter (D) in m: The least count of the diameter gauge to measure the inner diameter is 0.1 mm or 0.0001 m. So, the absolute uncertainty for this measurement will be ±0.0001 m or ±1e-4 m.

5. Length between pressure port (L) in m: This is measured using a standard measuring tape with the least count of 1 mm or 0.001 m. So, the absolute uncertainty for this measurement will be ±0.001 m or ±1e-3 m.

6. Zero rate viscosity (μ_0) in Pa.s: The resolution of the readings from the torsional rheometer is 1e-8 Pa.s. So, the absolute uncertainty for this reading will be ±5e-8 Pa.s.

7. Infinite rate viscosity (μ_∞) in Pa.s: The resolution of the readings from the torsional rheometer is 1e-8 Pa.s. So, the absolute uncertainty for this reading will be ±5e-8 Pa.s.

8. Consistency (c) in s: The resolution of the readings from the torsional rheometer is 1e-7 s. So, the absolute uncertainty for this reading will be ±5e-7 s.

9. Minimum diameter of the filament (D_{min}) in m: This measurement is generated from the pixel resolution and magnification of the high-speed camera, giving the measurement resolution of 0.0046 mm or 4.6e-6 m per pixel. So, the absolute uncertainty for this measurement will be ±4.6e-6 m.

10. Nozzle diameter (D_0) in m: This measurement is generated from the pixel resolution and magnification of the high-speed camera, giving the measurement resolution of 0.0046 mm or 4.6e-6 m per pixel. So, the absolute uncertainty for this measurement will be ±4.6e-6 m.

11. Time (t) in s: The time reading is generated from the frame rate of the high-speed camera, for our measurements the minimum frame rate used was 4000, giving the least count of 2.5e-4 s. So, the absolute uncertainty for this reading will be ±1.2e-4 s.

Table 5 lists the absolute uncertainty for the independent variables and the corresponding percentage uncertainty of C_f, Re and Wi along with the equation reference.

(a)

Percentage uncertainty, C_f	Absolute uncertainty for independent parameters					Equation reference
	T (°C)	$\dot{M}$ (kg/s)	ΔP (psi)	D (m)	L (m)	
±0.8 %	±0.05	±5e-5	±5e-4	±1e-4	±1e-3	(19 – 21)

(b)

Percentage uncertainty, Re	Absolute uncertainty for independent parameters						Equation reference
	T (°C)	$\dot{M}$ (kg/s)	D (m)	μ_0 (Pa.s)	μ_∞ (Pa.s)	c (s)	
±0.8 %	±0.05	±5e-5	±1e-4	±5e-8	±5e-8	±5e-7	(22) (23)

(c)

Percentage uncertainty, Wi	Absolute uncertainty for independent parameters			Equation reference
	D_{min} (m)	D_0 (m)	t (s)	
±6.0%	±4.6e-6	±4.6e-6	±1.2e-4	(7) (26)

Table 5: Percentage uncertainty calculations for (a) C_f, (b) Re and (c) Wi, with absolute uncertainty for independently measured variables for each of them, along with reference to the equation used.

Chapter 4

Results

This section brings together the measurements of C_f, Re and Wi obtained from section 3.4, 3.5 and 3.6 respectively and presents graphically as C_f versus Re plots and combines that with the value of Wi for each data point by color mapping. This allows for observation of any relation between C_f, Re, and Wi, and understand the dependency of C_f on Wi and Re. Furthermore, this section also discusses the transition from the value of Wi calculated from wall shear rate to a calculated value of Wi using bulk shear rate, to eliminate the dependency of Wi on ΔP, so a correlation between Wi and C_f can be establish without the need of conducting pipe flow tests (refer to section 4.2 for details).

4.1 Friction Factor

As discussed in section 3.3.4, for the water-based polymer solution test, we first obtained a set of data for C_f and Re for the baseline water test to confirm the alignment with the Newtonian values. Three tests per pipe size were conducted to check repeatability, the average of the three tests are presented for each pipe size in figure 15.
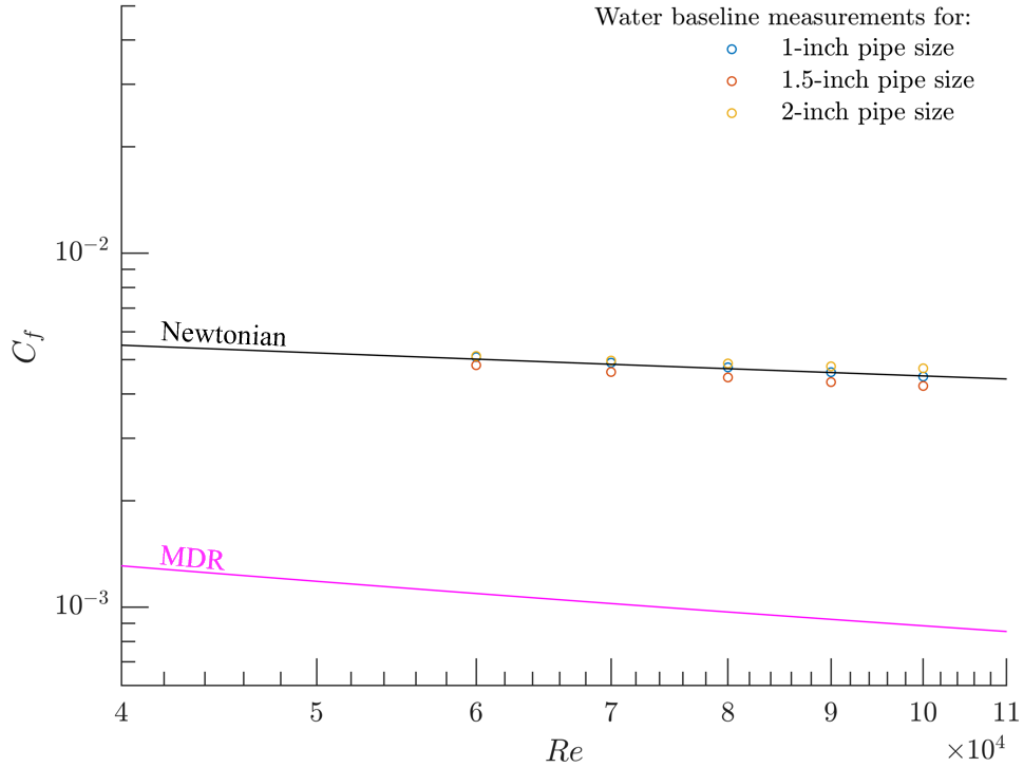
Figure 15: C_f versus Re plot for baseline water test showing the average of three test measurements for each pipe sizes.

In the above plot, the black curve represents the relation between C_f and Re for Newtonian fluids in smooth pipes, given by the equation 14, and the magenta color curve is representing the MDR asymptote curve as reported by Virk et al. (1970) and Virk (1971) in equation 17. The water baseline test measurements, being Newtonian, showed good alignment with the Newtonian curve. The 1-inch pipe size test shows a very close alignment, and the 1.5-inch and 2-inch pipe size test showed a small but consistent off-set from the Newtonian values but still within the uncertainty for the C_f as discussed in section 3.7. The close alignment and repeatability of these measurements provided enough confidence to proceed with the polymer solution tests.

The polymer solution test provided a set of data for C_f, Re and Wi for five different Re flow and 6-8 different %DR, amounting to 30-40 data points per pipe size. The outcome of each test in terms of the %DR achieved and the C_f–Re relation for each test is discussed next.

For the 1-inch pipe size, a total of 8 polymer tests were conducted with different degradation time for each test aiming to achieve an evenly spaced %DR. Table 6 provide the details of the %DR achieved corresponding to the degradation time identified for that test. Here, %DR is calculated as (ΔP_{water} - $\Delta P_{polymer}$)/ $\Delta P_{water} \times 100$, where ΔP_{water} and $\Delta P_{polymer}$ are the average ΔP value at mass flow of 1.681 kg/s, for water and polymer solution respectively.

Test	Degradation duration at 1300 RPM (s)	Average ΔP at mass flow of 1.681 kg/s (PSI)	%DR (%)
Water (Baseline)	-	0.816	0.0
Polymer test 1	0	0.194	76.2
Polymer test 2	30	0.223	72.7
Polymer test 3	50	0.302	63.0
Polymer test 4	90	0.346	57.5
Polymer test 5	220	0.412	49.6
Polymer test 6	600	0.486	40.4
Polymer test 7	1500	0.569	30.2
Polymer test 8	2880	0.596	27.0

Table 6: %DR achieved corresponding to the degradation time for the water-based polymer solution in 1-inch pipe size.

A total of 40 C_f values were obtained from these eight polymer solution tests, each corresponding to a Re value, as presented in figure 16.
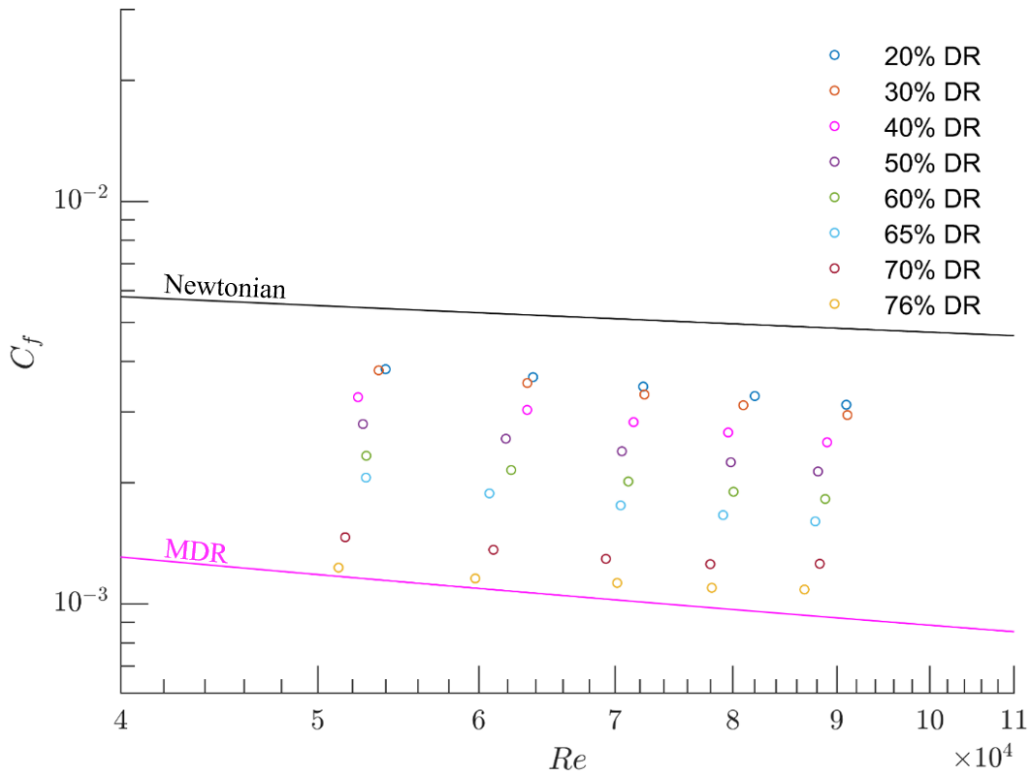
Figure 16: C_f versus Re plot for water-based polymer solution test in 1-inch pipe size, showing the five measurements for each %DR.

Here, each row of the same color data points represents the five mass flow rates measured for a specific %DR, and as the %DR decreases for each consecutive test, due to higher degradation, each row shifts up almost parallel to each other, implying no major polymer degradation within the range of Re measured. This applies more to 65% and lower DR cases. A small detachment of the 76% and 70% DR data points from the MDR line is seen for higher Re values because, for both these cases the initial polymer degradation was very less, and for higher Re values, the higher pump RPM caused some degradation in the polymer solution resulting in a lower %DR. Additionally, It can be observed that the 76% DR row, which is the undegraded 50 ppm polymer solution, almost approaches the MDR, the maximum drag reduction asymptote presented in equation 20. This implies that a concentration increase above 50 ppm would not result in any

significant increase in the DR, on the contrary, DR may decrease due to the increase in viscosity of the solution.

One more thing to note here is the shift in the Re values for each data point from the baseline Re values of 60000, 70000, 80000, 90000, and 100000 mentioned in section 3.3.1. This reduction in *Re* of about 10000 for each data point can be attributed to the increase in viscosity of the polymer solution compared to water.

For 1.5-inch pipe size, a total of 7 polymer tests were conducted with different degradation time for each test aiming to achieve an evenly spaced %DR. Table 7 provide the details of the %DR achieved corresponding to the degradation time identified for that test. If we compare the %DR value for the undegraded polymer solution (test 1) between 1-inch and 1.5-inch pipe size, it aligns with the observation by Lescarboura et al. (1971), that for a particular polymer concentration, the DR reduced as the pipe size increases.

Test	Degradation duration at 1300 RPM (s)	Average ΔP at mass flow of 2.575 kg/s (PSI)	%DR (%)
Water (Baseline)	-	0.204	0.0
Polymer test 1	0	0.059	71.2
Polymer test 2	20	0.072	64.8
Polymer test 3	60	0.085	58.4
Polymer test 4	160	0.102	50.1
Polymer test 5	340	0.119	41.8
Polymer test 6	1000	0.137	32.8
Polymer test 7	3200	0.158	22.9

Table 7: %DR achieved corresponding to the degradation time for the water-based polymer solution in 1.5-inch pipe size.

A total of 35 C_f values were obtained from these seven polymer solution tests, each corresponding to a *Re* value, as presented in figure 17.
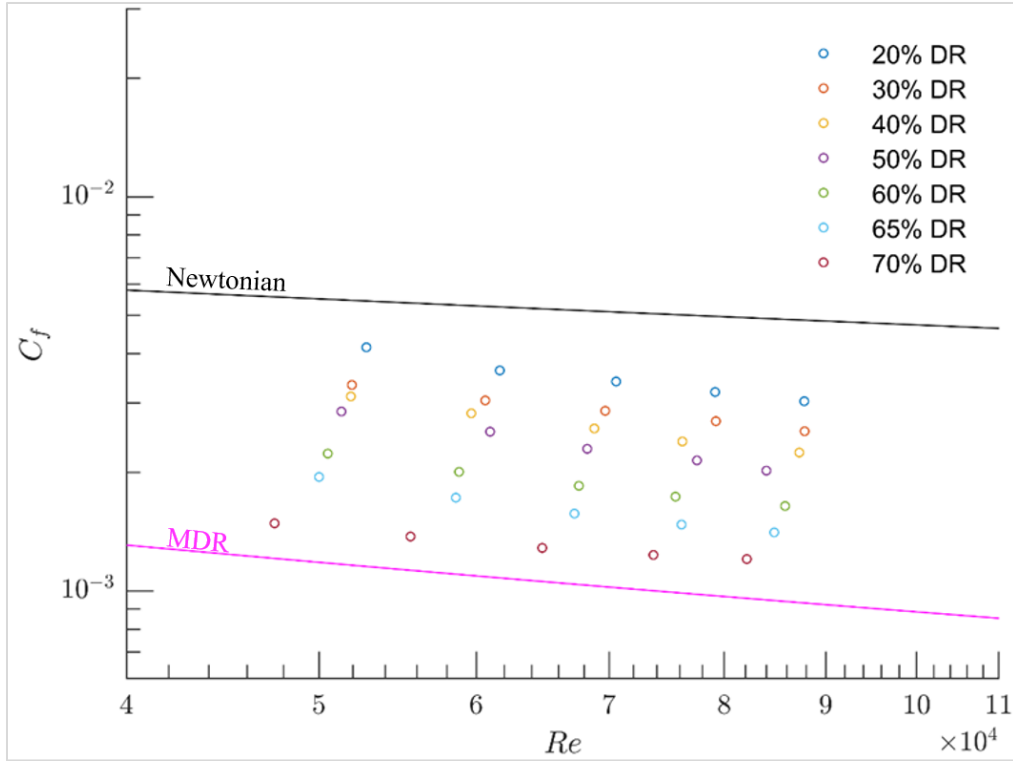
Figure 17: C_f versus Re plot for water-based polymer solution test in 1.5-inch pipe size, showing the five measurements for each %DR.

A similar shift in the Re values is observed due to the viscosity change as seen for the 1-inch case and the parallel trend of each %DR case also aligns with the previous observation from figure 16. For 1-inch and 1.5-inch pipe size test, the degradation was limited to 1300 pump PRM to manage the line pressure impact on the pump bearing seal, and for this reason the lowest %DR achieved was in the range of 20-30%.

For 2-inch pipe size, a total of 6 polymer tests were conducted with different degradation time for each test aiming to achieve an evenly spaced %DR. Table 8 provide the details of the %DR achieved corresponding to the degradation time identified for that test. The %DR value for the undegraded polymer solution (test 1) for 2-inch pipe size further supports the observation made previously that, for a particular polymer concentration, the DR reduced as the pipe size increases.

Test	Degradation duration at 1400 RPM (s)	Average ΔP at mass flow of 3.306 kg/s (PSI)	%DR (%)
Water (Baseline)	-	0.111	0.0
Polymer test 1	0	0.046	58.6
Polymer test 2	20	0.052	52.9
Polymer test 3	90	0.060	45.9
Polymer test 4	240	0.079	28.4
Polymer test 5	750	0.096	13.8
Polymer test 6	1960	0.104	6.7

Table 8: %DR achieved corresponding to the degradation time for the water-based polymer solution in 2-inch pipe size.

A total of 30 C_f values were obtained from these seven polymer solution tests, each corresponding to a Re value, as presented in figure 18.
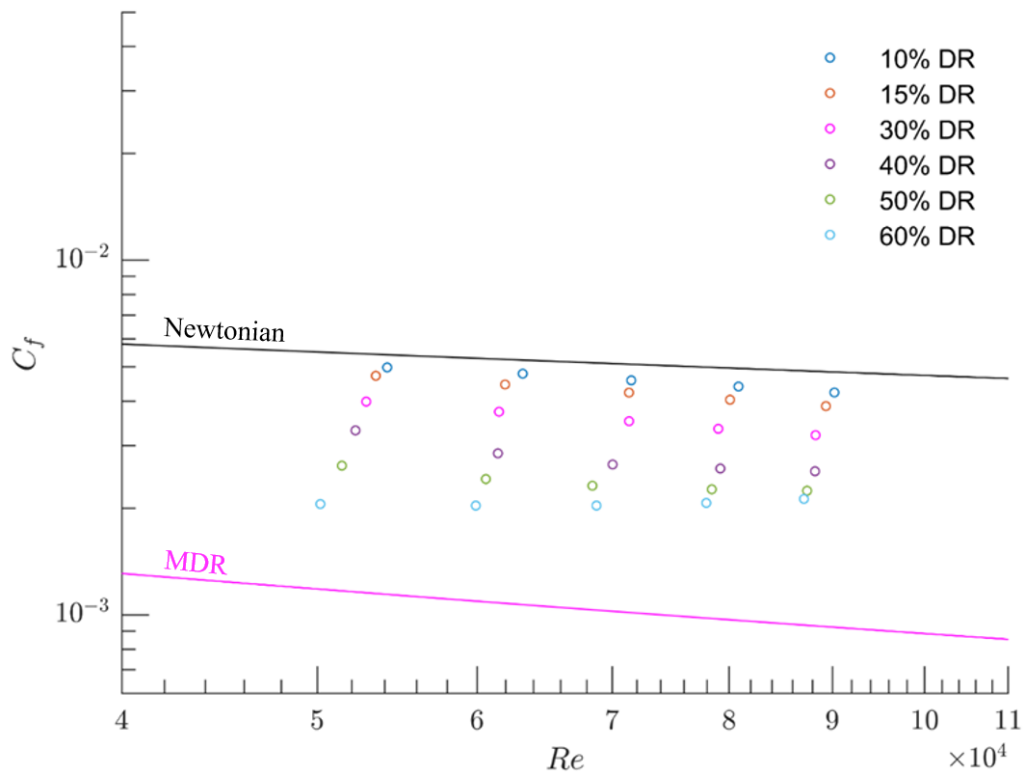
Figure 18: C_f versus Re plot for water-based polymer solution test in 2-inch pipe size, showing the five measurements for each %DR.

For the 2-inch pipe size as the line pressure for the same RPM reduces compared to 1-inch and 1.5-inch pipe sizes, the degradation was conducted at 1400 pump RPM, allowing to reach the lowest %DR of 6.7%, and populating the region of the plot that was not possible with smaller pipe diameters. Other observations like the shift in Re values and parallel shift between each %DR are similar to the previous cases.

4.2 Relation between C_f, Re and Wi

Each point on the C_f–Re plot represents a sample collected from the pipe flow setup. This sample was tested for extensional viscosity measurements (refer to section 3.6) and a corresponding Weissenberg number (Wi) value was associated for each sample point. These values were projected onto the C_f–Re plot using a color map and an alternate representation as a contour map, shown in figure 19 and 20 respectively for the 1-inch pipe size test. Subsequently, figure 21-22 and figure 23-24 represent the plots for 1.5-inch and 2-inch pipe size test respectively. The aim of these projections is to observe how the value of C_f changes in relation to Wi and Re along the entire data point range, and can a relation be established between these parameters based on the pattern observed.

It is to be noted, however, that even though the tests were designed so that the data point range fills most of the region between the Newtonian and MDR curve, there are a few localized regions where the point density is lower that other regions and this variance in point density can impact the contour projections in those areas. So, an objective approach and cross-referencing between color and contour plots are required for analyzing the plots.
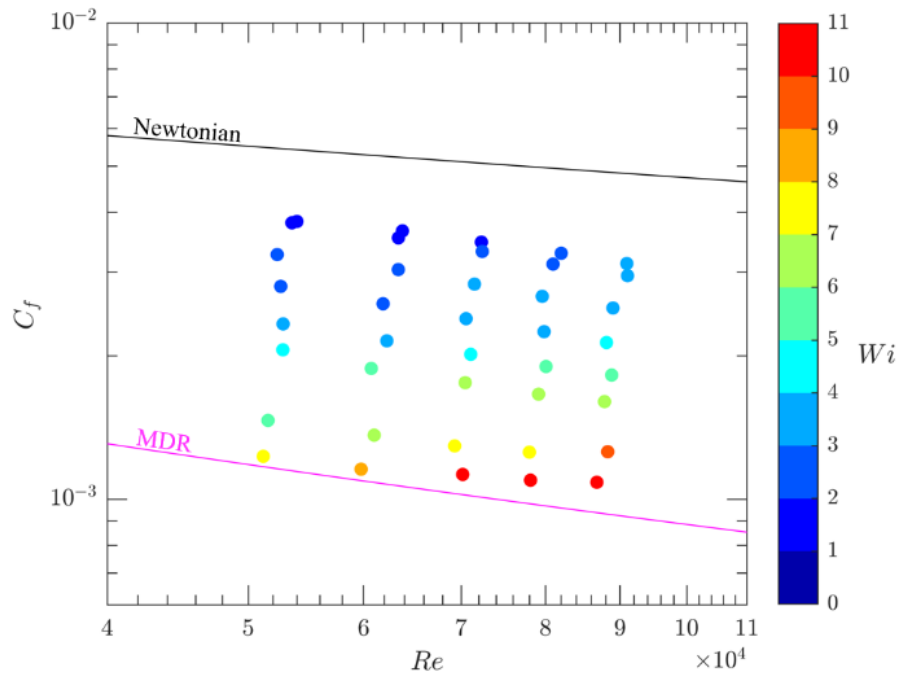
Figure 19: Data points on the $C_f - Re$ plot are color mapped with the measured value of Wi for 1-inch pipe size.
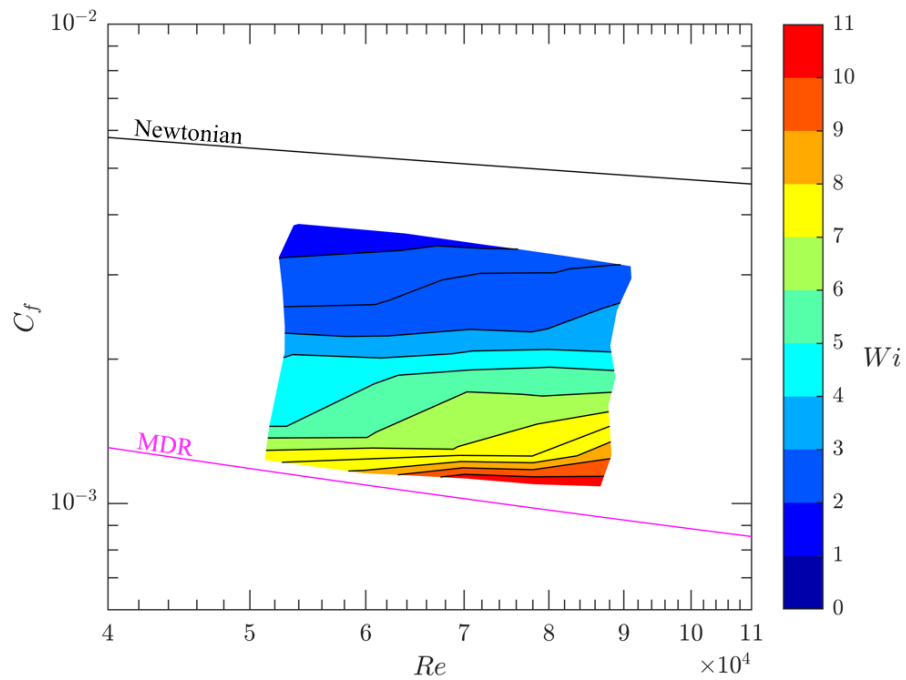
Figure 20: Data points on the $C_f - Re$ plot are contour mapped with the measured value of Wi for 1-inch pipe size.
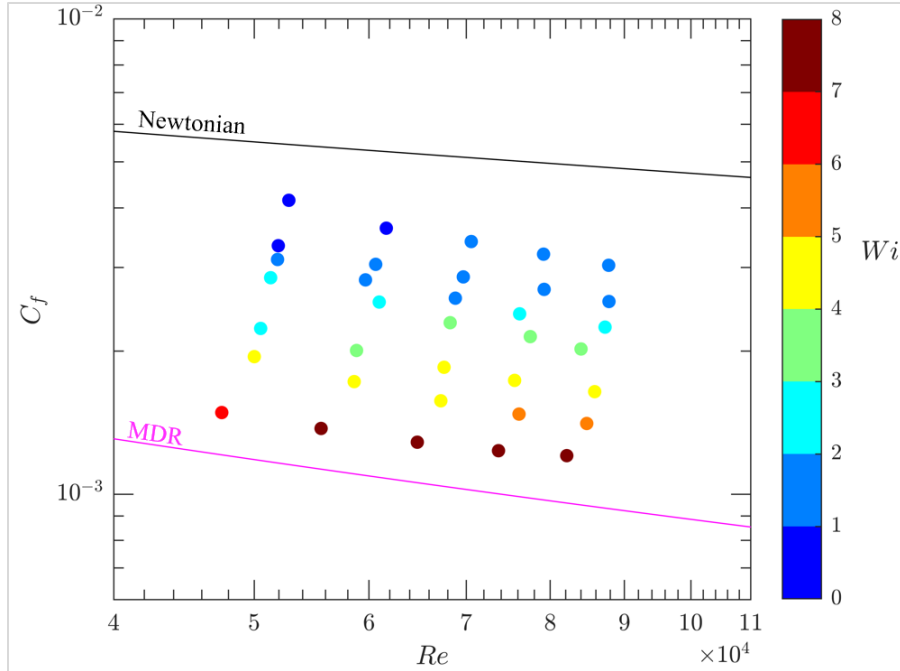
Figure 21: Data points on the $C_f - Re$ plot are color mapped with the measured value of Wi for 1.5-inch pipe size.
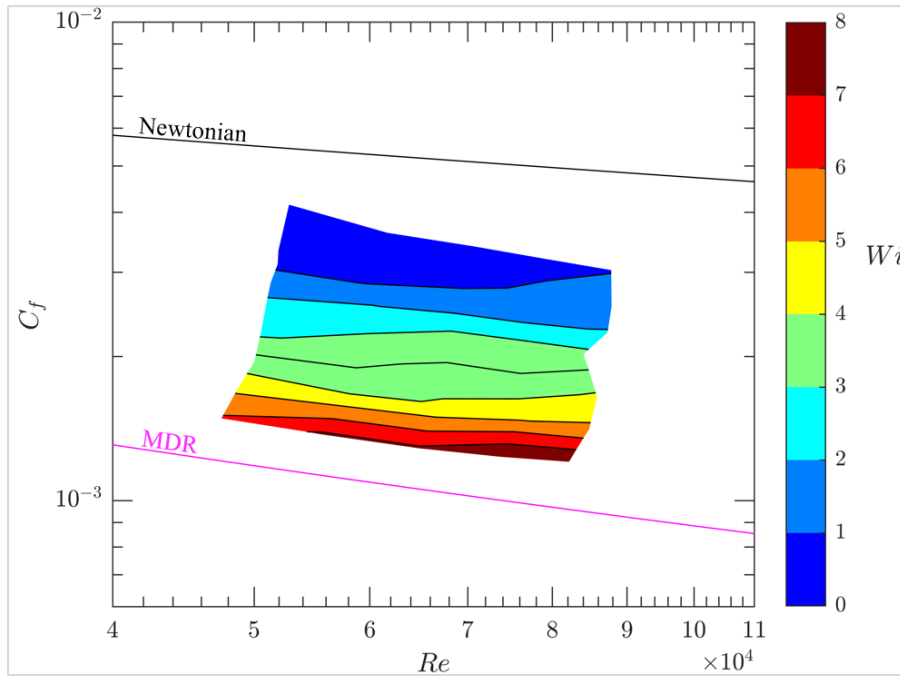
Figure 22: Data points on the $C_f - Re$ plot are contour mapped with the measured value of Wi for 1.5-inch pipe size.
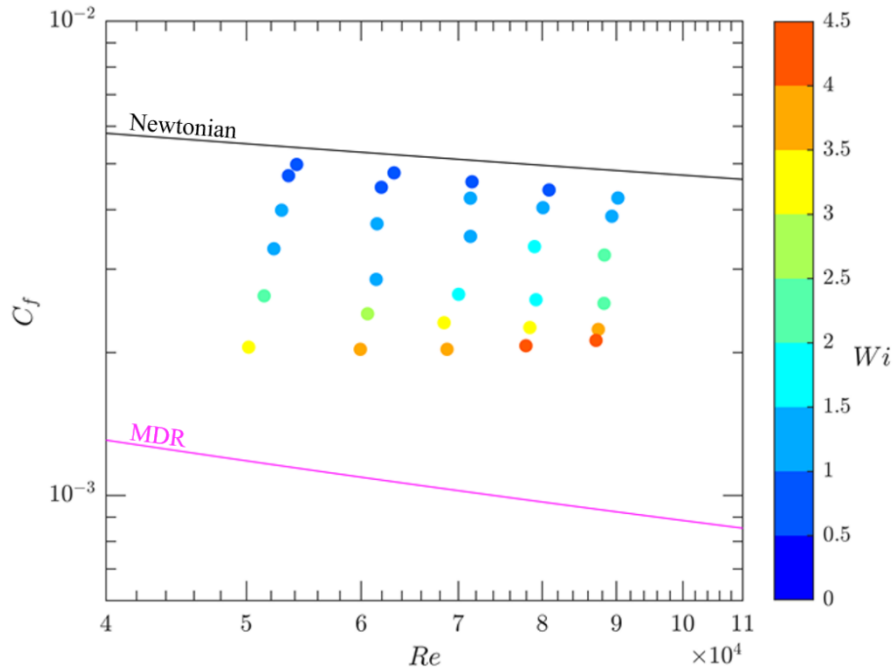
Figure 23: Data points on the $C_f - Re$ plot are color mapped with the measured value of Wi for 2-inch pipe size.
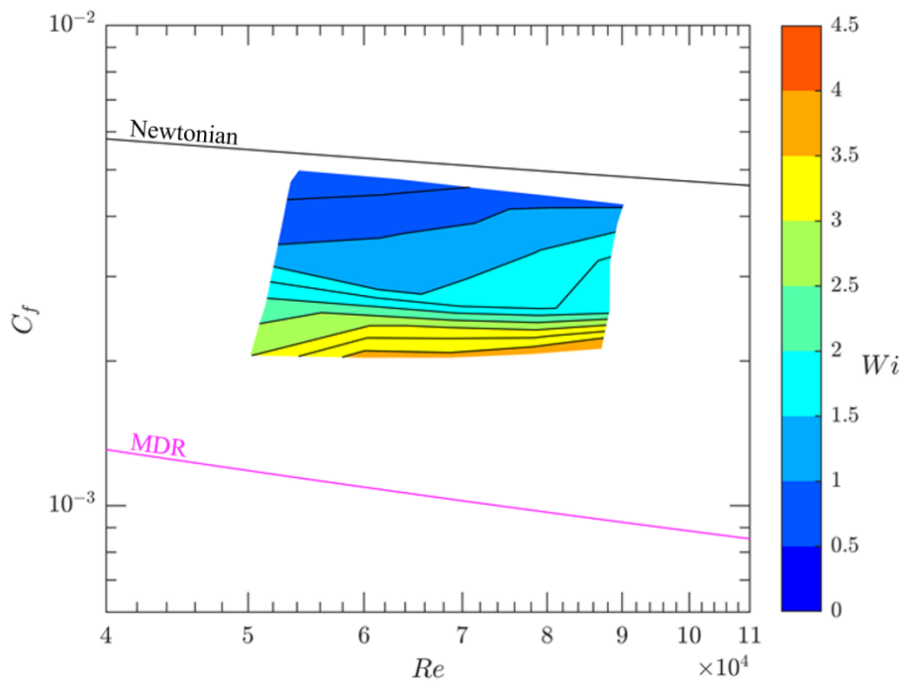
Figure 24: Data points on the $C_f - Re$ plot are contour mapped with the measured value of Wi for 2-inch pipe size.

The contour plots (20, 22 and 24), show a general horizontal alignment of the Wi value bands. From figures 19 and 20, it can be observed that a band for a particular value of Wi is aligned more horizontally towards the upper portion of the region where the data point density is more even compared to the lower portion. Same can be seen in figures 23 and 24 showing horizontal band towards the lower and higher up region, the middle portion when cross-referenced with the point data, show lower point density in that zone. This trend is more clearly observed in figures 21 and 22 with a more even and close-to-horizontal alignment of individual Wi bands, throughout the region. This demonstrates that the value of C_f changes significantly in relation to Wi and not so significantly compared to the change in Re, pointing towards a strong dependency of C_f on Wi, it can also be observed that the Wi band thickness increases as the Wi value decreases, suggesting that the rate of decrease in the value of Wi slows down as C_f increases. This change in Wi when compared to change in C_f suggests a roughly exponential relation between Wi and C_f. This provides evidence for the relation between the extensional properties of the polymer solution and drag reduction.

These relations lay a strong foundation towards developing a model describing the relationship between C_f, Re and Wi, with the ability to predict one from the other. However, in order to achieve that and truly develop a predictive model by eliminating the need for extensive pipe flow tests, we require an alternative approach in calculating Wi, since the current method (refer to section 3.6) utilizes wall shear rate (γ_s) which is calculated using equation 25.2, that requires the knowledge of shear stress at the wall (τ_w), which in turn is calculated using the pressure drop (ΔP) from the pipe flow test (refer to equation 24).

4.3 *Wi* calculated from bulk shear rate (γ_b)

The irony of predicting C_f from *Wi* without pipe flow tests, while *Wi* being a function of ΔP warrants for an alternate approach. *Wi* can also be calculated from the bulk hear rate (γ_b) in pipe flow, which is a function of the bulk velocity (V_b) and pipe diameter (D) and is expressed as

$$\gamma_b = \frac{8 \cdot V_b}{D} \, . \tag{28}$$

With this representation of shear rate, the Weissenberg number calculated from bulk shear rate (Wi_c) can be expressed as

$$Wi_c = \frac{8 \cdot V_b \cdot t_r}{D} \, . \tag{29}$$

With the above equation, a set of Wi_c values can be obtained corresponding to all data points presented in the previous section for all three pipe sizes. The following three figures (25, 26 and 27) represent the C_f–Re plot with the data points projected with the value of Wi_c and presented as a contour plot. These are similar to figures 20, 22 and 24 respectively with just *Wi* replaced by Wi_c. This gives an opportunity to compare the observations between Wi_c and *Wi* projections (from the previous section).
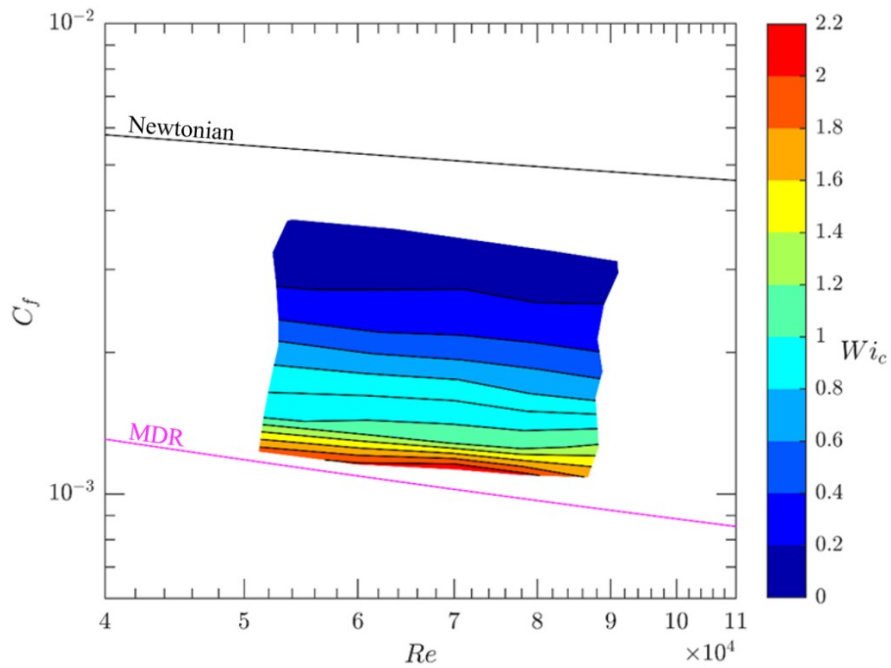
Figure 25: Data points on the $C_f - Re$ plot are contour mapped with the calculated value of Wi_c for 1-inch pipe size.
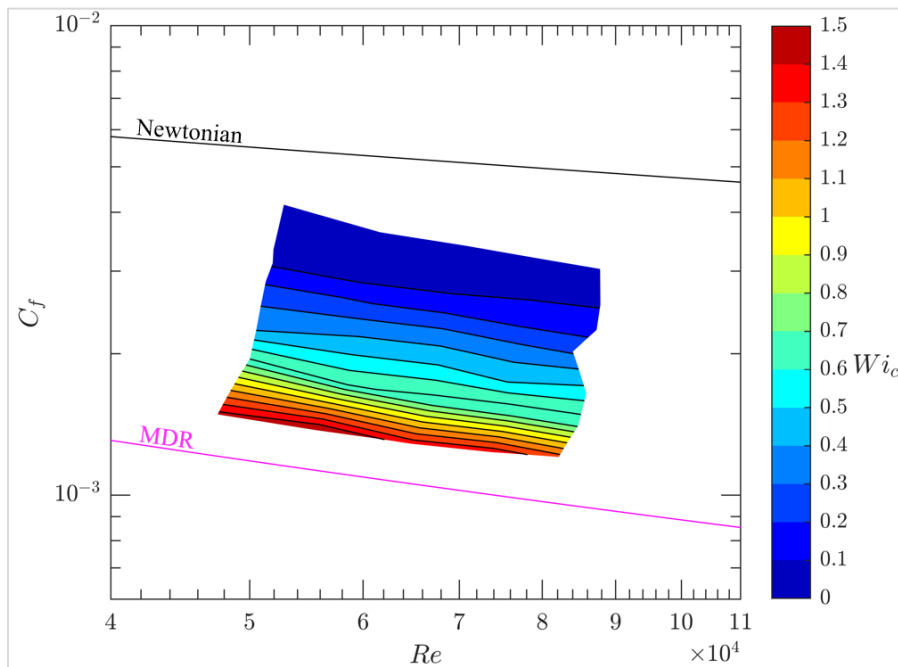
Figure 26: Data points on the $C_f - Re$ plot are contour mapped with the calculated value of Wi_c for 1.5-inch pipe size.
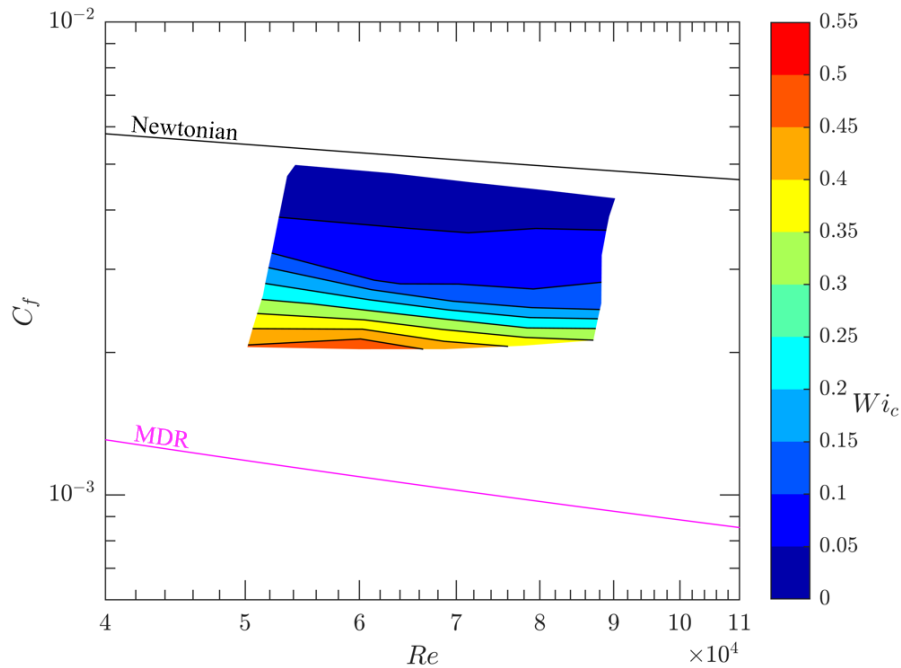
Figure 27: Data points on the $C_f - Re$ plot are contour mapped with the calculated value of Wi_c for 2-inch pipe size.

These updated plots with Wi_c show similar trends and observations as compared to the plots with Wi, providing confidence in utilizing Wi_c in place of Wi. Similar to previous observations, these plots exhibit the same horizontal alignment of the Wi_c bands, where the change in the value of Wi_c is less significant as one move along the horizontal axis (Re), suggesting a low dependence of Wi_c on Re, and showing significant change in the value of Wi_c along the vertical axis (C_f), suggestive of high dependency of C_f on Wi_c. The increase in the Wi_c band thickness as the value of Wi_c decreases is also observed, which means that the rate of decrease in the value of Wi_c slows down as C_f increases, aligning with the previous observation.

Figure 28 shows this relation between C_f and Wi_c, when expressed on a linear scale.
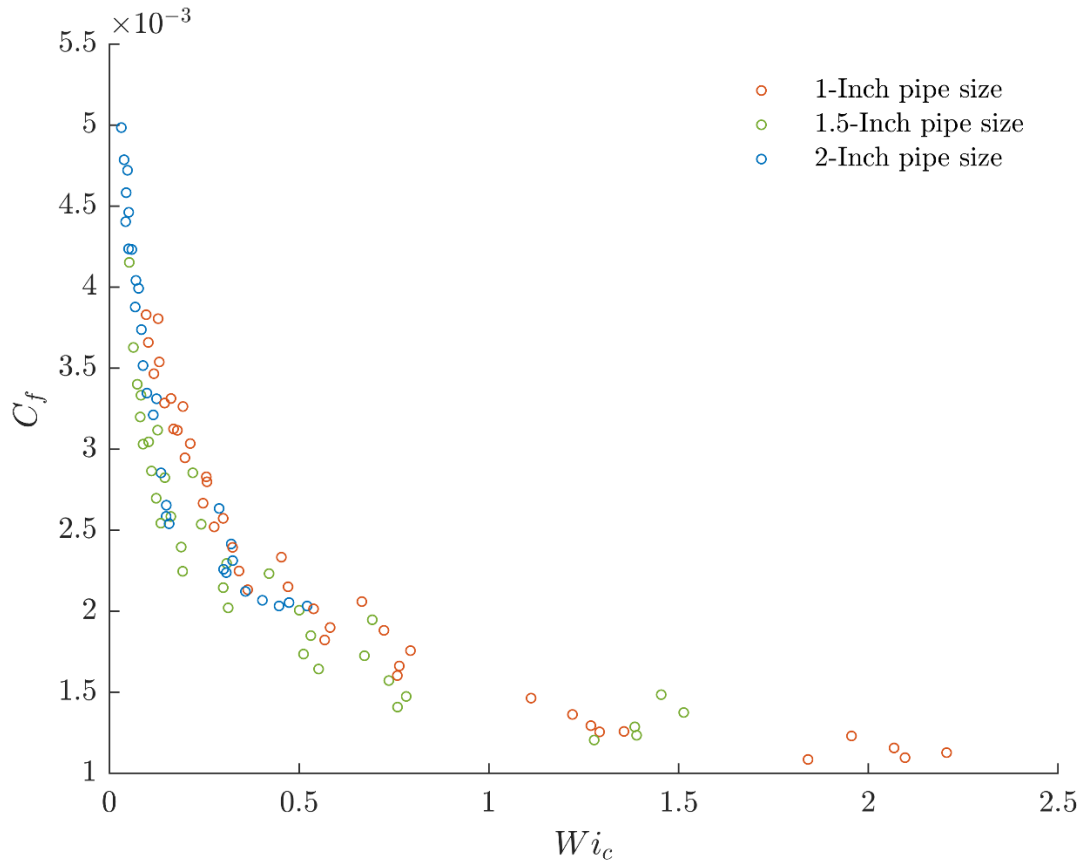
Figure 28: C_f versus Wi_c plotted for all three pipe sizes are expressed on a linear scale to show the relation between these two parameters.

This presents a good foundation for establishing a relationship between C_f, Wi_c, and Re, and towards the development of a robust predictive model for DR through polymer rheology. The extensive water-based pipe flow and rheological tests provided a strong base of repeatable test data and the alignment of the observations between Wi and Wi_c will serve as a proof of concept and will highly influence the way the diesel-based polymer solution tests will be designed and conducted.

Chapter 5

Design and commissioning of a hydrocarbon flow loop

The test with water-based polymer solution gave a good insight into the relationship between C_f, Re and Wi, but as discussed earlier, with the differences between the drag reducing polymers for water and hydrocarbons in terms of molecular weight, solubility and drag reducing capabilities, to achieve our objective of developing a predictive model for polymer drag reduction in hydrocarbons, a similar test approach is required with hydrocarbons. This presented a need for a flow facility that can safely run hydrocarbon-based polymer solutions and can produce repeatable measurements. As discussed earlier, the choice of using diesel as the base fluid was based on the facts that, firstly, diesel has a higher flash point (> 52 ºC) and low volatility, making it safer to handle at room temperature, and in a closed lab environment compared to other easily available hydrocarbons like gasoline and kerosine, and secondly, it has a much lower viscosity than crude oil, making the flow loop design simpler, manageable pump requirements and easier drainage of the loop for repeating tests. The flow loop facility developed for tests with diesel is similar in concept as the water test facility (detailed in section 3) with the key difference being the loop pipe size is 1-inch, a positive displacement pump is used instead of a centrifugal pump that was used in

the water-based flow loop, all components are rated for use with diesel, and the loop is designed to achieve flow Re up to 30000.

For designing the diesel flow loop, space was an important factor. With limited space in the lab, a vertical loop structure was adopted, that allowed the setup to have a small footprint area. This, in hindsight, provided easier access to equipment and sensors. The other major factor that influenced the design of the loop was the size and layout of the pump-motor assembly, as the loop's plumbing would have to be designed around that. The criterions that governed the selection of the pump and motor were compatibility with diesel fuel, capability to achieve flow rates up to 9.0 m^3/hr (~40 gpm) based on our calculation to achieve Re up to 30000, achieve this flow rate at low RPMs to avoid excessive polymer degradation, electrical compatibility with the available outlets in the lab, and cost. Once the space and pump-motor assembly design were established, the diesel loop, following the same concept from the water-based loop, was designed with a storage tank that can be used for mixing the polymer, the tank inlets into the positive displacement pump, that feeds into a 1-inch pipe loop. The loop consists of a pressure relief valve for safety, a pulsation dampener to stabilize the flow, a heat exchanger to regulate the temperature, a flow meter to measure flow rates, a thermocouple to measure fluid temperature, two pressure ports with tubing to a differential pressure transducer for ΔP measurements, diversion valves setup to be able to run the loop in either open or closed loop configurations and drainage ports at the lowest level before and after the pump stator, as the stator-rotor assembly is liquid tight seal in a positive displacement pump.

Additional safety features that were incorporated in the loop's design includes stainless steel spill trays placed under the entire loop for spill containment, proper ventilation ducts above the tank to extract any escaping vapors, and containment of diesel from the pressure transducer during the

bleeding process. Figure 29 shows an overview of the diesel flow loop with the key components highlighted. These components are detailed as follows:
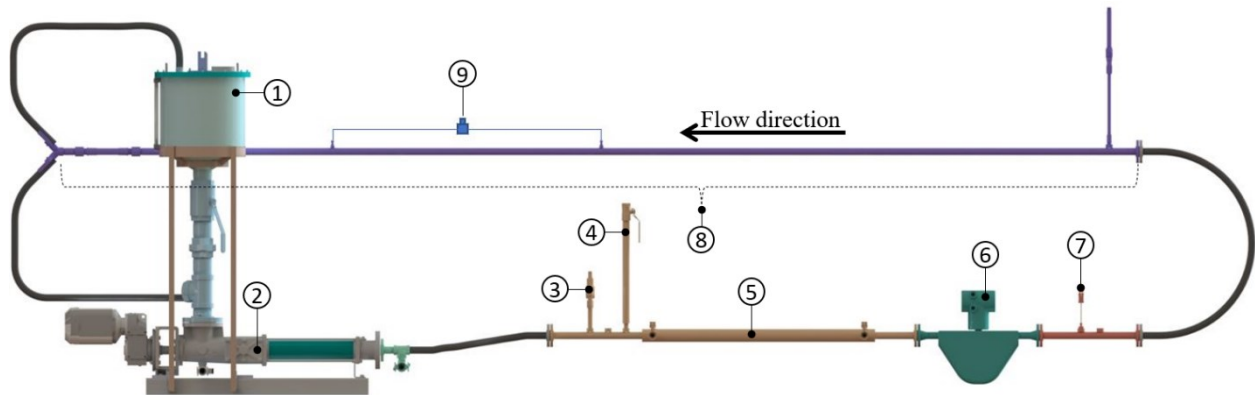
Figure 29: Overview of the pipe flow setup used for diesel-based tests, highlighting each component unit and flow direction.

1. Tank: 50 liters vertical stainless-steel tank with a 3-inch outlet.

2. Pump: NETZSCH progressive cavity pump, model-NM038BY01L06B, powered by a 3HP NORD gear motor (refer to appendix F for pump curve).

3. Pressure relief valve: Adjustable pressure relief valve set at 60 psi.

4. Pulsation dampener: In-house fabricated air column dampener to stabilize the flow.

5. Heat exchanger: In-house fabricated, concentric tube design, with a 2-inch tube jacketing the 1-inch flow pipe, with inlet and outlet ports on the 2-inch pipe to run cold/hot water to regulate the temperature.

6. Coriolis flow meter: Micro motion 1-inch F-Series Coriolis flow meter (F100S128CCAAEZZZZ) with an integral mount 1700 series transmitter (1700I12ABASZZZ) for mass flow readings.

7. Thermocouple: K-type thermocouple from Omega for temperature readings.

8. Test section: The test section is a 1-inch inner diameter, 5.08 m (200-inch) long, straight stainless-steel pipe with an upstream pressure port at 2.54 m (100-inch) from the upstream edge and the distance between the upstream and downstream port (L) = 1.27 m (50-inch).

9. Pressure transducer: A Validyne DP-15 pressure transducer is used and is connected to the pressure port on the test section through 1/8-inch double-ferrule brass tube fittings. The Diaphragm used in the pressure transducer is: 3-32 (± 2.0 psi).

Refer to appendix A for detailed drawing of the components and assembly of the diesel flow loop. The scope of the current work includes the design, development, and commissioning of the diesel loop. The following section details the baseline test procedure and results, that verify the loop stability and repeatability, making the loop ready for future polymer testing.

Once the loop component assembly was completed and the pump was commissioned, the entire loop was dry tested for leaks using compressed air. Upon the confirmation of no active leaks, the loop was filled with diesel fuel and the first trial run was conducted following the safe operating procedure (appendix E). During this run, the pump-VFD calibration was completed, and all equipment readings were verified. This trial also helped clean the loop from inside. The diesel was filtered at a high flow rate and then drained completely. Fresh Diesel was then introduced in the loop and was made to run through a finer filter to extract any remaining contaminant. A chiller unit was connected to the heat exchanger for temperature stabilization and the loop was run progressively to its limits to verify the Re range. The loop was able to achieve Re of 30000 at 372 RPM of the pump (maximum rated pump RPM is 400).

5.1 Calculation of mass flow rate

The test Re for diesel test was set to 5000, 10000, 15000, 20000, 25000 and 30000 as a baseline, a diesel sample was tested for shear viscosity following the same procedure as mentioned in section 3.5. Measured viscosity of diesel (μ_d) = 0.00344 kg/m-s, at 20±0.5 °C. and measured density of diesel (ρ_d) = 843.0 kg/m^3, at 20±0.5 °C. Table 9 mentions the mass flow rate values corresponding to the Re range using equation (21) and its corresponding VFD set value to achieve that mass flow.

	Pipe size = 1-inch	
	D = 0.0267 m	
Re	$\dot{M}_d$ (kg/s)	VFD (Hz)
5000	0.360	8.9
10000	0.720	17.4
15000	1.080	26.0
20000	1.440	34.8
25000	1.800	43.7
30000	2.160	52.9

Table 9: Mass flow rates with their corresponding VFD set point values are listed to achieve the required Re for pipe flow test with diesel for 1-inch pipe size with a measured inner diameter (D).

5.2 De-airing and transducer bleeding procedure:

When the loop is first filled with diesel, there are many air pockets all around the loop at locations like pipe joints, pipe bends and transducer tubing. These pockets, if not removed, can mix with the flow stream, and negatively impact the measurements. So, to ensure the removal of all air pockets and micro bubbles, a systematic process is followed to get the same level of flow quality every time. This process is explained step by step as follows:

Step 1: Ensure open loop valve configuration (refer to appendix E for valve configuration).

Step 2: Ensure both the pressure transducer valves are closed.

Step 3: Set the VFD at 10 Hz for 5 minutes to allow bigger air bubbles to escape from the open surface in the tank.

Step 4: During this 5 minute, in open loop configuration, open Valve-V3 for 5 seconds then close it. This is to let any trapped bubbles escape from the closed loop section.

Step 5: Stop VFD and let the system rest for 5 minutes. This will allow micro bubbles to coagulate into bigger bubbles.

Step 6: Set the VFD to 20 Hz for 15 seconds, this will dislodge air bubbles trapped in the pipe joints. These bubbles will now be visible in the flow stream.

Step 7: Bring the VFD down from 20 Hz to 8 Hz and run for 5 minutes. Follow step 4 intermittently. This will allow the dislodged bubbles to escape through the tank open surface.

Step 8: Repeat steps 5 to 7 two more times.

Step 8: Stop VFD and allow the fluid to rest for 10 minutes. This will allow any remaining micro bubbles in the stream to rise and accumulate, forming bigger bubbles.

Step 9: Repeat steps 5 to 7 two more times.

Step 10: Continue running the VFD at 10 Hz for 10-15 minutes, use this run time to regulate the fluid temperature to achieve 20±0.5ºC.

Step 11: Set VFD to 15 Hz (still in open loop configuration). With the pressure transducer bypass valve open, open both bleed valves.

Step 12: Very slowly open both pressure port valves, allowing diesel into the transducer. This will start the bleeding. Let the bleeding continue for 3-4 minutes.

Step 13: Close both bleed valves.

Step 14: With the transducer bypass valve open, keep running at 15 Hz for 2 minutes. This will push out any air bubbles in the transducer tubing, through the bypass line into the main pipe, which can then be escaped out in the tank.

Step 15: Stop VFD and close the transducer bypass valve.

Step 16: Ensure fluid temperature within 20±0.5 ºC, if not, set the VFD at 10 Hz with the heat exchanger running till the correct temperature is achieved.

The system will now be ready for the test to begin.

5.3 Test procedure for baseline diesel test.

Three independent tests with diesel are conducted to confirm alignment with the Newtonian C_f- Re curve (14) and repeatability of the results. Before the test, the tank is filled with 35 liters of diesel, which is introduced into the loop, the loop de-airing and transducer bleeding process is then executed as detailed in section 5.2. The test is run using the LabVIEW software, the operator can control the VFD frequency (Hz) that translates to the pump RPM to achieve the required mass flow rates (refer to table 9). Table 10 breaks down the test procedure steps to run the baseline diesel test for the six mass-flow values and aligns each step with the data log time and providing actions or a frequency set values against each step, while maintaining the flow temperature within 20±0.5 ºC.

Step	Log time stamp	Action (Diesel test)			Temperature condition
1	-	Set closed loop configuration and tank outlet open.			
2	-	Turn ON: VFD (set at zero Hz), flow meter and transducer demodulator.			
3		Open both pressure port valves and close the transducer bypass valve.			
4	0	Start data log.			
5	120	Set VFD to 10 Hz.			20±0.5 ºC
			Hz	Verify $\dot{M}_d$ values	
6	420	Set VFD →	8.9	0.360	
7	780	Set VFD →	17.4	0.720	
8	1140	Set VFD →	26.0	1.080	
9	1500	Set VFD →	34.8	1.440	
10	1860	Set VFD →	43.7	1.800	
11	2220	Set VFD →	52.9	2.160	
12	2580	Set VFD →	0.0	0.0	-
13	2700	Stop data log.			-
14	-	Open the transducer bypass valve and then close both pressure port valves.			-
15	-	Turn OFF: - VFD, flow meter and transducer demodulator			-
16	-	Drain the loop. (refer to appendix E for procedure)			-

Table 10: Step-by-step test procedure aligning with the LabVIEW log time stamp, for baseline diesel pipe flow test for 1-inch pipe sizes.

5.4 Measurements

Three tests were conducted as per the procedure mentioned in section 5.3 to get the baseline data and confirm repeatability. The pressure drop (ΔP) versus time (t) plots are presented for all three tests.
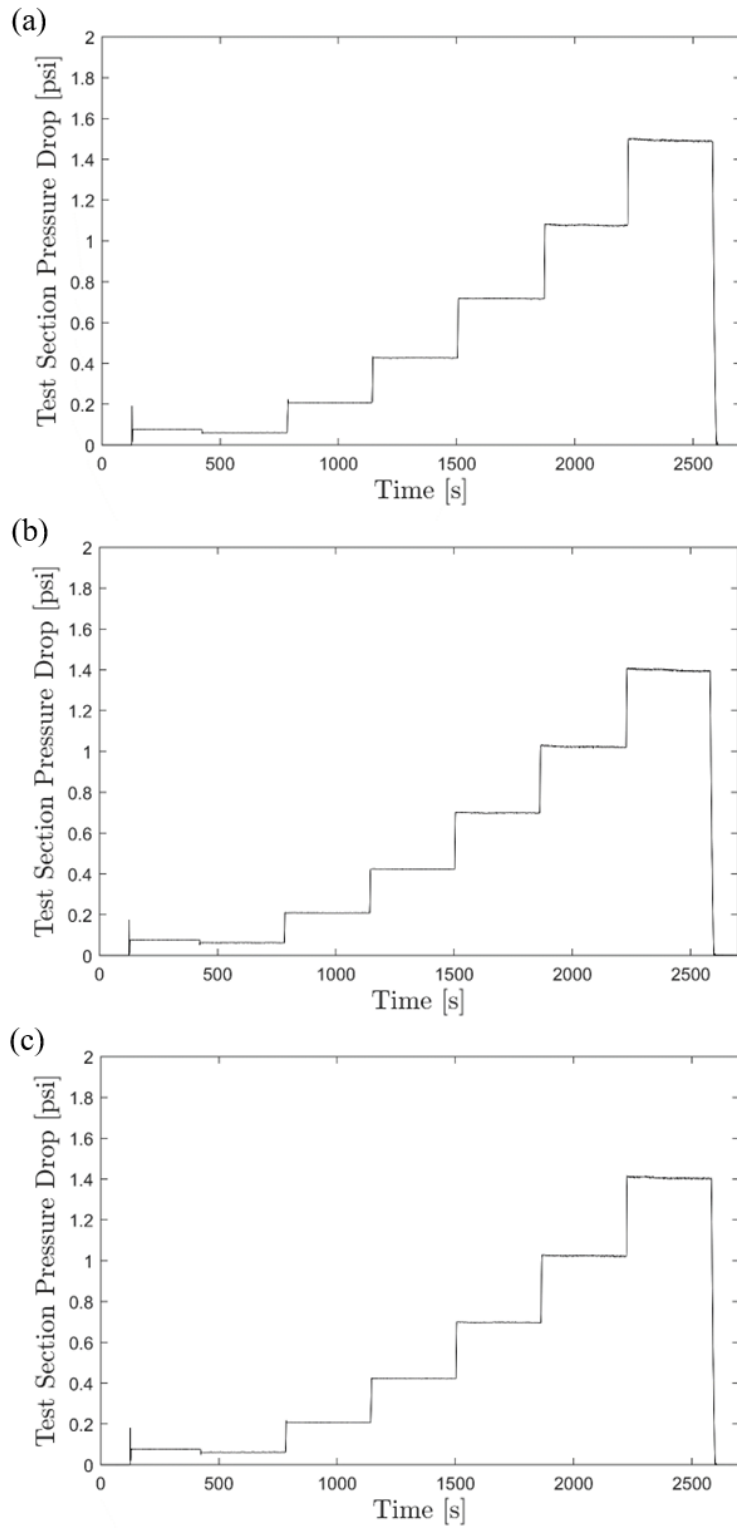
Figure 30: ΔP versus time (t) plots for diesel baseline test in 1-inch pipe sizes for (a) Test 1, (b) Test 2, and (c) Test 3, showing the measurements for six Re values for each test.

It can be observed from figure 30 that the change in the value of ΔP is immediate as the mass flow rate changes and stays stable for the entire duration of 6 minutes. This is due to the positive displacement pump that gives an immediate change in mass flow as the RPM increases and a steady flow rate for a fixed RPM of the pump, unlike the centrifugal pump that required a PID controller to achieve this (refer to the water-based plots in appendix B to observe the contrast). All three plots demonstrate a stable ΔP measurement and repeatable results.

The ΔP values were utilized from these tests along with the density and viscosity values (section 5.1) to calculate C_f (reference to equations 20 and 21) and Re (reference to equation 23). The $C_f - Re$ data for the three tests are presented in figure 31.
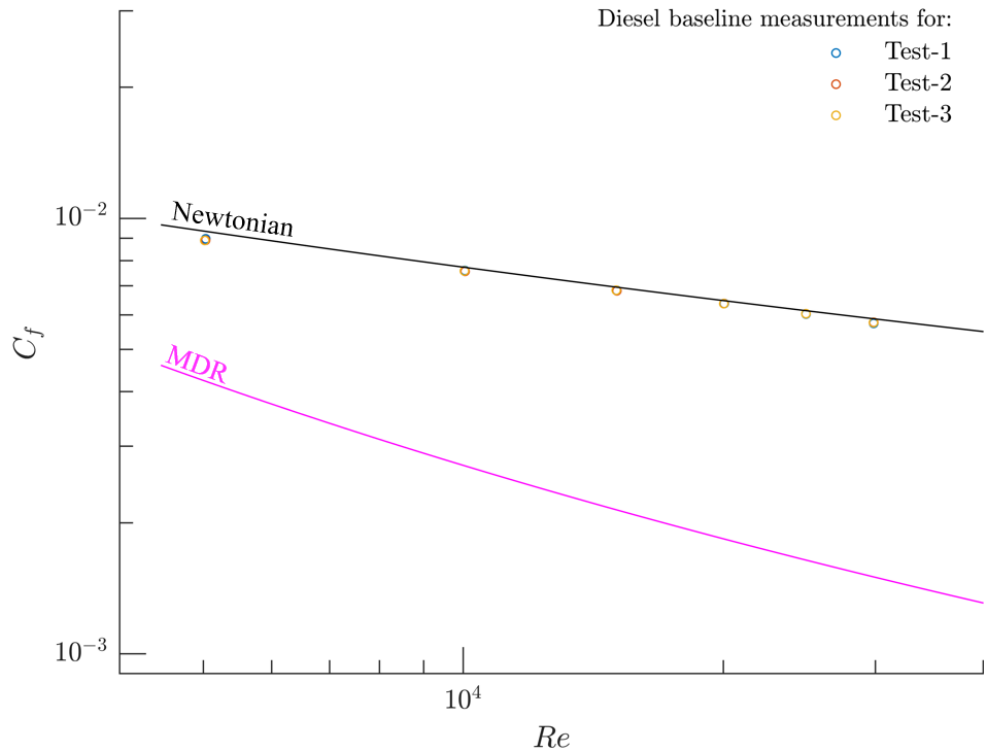
Figure 31: C_f versus Re plot for diesel baseline test in 1-inch pipe sizes, showing the overlapped measurements of three tests each for six Re values.

The tests results show good alignment with the Newtonian C_f –Re curve (14), there is a small noticeable off-set between the data points and the Newtonian curve, but this variance is within the measurement uncertainty discussed in section 3.7. The different colors for each test are not clear because of a good overlap between the three tests, suggesting good repeatability.

These results demonstrate that the diesel loop is working as it was designed to and can achieve the maximum required Re of 30000. The results also indicate the effectiveness of the de-airing and transducer bleeding process, and the stability of the heat exchanger in maintaining the temperature within 20 ± 0.5 ºC. Additionally, these tests have also provided the opportunity to test the loop filling and draining process and fine tune any step to ensure personnel and equipment safety. All of this provides the required confidence in the diesel flow loop and confirms its readiness for the future polymer solution tests.

Chapter 6

Conclusions and future work

The following sections discusses the conclusion of the water-based polymer tests, its impact on the design of diesel tests, and lays down the framework for the future experimental work to be conducted on the diesel flow loop.

6.1 Conclusion

Drag reduction in turbulent pipe flow has a major impact in hydrocarbon transport through pipelines over long distances, but the lack of mathematical understanding of this phenomenon has limited it to a trial-based use in industries. The present work on the water-based polymer solution tests have played an important role in expanding our understanding of how the rheological properties of polymer solutions influences drag reduction in turbulent pipe flows and is an important first step towards the progressive development of the model to predict DR from rheology.

Through the baseline tests measurement, and its alignment to the Newtonian values, the measurement capability and repeatability of the water flow loop was established, which was

crucial for the validation of all later tests and measurements. The polymer solution tests, thereafter, provided a significant data set over a wide range of C_f and Re. The span of this data set, along with the extensional rheological measurements for Wi for each data point has helped in drawing a correlation for the values of Wi based on C_f–Re point grid. These contour map projections have provided the following key observations:

1. The horizontal alignment of the Wi value bands on the C_f–Re data set in the contour map demonstrates that C_f has a high dependency on Wi, and a low dependency on Re.

2. The change in the value of C_f compared to the value of Wi is not a linear relation and can be observed from the varying thickness of the Wi bands. This suggests that the decay of Wi slows down for a constant increase in C_f.

3. Wi and C_f are inversely related. So, as the value of Wi increases, the C_f value decreases. In other words, the higher the relaxation time of a solution, the lower will be its C_f, leading to a higher drag reduction.

These observations will serve as a foundation for the development of an initial model to predict drag reduction from the extensional properties of the solution and have been instrumental in establishing confidence that will drive the future work on diesel, which will provide scalable models that can be utilized at a larger scale.

The water test facility has also provided a good reference for the design and fabrication of the diesel flow loop, which extends further in terms of safety and ease of use. The successful assembly and commissioning of the diesel flow loop was achieved, and the three baseline test results for the relation between C_f and Re exhibits a close and consistent alignment to the expected Newtonian values, deeming the diesel flow loop measurement both accurate and repeatable.

6.2 Future work

The future work entails test on the diesel flow loop similar to the water-based polymer solution tests, a detailed account is summarized as follows:

1. Six *Re* values and their corresponding mass flow rates have been identified for the diesel-polymer test (refer to section 5.1)

2. A polymer concentration test will be run to identify the relation between concentration (ppm) and %DR. This will be an exclusive test for diesel loop as intentional degradation method that was applied for the water-polymer test using the centrifugal pump will not work for the diesel loop due to the use of positive displacement (low shear) pump.

3. Once the ppm - %DR relation is established, the diesel-polymer test can be designed and executed.

4. Based on the results from the diesel test a corelative model will be developed and it will be tested experimentally.

5. The success of the diesel tests will pave the path for future tests with progressively larger diameter pipes, aiming at refining the predictive model as more and more data is gathered.

References

Anna, S. L., and G. H. McKinley. "Elasto-capillary thinning and breakup of model elastic liquids." Journal of Rheology 45, no. 1 (2001): 115-138.

Barnes, H. A., J. F. Hutton, and K. Walters. An introduction to rheology. Vol. 3. Elsevier (1989): 75-96

Benedict, R. P. "Fundamentals of pipe flow." (No Title) (1980): 6.2, 229-230.

Benedict, R. P. "Fundamentals of pipe flow." (No Title) (1980): 6.5, 235.

Benedict, R. P. "Fundamentals of pipe flow." (No Title) (1980): 6.6, 237.

Benzi, R., E. DE ANGELIS, V. S. L'vov, I. Procaccia, and V. Tiberkevich. "Maximum drag reduction asymptotes and the cross-over to the Newtonian plug." Journal of Fluid Mechanics 551 (2006): 185-195.

Blasius P.R.H., "The Similarity Law for Friction Processes in Liquids," Phys. Z., Vol. 12 (1911): 1175.

Burger, E. D., W. R. Munk, and H. A. Wahl. "Flow increase in the Trans Alaska Pipeline through use of a polymeric drag-reducing additive." Journal of petroleum Technology 34, no. 02 (1982): 377-386.

Burgers, J. M. "Mechanical considerations-model systems-phenomenological theories of relaxation and of viscosity." First report on viscosity and plasticity 1 (1935).

Cheng, N. S. "Formula for the viscosity of a glycerol− water mixture." Industrial & engineering chemistry research 47, no. 9 (2008): 3285-3288.

Chhabra, R. P. "Non-Newtonian fluids: an introduction." Rheology of complex fluids (2010): 3-34.

Colebrook, C. F., and C. M. White. "Experiments with fluid friction in roughened pipes." Proceedings of the Royal Society of London. Series A-Mathematical and Physical Sciences 161, no. 906 (1937): 367-381.

Cross, M. M. "Rheology of non-Newtonian fluids: a new flow equation for pseudoplastic systems." Journal of colloid science 20, no. 5 (1965): 417-437.

Darcy, H., and J. Weisbach. "Investigations on the motion of water in pipes and the laws derived from it. " Journal for Pure and Applied Mathematics, 56 (1857): 237-318.

Goldstein, R. J., R. J. Adrian, and D. K. Kreid. "Turbulent and transition pipe flow of dilute aqueous polymer solutions." Industrial & Engineering Chemistry Fundamentals 8, no. 3 (1969): 498-502.

Goudar, C. T., and J. R. Sonnad. "Comparison of the iterative approximations of the Colebrook-White equation: Here's a review of other formulas and a mathematically exact formulation that is valid over the entire range of Re values: Fluid Flow and Rotating Equipment." Hydrocarbon processing (International ed.) 87, no. 8 (2008).

Graham, M. D. "Drag reduction in turbulent flow of polymer solutions." Rheology reviews 2, no. 2 (2004): 143-170.

Hagen, G., and J. L. Poiseuille. "Memoir on the Viscosity of Liquids." Ann. Chim. Phys., 73 (1839): 337-381.

Jones, D. M., K. Walters, and P. R. Williams. "On the extensional viscosity of mobile polymer solutions." Rheologica Acta 26 (1987): 20-30.

Von Karman, Th. "On laminar and turbulent friction." (1946).

Kumor, S. M., and N. D. Sylvester. "Effects of a drag-reducing polymer on the turbulent boundary layer." In AICHE Symposium Series, vol. 69, no. 130. 1973.

L'vov, V. S., A. Pomyalov, I. Procaccia, and V. Tiberkevich. "Drag reduction by polymers in wall bounded turbulence." Physical review letters 92, no. 24 (2004): 244503.

Lescarboura, J. A., J. D. Culter, and H. A. Wahl. "Drag reduction with a polymeric additive in crude oil pipelines." Society of Petroleum Engineers Journal 11, no. 03 (1971): 229-235.

Lumley, J. L. "Drag reduction by additives." Annual review of fluid mechanics 1, no. 1 (1969): 367-384.

Moody, L. F. "Friction factors for pipe flow." Transactions of the American Society of Mechanical Engineers 66, no. 8 (1944): 671-678.

Nadolink, R. H., and W. W. Haigh. "Bibliography on skin friction reduction with polymers and other boundary-layer additives." (1995): 351-460.

Nesyn, G. V., R. Z. Sunagatullin, V. P. Shibaev, and A. Y. Malkin. "Drag reduction in transportation of hydrocarbon liquids: From fundamentals to engineering applications." Journal of Petroleum Science and Engineering 161 (2018): 715-725.

Nikuradse J. "law of turbulent flow in smooth pipe." Forsch.-Arb. Ing.-Wesen, No. 356 (1932)

Nikuradse, J. "Flow laws in rough pipes." VDI Research Paper, 361 (1933): 1-30.

Owolabi, B. E., D. J. C. Dennis, and R. J. Poole. "Turbulent drag reduction by polymer additives in parallel-shear flows." Journal of Fluid Mechanics 827 (2017): R4.

Petrie, C. J. S. "Extensional viscosity: A critical discussion." Journal of Non-Newtonian Fluid Mechanics 137, no. 1-3 (2006): 15-23.

Poole, R. J. "The deborah and weissenberg numbers." Rheol. Bull 53, no. 2 (2012): 32-39.

Prandtl, L. Recent results of turbulence research. No. NACA-TM-720. 1933.

Rudd, M. J. "Drag Reduction." Chem. Eng. Symp. Ser. III, 67, 21 (1971).

Rudd, M. J. "Velocity measurements made with a laser dopplermeter on the turbulent pipe flow of a dilute polymer solution." Journal of Fluid Mechanics 51, no. 4 (1972): 673-685.

Ryskin, G. "Turbulent drag reduction by polymers: a quantitative theory." Physical review letters 59, no. 18 (1987): 2059.

Serghides, T. K. "Estimate friction factor accurately." Chemical engineering (New York, NY) 91, no. 5 (1984): 63-64.

Swamee, P. K., and A. K. Jain. "Explicit equations for pipe-flow problems." Journal of the hydraulics division 102, no. 5 (1976): 657-664.

Tabor, M., and P. G. De Gennes. "A cascade theory of drag reduction." Europhysics Letters 2, no. 7 (1986): 519.

Toms, B. A. "Proc (1st) Intern Congr Rheology, vol II." (1948): 135.

Trouton, F. T. "On the coefficient of viscous traction and its relation to that of viscosity." Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character 77, no. 519 (1906): 426-440.

Virk, P. S., H. S. Mickley, and K. A. Smith. "The ultimate asymptote and mean flow structure in Toms' phenomenon." (1970): 488-493.

Virk, P. S. "An elastic sublayer model for drag reduction by dilute solutions of linear macromolecules." Journal of Fluid Mechanics 45, no. 3 (1971): 417-440.

White, C. M., and M. G. Mungal. "Mechanics and prediction of turbulent drag reduction with polymer additives." Annu. Rev. Fluid Mech. 40 (2008): 235-256.

Appendix A

Engineering drawings for diesel flow loop

This section provides an overview of the diesel flow facility (refer to figure A1), followed by highlighting the key component units (refer to figure A2) and presenting the detailed engineering drawings for each component up to the main assembly level. The drawings include GD&T, material information and welding details that were used in fabrication and assembly of the flow facility components.
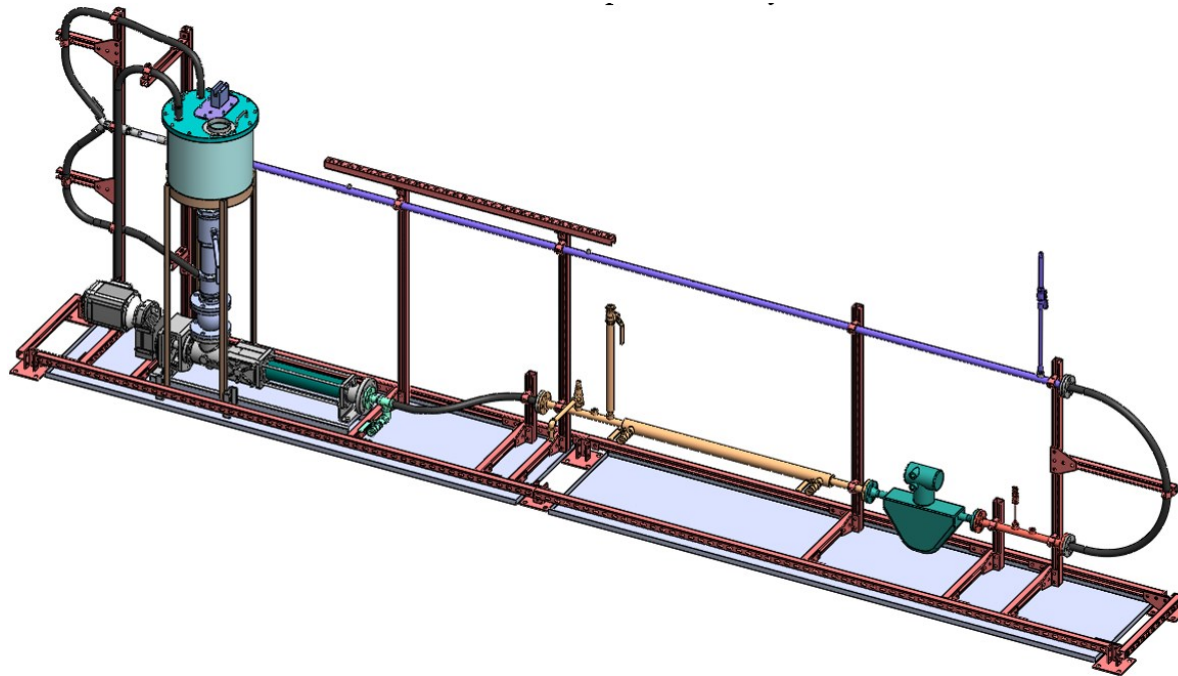
Figure A1: An overview of the diesel flow loop.

Figure A2: Diesel flow loop drawing reference that highlights key component units with reference to the drawing number.
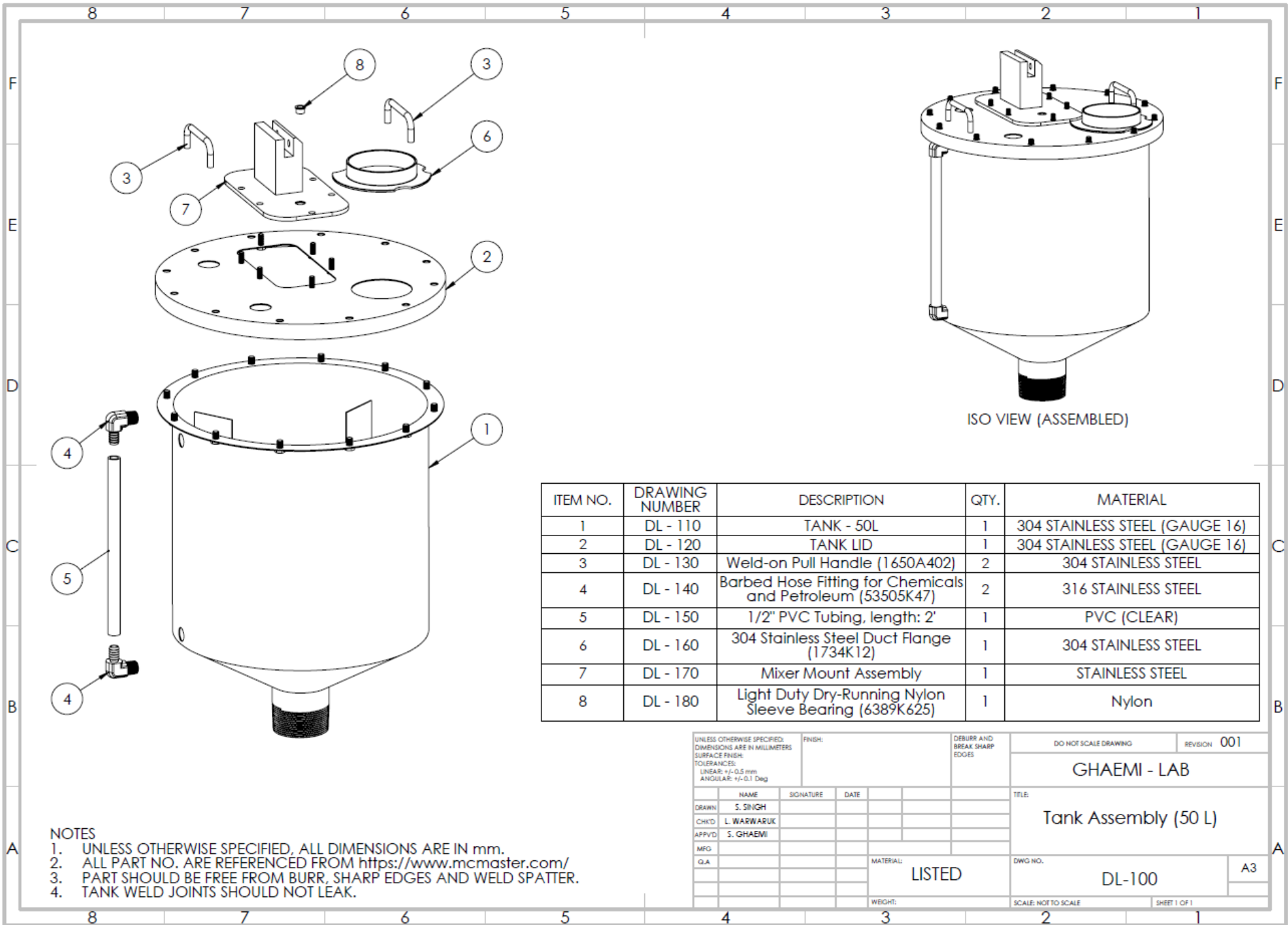
ISO VIEW (ASSEMBLED)

ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL - 110	TANK - 50L	1	304 STAINLESS STEEL (GAUGE 16)
2	DL - 120	TANK LID	1	304 STAINLESS STEEL (GAUGE 16)
3	DL - 130	Weld-on Pull Handle (1650A402)	2	304 STAINLESS STEEL
4	DL - 140	Barbed Hose Fitting for Chemicals and Petroleum (53505K47)	2	316 STAINLESS STEEL
5	DL - 150	1/2" PVC Tubing, length: 2'	1	PVC (CLEAR)
6	DL - 160	304 Stainless Steel Duct Flange (1734K12)	1	304 STAINLESS STEEL
7	DL - 170	Mixer Mount Assembly	1	STAINLESS STEEL
8	DL - 180	Light Duty Dry-Running Nylon Sleeve Bearing (6389K625)	1	Nylon

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4. TANK WELD JOINTS SHOULD NOT LEAK.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
   LINEAR: +/- 0.5 mm
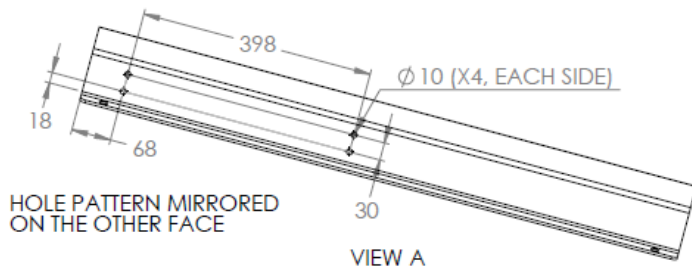   ANGULAR: +/- 0.1 Deg

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING   REVISION 001

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:

Tank Assembly (50 L)

MATERIAL:
LISTED

DWG NO.
DL-100

A3

WEIGHT:

SCALE: NOT TO SCALE   SHEET 1 OF 1

Component Details:

1. Tank cylinderical wall (Qty. 1): 304 STAINLESS STEEL (16 GAUGE)

ISO VIEW

BLANK SIZE — 1257, 369

2. Conical Tank Bottom: 304 STAINLESS STEEL (16 GAUGE)

ISO VIEW

Ø 462, 48°, Ø 103

BLANK SIZE

3. Tank Rim for Lid: 304 STAINLESS STEEL (16 GAUGE)

4. Tank Baffel (x4): 304 STAINLESS STEEL (16 GAUGE)

320, 70, 120°

FRONT VIEW

Ø 397, Ø 448

TOP VIEW

5. 3" Threaded pipe fitting (9157K402)

6. 3/8 - 24, 3/4" long Bolt (total 12) welded on the Tank Rim holes (Dia. 10 mm).

30° (same between each hole, x 12)
55°
211 (x 12) (center to center)
90°
90°
90°
90°
Ø 10 (x 12)
Ø 448
Ø 397(ID)
5.0 / 20 - 60 (x4)
A

35
Ø 22(x 2)
354
371
90
Ø 89
Ø 400(OD)
240°

50
70
SECTION A-A
□ ±0.5
5.0
0.8
0.8
A
// ±0.5 A

6 x 12
4
3
1
2
5

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/ PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4. TANK WELD JOINTS SHOULD NOT LEAK.

30° (same between each hole, x 12)

A

Ø 12 (x12)

Ø 34 (X2)

R20 (x4)

Ø 8 (x6)

98

211

170

160

112

20

100

112

40

50

98

Ø 453

50

50

Ø 95

60

60

110

A

3
X 6

1

2

SECTION A-A

0.8 / 10-118.6

TOP VIEW

□ ±0.5

1.6 (TOP LID PLATE - 16 GAUGE)

25.4
(LID SKIRTING)

Ø 453

SIDE VIEW

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

2. LID SKIRTING BLANK: 304 STAINLESS STEEL (16 GAUGE)

3.
5/16-24, 3/4" LONG BOLT
WELDED TO THE LID AT THE
6 MIXER HEAD MOUNTING
HOLES (Dia. 8 mm)

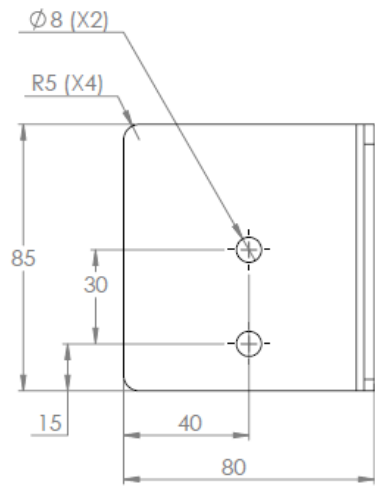1424

25.4

BLANK SIZE

ISO VIEW

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/-0.5 mm ANGULAR: +/-0.1 Deg.	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION	001
					GHAEMI - LAB			
	NAME	SIGNATURE	DATE		TITLE:			
DRAWN	S. SINGH							
CHK'D	L. WARWARUK				Tank Lid (50 L)			
APPV'D	S. GHAEMI							
MFG								
Q.A				MATERIAL: 304 STAINLESS STEEL (GAUGE 16)	DWG NO. DL - 120			A3
				WEIGHT:	SCALE: NOT TO SCALE		SHEET 1 OF 1	

MODIFICATIONS:

Circular cutouts required on the flange for clearances

68   85

R43

R18

78

8

85

8   R18

TOP VIEW

ISO VIEW

EXTERNAL PART - MODIFIED

6.063in
4.063in

1in

1in

0.125in

Trade Size: 4in

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR AND SHARP EDGES

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION 001
					GHAEMI - LAB		
	NAME	SIGNATURE	DATE		TITLE:		
DRAWN	S. SINGH				304 Stainless Steel Duct Flange McMaster Carr Part No. : 1734K12		
CHK'D	L. WARWARUK						
APPV'D	S. GHAEMI						
MFG							
Q.A							
				MATERIAL: LISTED	DWG NO. DL - 160		A3
				WEIGHT:	SCALE: NOT TO SCALE	SHEET 1 OF 1	
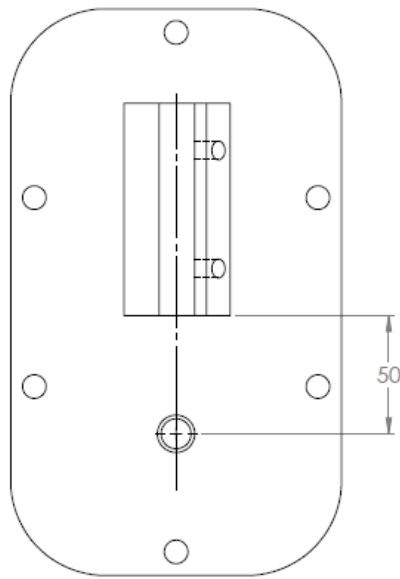
91

TOP VIEW

50

EXPLODED VIEW

②

①

ISO VIEW

FRONT VIEW

7

5
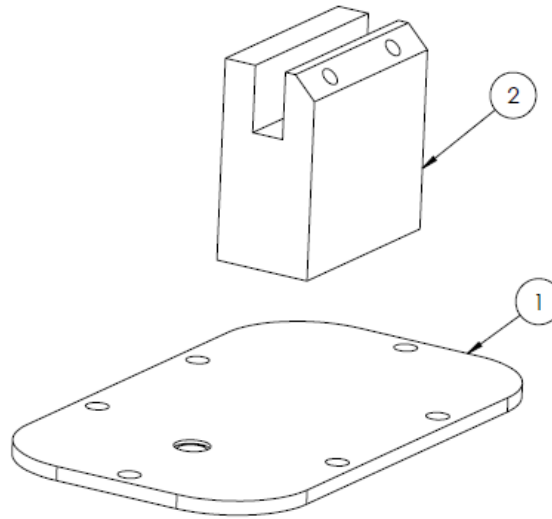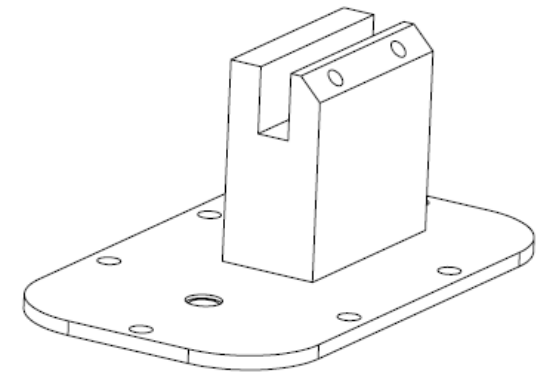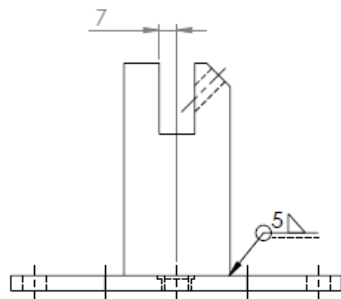
ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL - 171	Mixer Base Plate	1	304 STAINLESS STEEL
2	DL - 172	Mixer Mount Block	1	304 STAINLESS STEEL

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: +/- 0.5 mm
ANGULAR: +/- 0.1 Deg

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION 001

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:

Mixer Mount Assembly

MATERIAL:
LISTED

DWG NO.
DL-170

A3

WEIGHT:

SCALE: NOT TO SCALE

SHEET 1 OF 1

Ø10 (x6)

R40 (x4)

60

50

A

A

20

100

180

170

60

60

70

70

TOP VIEW

Ø15.9

1.6

Ø12.7

DETAIL B

ISO VIEW

B

SECTION A-A

6.4 (1/4")

FRONT VIEW

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.5 mm ANGULAR: +/- 0.1 Deg	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION 001
					GHAEMI - LAB		

	NAME	SIGNATURE	DATE		TITLE:		
DRAWN	S. SINGH						
CHK'D	L. WARWARUK				Mixer Base Plate		
APPV'D	S. GHAEMI						
MFG							
Q.A			MATERIAL: LISTED		DWG NO. DL-171		A3
			WEIGHT:		SCALE: NOT TO SCALE	SHEET 1 OF 1	

93

7.5

7.5

C

10 X 45°

135°

90   60

45

FRONT VIEW

25   25

90

SIDE VIEW

ISO VIEW

Ø7.9 (X2)

3/8 - 24 Tap (x2)

VIEW C
⌒ 45.00°

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

GHAEMI - LAB

	NAME	SIGNATURE	DATE		TITLE:
DRAWN	S. SINGH				
CHK'D	L. WARWARUK				Mixer Mount Block
APPV'D	S. GHAEMI				
MFG					
Q.A					

MATERIAL:
LISTED

DWG NO.
DL-172

A3

WEIGHT:

SCALE: NOT TO SCALE

SHEET 1 OF 1

94

Flange hole alignment with Tee
and Valve handle orientation

45°
25°
45°
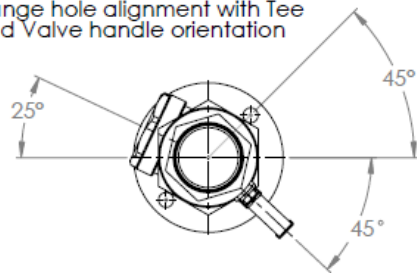
TOP VIEW
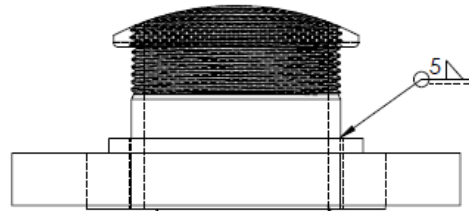
DETAIL A

Overall Dimension
is from this face

3" Nipple (#5)
unthreaded face
should be coplaner
with the flange face

5

672

A

FRONT VIEW

1

3

7

2

3

6

5

4
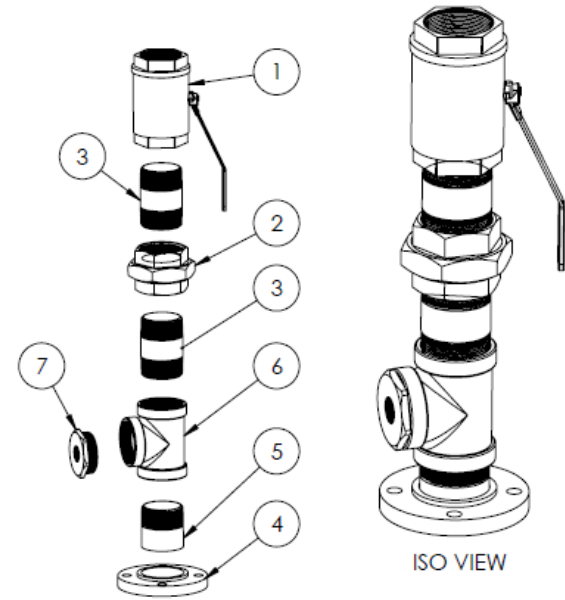
EXPLODED VIEW

ISO VIEW
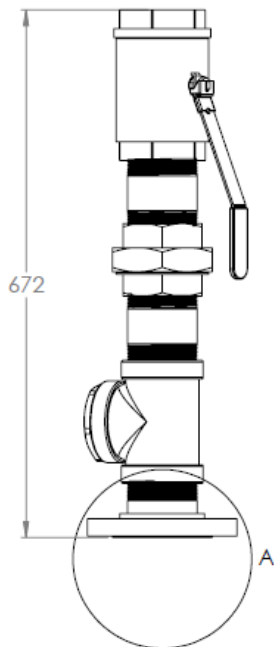
ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	-	3" Full-Port ball valve (46495K28)	1	304 Stainless Steel
2	-	3" pipe union (4464K494)	1	304 Stainless Steel
3	-	3" x 5" Pipe Nipple (4830K357)	2	304 Stainless Steel
4	-	3" Slip-on Forged Pipe Flange (44685K186)	1	304 Stainless Steel
5	-	3" x 3-1/2" Pipe Nipple, one side threaded (9157K8)	1	304 Stainless Steel
6	-	3" Tee (4464K142)	1	304 Stainless Steel
7	-	3" to 1" Bushing Adapter (4464K177)	1	304 Stainless Steel

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4. ALL PHERIPARAL WELD JOINTS SHOULD NOT LEAK.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: +/- 0.5 mm
ANGULAR: +/- 0.1 Deg.

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 001

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:

Tank Outlet Fittings

MATERIAL:
LISTED

DWG NO.
DL - 200

A3

WEIGHT:

SCALE:1:10

SHEET 1 OF 1

FRONT VIEW

142.4   142.4

114   114

SIDE VIEW

ISO VIEW

228.4

Pump Inlet Port

200

120.7

197.1

TOP VIEW

3

2

3

2

1

EXPLODED VIEW

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DL - 310	NETZSCH Pump Base	1
2	DL - 320	Tank Frame Mounting Bracket - A	2
3	DL - 330	Tank Frame Mounting Bracket - B	2

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

970
(MOUNTING HOLE)

268

1050

TOP VIEW

ISO VIEW

398

Ø 10 (X4, EACH SIDE)

18

68

30

HOLE PATTERN MIRRORED
ON THE OTHER FACE

VIEW A

SIDE VIEW

A

105°

240
(MOUNTING HOLE)

FRONT VIEW

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.5 mm ANGULAR: +/- 0.1 Deg | FINISH: | | | DEBURR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION 001 |

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:

NETZSCH Pump Base

| MATERIAL: STRUCTURAL STEEL | DWG NO. DL-310 | A3 |
| WEIGHT: | SCALE: NOT TO SCALE | SHEET 1 OF 1 |

TOP VIEW

90°

ISO VIEW

FRONT VIEW

83
15°
Ø 10 (X2)
50
19
16

SIDE VIEW

Ø 8.00 (X2)
R5 (X4)
85
30
15
40
80

BLANK SIZE

163
40
75°
50
85
30
19
16
78.8
(BENDING LINE)
15

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

98

TOP VIEW

90°

ISO VIEW

SIDE VIEW

Ø 8 (X2)
R5 (X4)
85
30
15
40
80

FRONT VIEW

83
15°
Ø 10 (X2)
50
19
16

BLANK SIZE

163
40
75°
85
30
50
15
78.8
(BENDING LINE)
16
19

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

Ø 402.0
(Ring Inside Dia.)

90°

A

90°   90°

Ø 240.0
(Ring Inside Dia.)

A

45°

TOP VIEW

NO WELD ON TOP FACE

120°

20.8

1.8 x 3.2 ⌵ 25.4 (x4)

(x4) 5 ⌒

5 ⌒

(x4)

DETAIL B

(x8) 5 / 50.8

67.6   50.8

1156.3

142.4   142.4

SIDE VIEW

B

SECTION A-A

1

3

3   3

3   3

2

4

5   5

4

EXPLODED VIEW

ISO VIEW

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.

ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL - 410	Upper Ring	1	304 STAINLESS STEEL (GAUGE-11)
2	DL - 420	Lower Ring	1	304 STAINLESS STEEL (GAUGE-11)
3	DL - 430	T Bar (1352T111)	4	304 STAINLESS STEEL
4	DL - 440	90 Degree Angle - A (8993K42)	2	304 STAINLESS STEEL
5	DL - 450	90 Degree Angle - B (8993K42)	2	304 STAINLESS STEEL

Ø 402.0
(INSIDE DIA.)

TOP VIEW

ISO VIEW

25.4   50.8   50.8

R10.0 (X2)

SIDE VIEW

50.8

1263.0

BLANK SIZE

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR AND SHARP EDGES

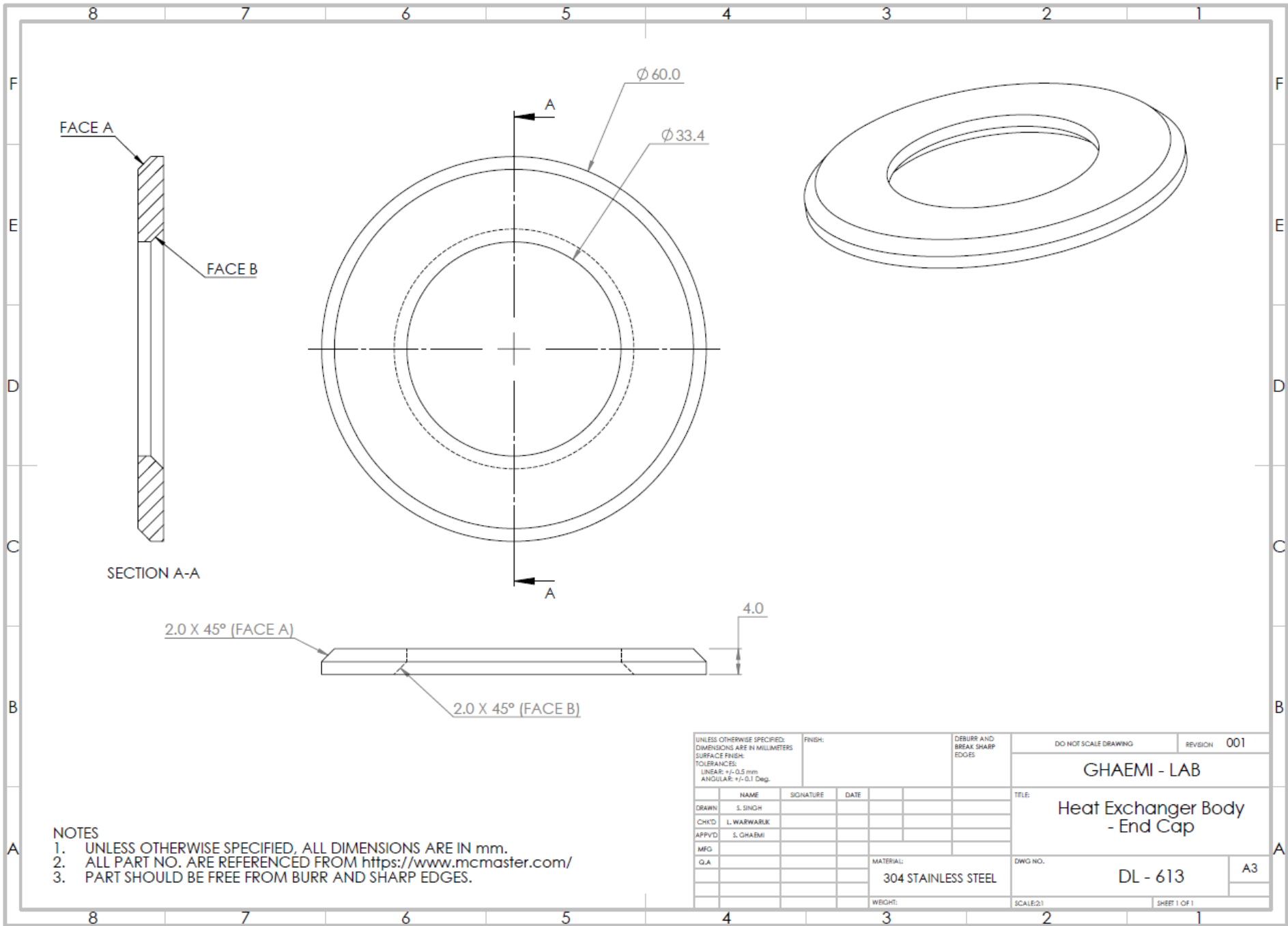| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 001

GHAEMI - LAB

	NAME	SIGNATURE	DATE		TITLE:
DRAWN	S. SINGH				TANK SUPPORT - UPPER RING
CHK'D	L. WARWARUK				
APPV'D	S. GHAEMI				
MFG					
Q.A			MATERIAL: 304 STAINLESS STEEL (GAUGE - 11)	DWG NO. DL - 410	A3

WEIGHT: SCALE: NOT TO SCALE   SHEET 1 OF 1

Ø 240.0
(INSIDE DIA.)

TOP VIEW

ISO VIEW

30.0

SIDE VIEW

30.0

754.0

BLANK SIZE

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR AND SHARP EDGES

MODIFICATIONS:

T-Bar to be cut at an angle from both sides

ISO VIEW

60°   120°

104.5

SIDE VIEW

1"±0.078

1"±0.078

1/8"

1 ft.

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR AND SHARP EDGES

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION 001
				GHAEMI - LAB		
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	S. SINGH					
CHK'D	L. WARWARUK				TANK SUPPORT - T BAR	
APPV'D	S. GHAEMI					
MFG						
Q.A			MATERIAL:		DWG NO.	
			304 STAINLESS STEEL		DL - 430	A3
			WEIGHT:		SCALE: NOT TO SCALE	SHEET 1 OF 1

EXTERNAL PART - MODIFIED

MODIFICATIONS:
Two holes to be made on the angle bar

ISO VIEW

1" ± 1/8

1" ± 1/8

3/16"

6 ft. ±1"

Ø 8.0 (x2)

76.2

SIDE VIDE 25.4

TOP VIEW

EXTERNAL PART - MODIFIED

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR AND SHARP EDGES

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION 001
				GHAEMI - LAB		
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN	S. SINGH					
CHK'D	L. WARWARUK			TANK SUPPORT - T BAR (A)		
APPV'D	S. GHAEMI					
MFG						
Q.A			MATERIAL:	DWG NO.		
			304 STAINLESS STEEL	DL - 440		A3
			WEIGHT:	SCALE: NOT TO SCALE	SHEET 1 OF 1	

MODIFICATIONS:
Two holes to be made on the angle bar

ISO VIEW

1" ± 1/8

1" ± 1/8

3/16"

6 ft. ± 1"

Ø 8.0 (X2)

76.2

25.4

SIDE VIEW

TOP VIEW

EXTERNAL PART - MODIFIED

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR AND SHARP EDGES

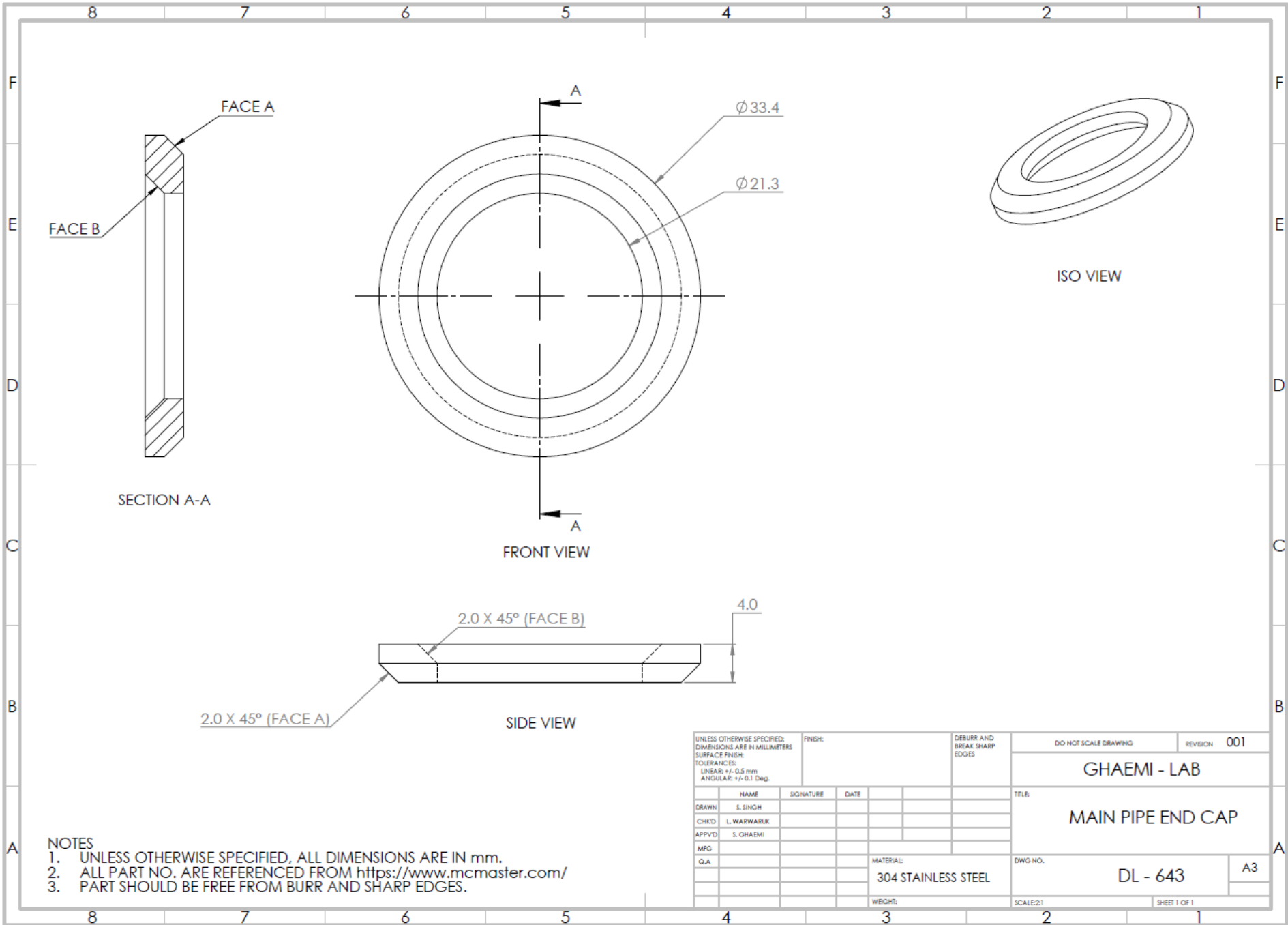| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION 001
				GHAEMI - LAB		

	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	S. SINGH				
CHK'D	L. WARWARUK			TANK SUPPORT - T BAR (B)	
APPV'D	S. GHAEMI				
MFG					
Q.A			MATERIAL: 304 STAINLESS STEEL	DWG NO. DL - 450	A3
			WEIGHT:	SCALE: NOT TO SCALE	SHEET 1 OF 1

105

A

Flange holes should be
vertically oriented at 45°
to the elbow male end
shaft

45°

6

7

2

ISO VIEW

4

3

1

5

EXPLODED VIEW

1" Nipple (#7) unthreaded
face should be coplaner
with the flange face

5

DETAIL A
SCALE 2 : 3

ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	-	1" Elbow Male-Female (4464K41)	1	304 Stainless Steel
2	-	1" Tee (4464K53)	1	304 Stainless Steel
3	-	1" x 3" Threaded Pipe Nipple (4830K225)	1	304 Stainless Steel
4	-	1" Full port ball valve (4024T75)	1	304 Stainless Steel
5	-	1" Coupling Socket with Male NPT (53015K132)	1	316 Stainless Steel
6	-	1" Slip-on Forged Pipe Flange (44685K181)	1	304 Stainless Steel
7	-	1" x 3" One Side Threaded Pipe Nipple (9157K45)	1	304 Stainless Steel

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4. ALL PHERIPARAL WELD JOINTS SHOULD NOT LEAK.

Both flange's hole-orientation should be in-line and also vertically oriented at 45° with the three weld bung's axis.
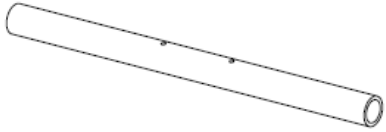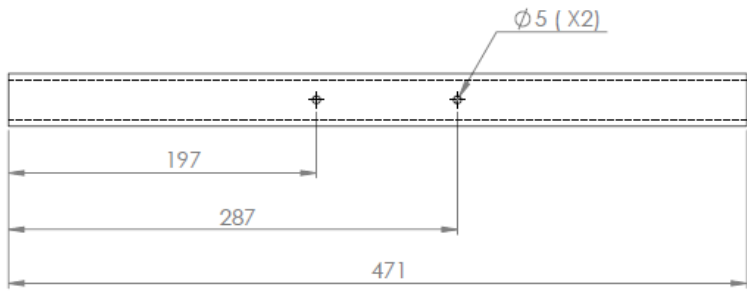
45° 90° 45°

SIDE VIEW

A

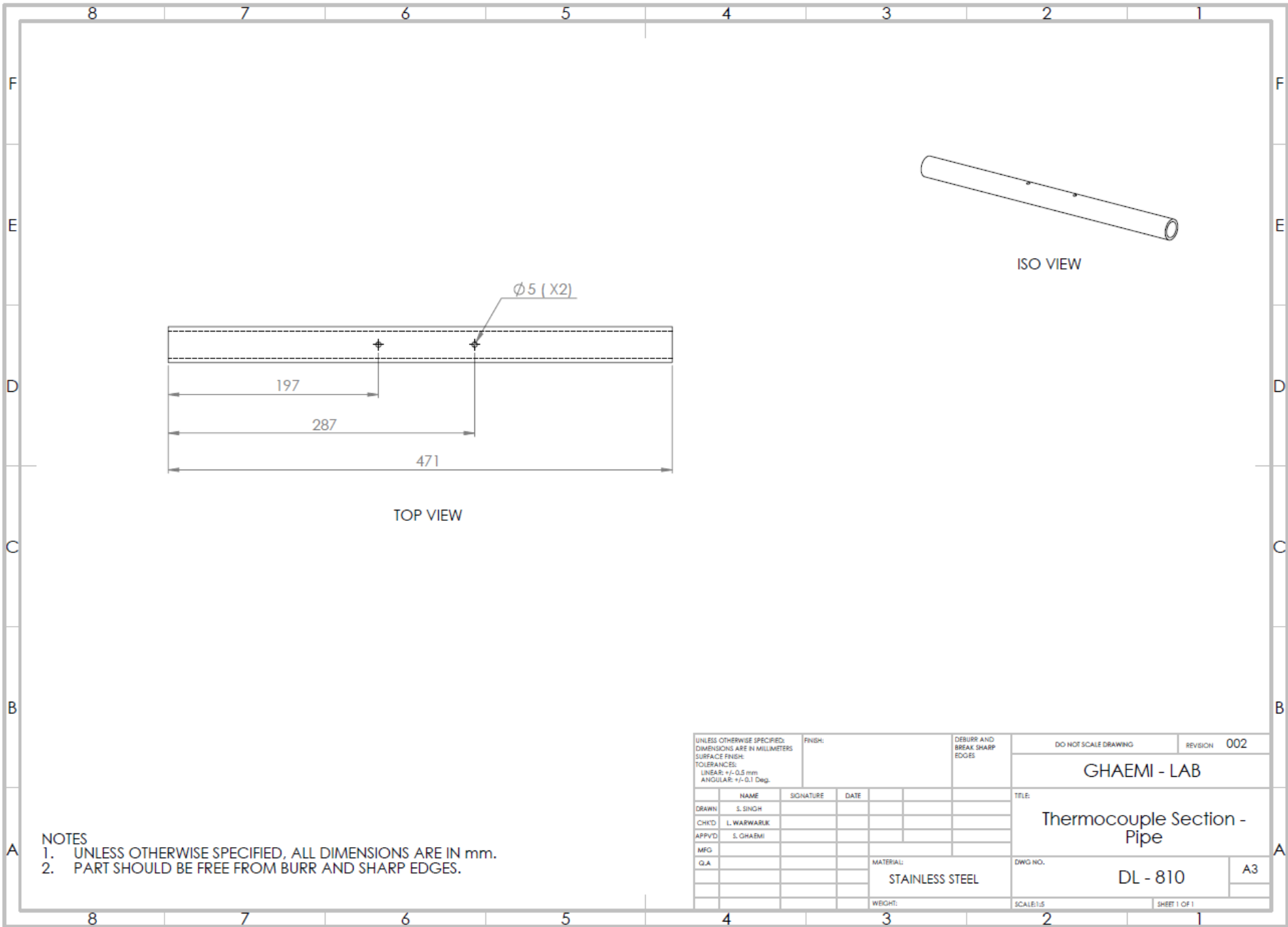190

275

360

1735

45° (x3)

FRONT VIEW

ISO VIEW

OUTER DIMENSIONS ARE FROM THIS FACE

5 (x2)

435

5.0 (x2)

TOP VIEW

DETAIL A

EXPLODED VIEW

1
2
3
4
5
6
7
8
9

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4.   ALL PHERIPARAL WELD JOINTS SHOULD NOT LEAK.

ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL-610	HEAT EXCHANGER BODY	1	STAINLESS STEEL
2	-	304 SS, FORGED PIPE FLANGE (44685K181)	2	304 STAINLESS STEEL
3	-	1" FULL PORT VALVE (4024T75)	1	STAINLESS STEEL
4	DL-640	OSCILLATION DAMPNER (ASM)	1	304 STAINLESS STEEL
5	-	THREADED BUNG - FOR 3/4" PIPE (4464K473)	3	304 STAINLESS STEEL
6	-	STANDARD-WALL 1" NPS THREADED PIPE NIPPLE (9157K35)	2	304 STAINLESS STEEL
7	-	PRESSURE-RELIEF VALVE (4703K547)	1	STAINLESS STEEL
8	-	1/2" STRAIGHT PIPE CONNECTOR (4464K354)	1	304 STAINLESS STEEL
9	-	1/2" x 5" PIPE NIPPLE (4830K177)	1	304 STAINLESS STEEL

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
   LINEAR: +/- 0.5 mm
   ANGULAR: +/- 0.1 Deg.

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 004

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:
Heat Exchanger + Oscillation Dampner (ASM)

MATERIAL:
LISTED

DWG NO.
DL - 600

A3

WEIGHT:

SCALE:1:20

SHEET 1 OF 1

107

② ③ ①

EXPLODED VIEW

ISO VIEW

90°

435

A

FRONT VIEW

SIDE VIEW

90° (x2)

45° (x2)

DETAIL A
SCALE 1 : 1

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL
     DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM
     https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR, SHARP
     EDGES AND WELD SPATTER.
4.   ALL PERIPHERAL WELD JOINTS SHOULD
     NOT LEAK.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL-611	CORE PIPE - 1-INCH	1	304 STAINLESS STEEL
2	DL-612	OUTER JACKET PIPE - 2-INCH	1	304 STAINLESS STEEL
3	DL-613	JACKET END CAP	2	304 STAINLESS STEEL

108

Ø25.4 (NOMINAL PIPE SIZE - SCHEDULE-40)

ISO VIEW

Ø15.0 (x3)

SIDE VIEW

190

275

360

1735

FRONT VIEW

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR AND SHARP EDGES.

ISO VIEW

Ø 50.8 (NOMINAL PIPE SIZE - SCHEDULE-40)

2.0 X 45° (BOTH ENDS)

Ø 33.4 (X2)

A

SIDE VIEW

50.0

1088.0

50.0

FRONT VIEW

DETAIL A

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR AND SHARP EDGES.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.5 mm ANGULAR: +/- 0.1 Deg.	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION	001
					GHAEMI - LAB			
	NAME	SIGNATURE	DATE		TITLE:			
DRAWN	S. SINGH				Heat Exchanger Body - OUTTER JACKET PIPE 2-INCH			
CHK'D	L. WARWARUK							
APPV'D	S. GHAEMI							
MFG								
Q.A			MATERIAL: 304 STAINLESS STEEL		DWG NO. DL - 612			A3
			WEIGHT:		SCALE:1:10		SHEET 1 OF 1	

110

FACE A

Ø 60.0

Ø 33.4

A

FACE B

SECTION A-A

A

4.0

2.0 X 45° (FACE A)

2.0 X 45° (FACE B)

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR AND SHARP EDGES.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.5 mm ANGULAR: +/- 0.1 Deg.	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION	001
				GHAEMI - LAB			

	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	S. SINGH				Heat Exchanger Body - End Cap	
CHK'D	L. WARWARUK					
APPV'D	S. GHAEMI					
MFG						
Q.A			MATERIAL: 304 STAINLESS STEEL	DWG NO. DL - 613	A3
			WEIGHT:	SCALE:2:1	SHEET 1 OF 1

111

ISO VIEW

1

EXPLODED VIEW

2   3

34

A

FRONT VIEW

90°

45°

DETAIL A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL-641	OSCILLATION DAMPNER - MAIN PIPE 1-INCH	1	304 STAINLESS STEEL
2	-	STANDARD-WALL THREADED PIPE NIPPLE, THREADED ON ONE END, 1/2 NPT, 1-1/2" LONG (9157K23)	1	304 STAINLESS STEEL
3	DL-643	MAIN PIPE END CAP	1	304 STAINLESS STEEL

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4.   ALL PERIPHERAL WELD JOINTS SHOULD NOT LEAK.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
    LINEAR: +/- 0.5 mm
    ANGULAR: +/- 0.1 Deg.

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION   001

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:
Oscillation Dampener (ASM)

MATERIAL:
LISTED

DWG NO.
DL - 640

A3

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

ISO VIEW

1 NPT PIPE SIZE, 11 1/2 TPI, 0.68" THREAD ENGAGEMENT

Ø 25.4 (1" NPS - Schedule 40)

500.0

2.0 X 45°

FRONT VIEW

| | | UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.5 mm ANGULAR: +/- 0.1 Deg. | FINISH: | | DEBURR AND BREAK SHARP EDGES | REVISION 001 |

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:
Oscillation Dampener - Main Pipe 1-Inch

MATERIAL:
304 STAINLESS STEEL

DWG NO.
DL - 641

A3

WEIGHT: SCALE:1:5   SHEET 1 OF 1

NOTES
1.   UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2.   ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3.   PART SHOULD BE FREE FROM BURR AND SHARP EDGES.

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FACE A

FACE B

SECTION A-A

A

Ø 33.4

Ø 21.3

FRONT VIEW

A

ISO VIEW

2.0 X 45° (FACE B)

4.0

2.0 X 45° (FACE A)

SIDE VIEW

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR AND SHARP EDGES.

	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	S. SINGH				MAIN PIPE END CAP	
CHK'D	L. WARWARUK					
APPV'D	S. GHAEMI					
MFG						
Q.A			MATERIAL:		DWG NO.	
			304 STAINLESS STEEL		DL - 643	A3
			WEIGHT:		SCALE:2:1	SHEET 1 OF 1

114

OUTER DIMENSIONS ARE FROM THIS FACE

5 (x2)

DETAIL A

Both flange's hole-orientation should be in-line and also vertically oriented at 45° with the two weld bung's axis.

45°

5 (x2)

A

197
287
471

FRONT VIEW

5

4

3

1

2

2

6

1

EXPLODED VIEW

ISO VIEW
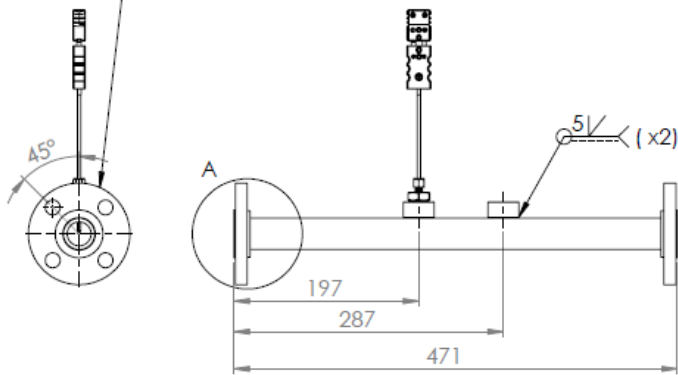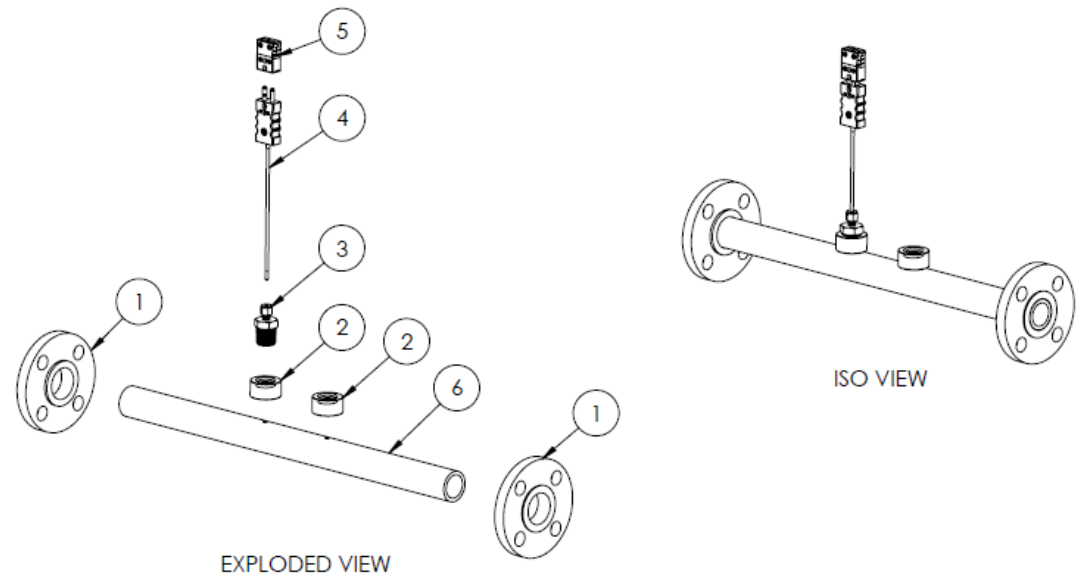
ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	-	Low-Pressure Forged Pipe Flange (44685K181)	2	304 Stainless Steel
2	-	Threaded Pipe Fitting (4464K473)	2	304 Stainless Steel
3	-	Yor-Lok Fitting for Stainless Steel Tubing (5182K21)	1	304 Stainless Steel
4	-	Bendable Thermocouple Probe for Liquid and Gas (K-Type)	1	
5	-	Thermocouple Connector	1	
6	DL - 810	1" Pipe (Schedule 40)	1	Stainless Steel

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
    LINEAR: +/- 0.5 mm
    ANGULAR: +/- 0.1 Deg.

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 004

GHAEMI - LAB

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

TITLE:

Thermocouple Section

MATERIAL:
LISTED

DWG NO.
DL - 800

A3

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4. ALL PHERIPARAL WELD JOINTS SHOULD NOT LEAK.

ISO VIEW

Ø 5 (X2)

197

287

471

TOP VIEW

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. PART SHOULD BE FREE FROM BURR AND SHARP EDGES.

116

Facing the Flange side, the diverter valve handels should be on the left side

Flange's hole-orientation should be vertically oriented at 45° with the three weld bung's axis (Ref. detail A, B and C)

DETAIL D

45°

DETAIL A

DETAIL B

DETAIL C

ISO VIEW

Center line of the 3-1/2" Nipple (Item No. 11)

A   B   C   E

2540

142

3810

5053

FRONT VIEW

681

D

SIDE VIEW

5

Outer Dimensions are from this Face

DETAIL E

EXPLODED VIEW

ITEM NO.	DRAWING NUMBER	DESCRIPTION	QTY.	MATERIAL
1	DL - 910	Main Test Section	1	Stainless Steel
2	-	Dual Shut-Off Threaded Diverting Valve (4017T14)	1	Stainless Steel
3	-	Threaded Pipe Fitting - 1/2" Bung (4464K473)	1	304 Stainless Steel
4	-	304 SS Forged Pipe Flange (44685K181)	1	304 Stainless Steel
5	-	Ultra-Corrosion Resistant Full-Port On/Off Valve (46495K21)	1	Stainless Steel
6	-	Standard-Wall Pipe Nipple (4830K179)	1	304 Stainless Steel
7	-	Compact Flow Sight for Chemicals (5071K31)	1	Stainless Steel/FEP
8	-	Compact Flow Sight for Chemicals (5071K43)	1	Stainless Steel/FEP
9	-	Threaded Pipe Fitting (4464K356)	2	304 Stainless Steel
10	-	Standard-Wall Pipe Nipple (4830K148)	1	304 Stainless Steel
11	-	1" to 3/4" Adaptor (1432N56)	2	304 Stainless Steel
12	-	Threaded Pipe Fitting - 1/8" Bung (4464K364)	2	304 Stainless Steel
13	-	Yor-Lok Fitting 1/8" Tube, 1/8" male (5182K804)	2	Stainless Steel

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. ALL PART NO. ARE REFERENCED FROM https://www.mcmaster.com/
3. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
4. ALL PHERIPARAL WELD JOINTS SHOULD NOT LEAK.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/-0.5 mm ANGULAR: +/-0.1 Deg.	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 005
				GHAEMI - LAB	
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	S. SINGH				
CHK'D	L. WARWARUK			Main Section	
APPV'D	S. GHAEMI				
MFG					
Q.A			MATERIAL: LISTED	DWG NO. DL - 900	A3
			WEIGHT:	SCALE:1:50	SHEET 1 OF 1

Ø25.4 (Nominal Pipe Size - Schedule 40)

1 NPT PIPE SIZE, 11 1/2 TPI, 0.68" THREAD ENGAGEMENT

Ø1   Ø1   Ø15

ISO VIEW

SIDE
VIEW

TOP VIEW

142

2540

3810

4735

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/-0.5 mm ANGULAR: +/-0.1 Deg.	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 002

GHAEMI - LAB

	NAME	SIGNATURE	DATE		TITLE:
DRAWN	S. SINGH				Main Section - Pipe
CHK'D	L. WARWARUK				
APPV'D	S. GHAEMI				
MFG					
Q.A			MATERIAL:		DWG NO.

MATERIAL: Stainless Steel

DWG NO. DL - 910

A3

WEIGHT: SCALE:1:50   SHEET 1 OF 1

TOP VIEW

970

Ø15 (Through Holes, x4)

115

240

527

ISO VIEW

25.4 (Skirting Height)

2500

1.6 (Base Thickness - 16 Gauge)

FRONT VIEW

1.6 (Skirting Thickness - 16 Gauge)

5

1.6 (Skirting Thickness - 16 Gauge)

DETAIL A

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
3. WELD JOINTS SHOULD NOT LEAK.

	NAME	SIGNATURE	DATE
DRAWN	S. SINGH		
CHK'D	L. WARWARUK		
APPV'D	S. GHAEMI		
MFG			
Q.A			

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
  LINEAR: +/- 0.5 mm
  ANGULAR: +/- 0.1 Deg

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 001

GHAEMI - LAB

TITLE:

SPILL PROOFING TRAY
(PUMP SIDE)

MATERIAL:
16 GAUGE
STAINLESS STEEL

DWG NO.
-

A3

WEIGHT:

SCALE: NOT TO SCALE

SHEET 1 OF 1

TOP VIEW

600

2902

A

ISO VIEW

25.4(Skirting Height)

1.6 (Base Thickness - 16 Gauge)

SIDE VIEW

1.6 (Skirting Thickness - 16 Gauge)

5

1.6 (Skirting Thickness - 16 Gauge)

DETAIL A

NOTES
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN mm.
2. PART SHOULD BE FREE FROM BURR, SHARP EDGES AND WELD SPATTER.
3. WELD JOINTS SHOULD NOT LEAK.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.5 mm ANGULAR: +/- 0.1 Deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 001
				GHAEMI - LAB	

	NAME	SIGNATURE	DATE		TITLE:
DRAWN	S. SINGH				SPILL PROOFING TRAY (FLOW METER SIDE)
CHK'D	L. WARWARUK				
APPV'D	S. GHAEMI				
MFG					
Q.A				MATERIAL: 16 GAUGE STAINLESS STEEL	DWG NO. – A3
				WEIGHT:	SCALE: NOT TO SCALE SHEET 1 OF 1

120

Appendix B

Pressure-drop (ΔP) versus time (t) plots

This section provides the pressure-drop (ΔP) versus time (t) data from the pipe flow tests for water-based polymer solution. The data for each %DR and all three test sections are presented. As detailed in table 4, after the initial 2 minutes at zero flow rate, the pump was set at 600 RPM for the next 5 minutes to mix the polymer solution batch with the de-aired water in the loop. As the pump ramps up, it takes a while for the polymer solution to mix and reach the test section from the tank. Until then, only water flows in the test section. This translates to a higher ΔP reading for water flow and immediate reduction in ΔP as the polymer solution reaches the test section. This can be observed from each plot showing that initial spike in ΔP reading followed by a lower stable value which represents mixing of the polymer solution. At the end of 7 minutes (420 seconds), the polymer is degraded for a set degradation time (t_{dg}) to achieve the required %DR, this is the region of the plot that shows a period of zero ΔP, since the transducer is isolated during this time. For the first plot of each test section (MDR case), no degradation was performed. Post degradation, the five mass flow values are set (refer to table 1), each running for 6 minutes. This is represented by the following five steps in the ΔP readings as seen in each plot.

B.1 For test section with 1-inch ID
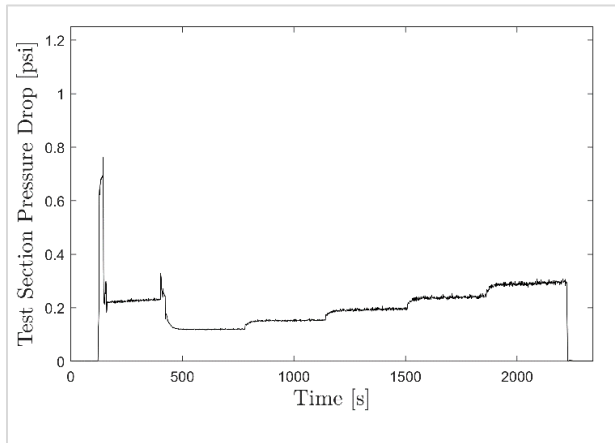
Figure B.1a: ΔP versus *t* plot for 76% DR.
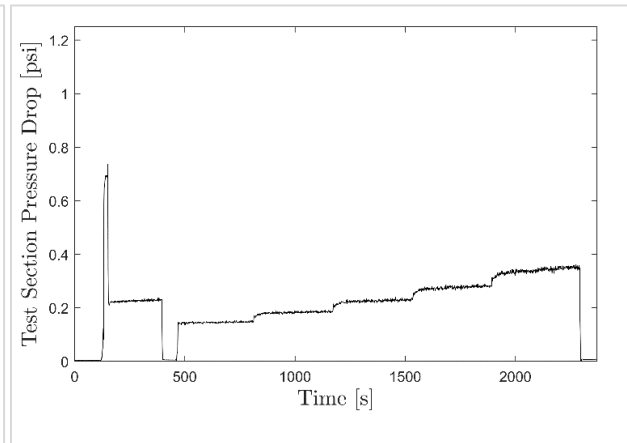
Figure B.1b: ΔP versus *t* plot for 70% DR.
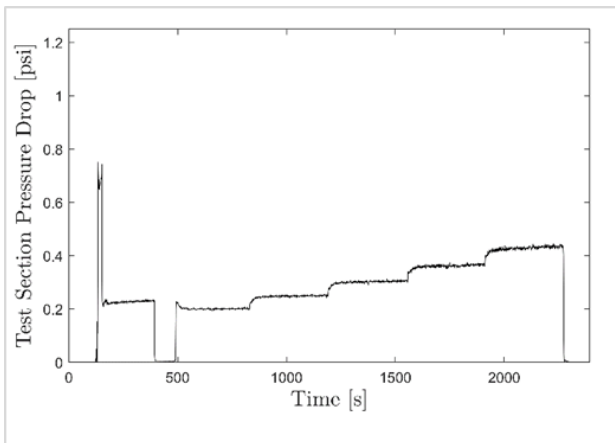
Figure B.1c: ΔP versus *t* plot for 65% DR.
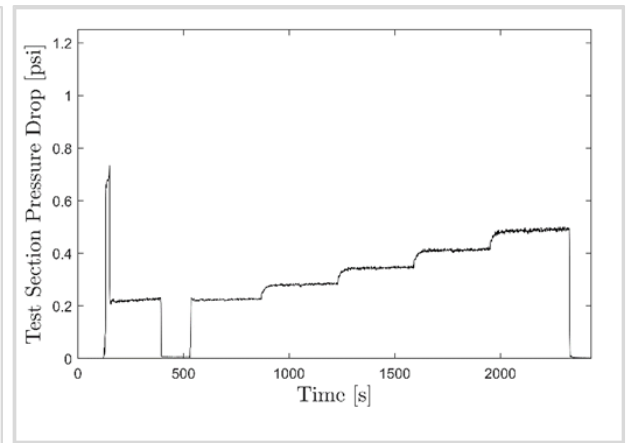
Figure B.1d: ΔP versus *t* plot for 60% DR.
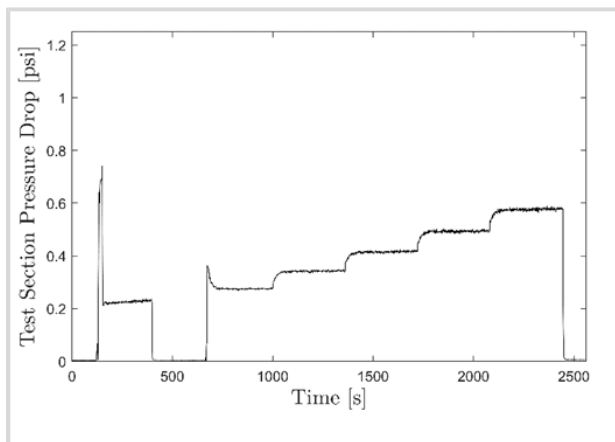
Figure B.1e: ΔP versus *t* plot for 50% DR.
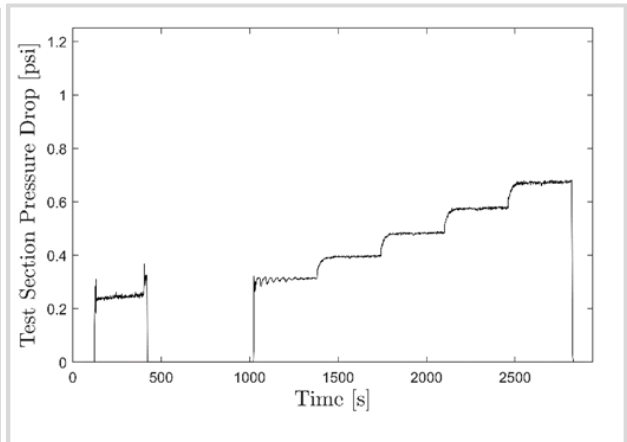
Figure B.1f: ΔP versus *t* plot for 40% DR.
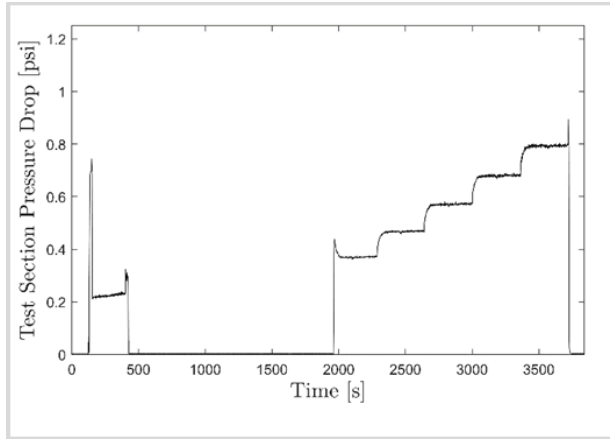
Figure B.1g: ΔP versus *t* plot for 30% DR.
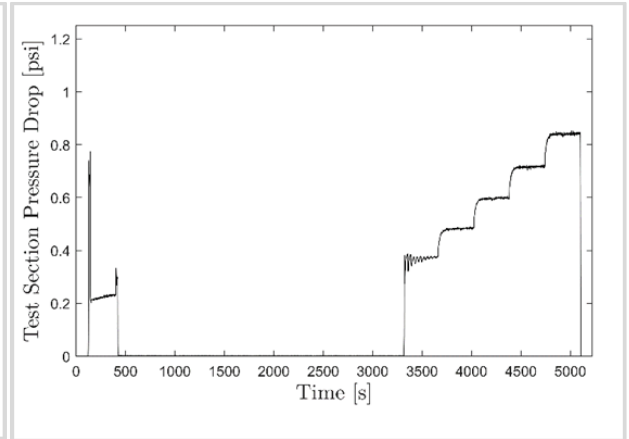
Figure B.1h: ΔP versus *t* plot for 20%

B.2 For test section with 1.5-inch ID
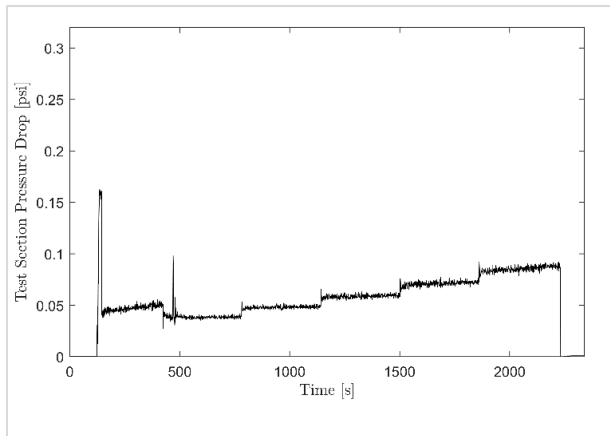
Figure B.2a: ΔP versus *t* plot for 70% DR.
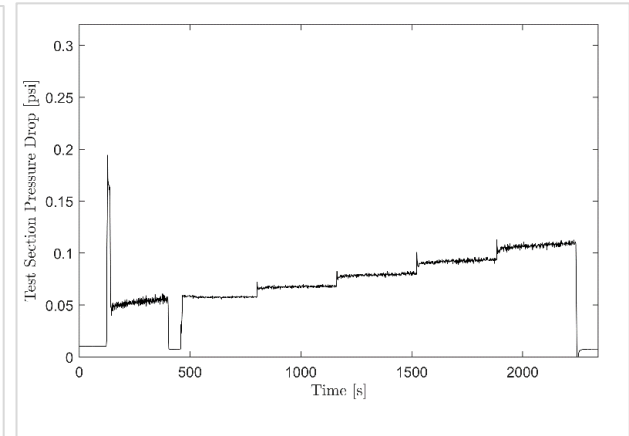
Figure B.2b: ΔP versus *t* plot for 65% DR.
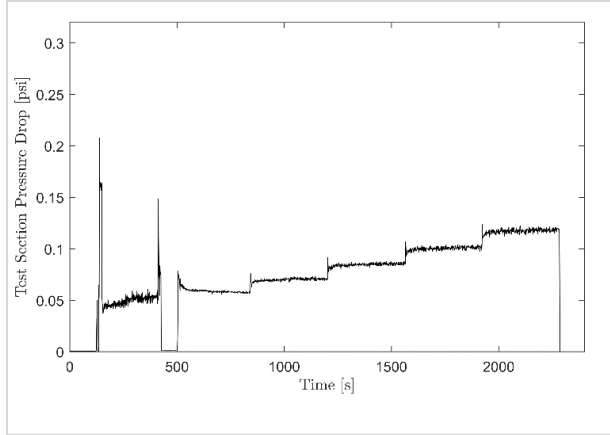
Figure B.2c: ΔP versus t plot for 60% DR.
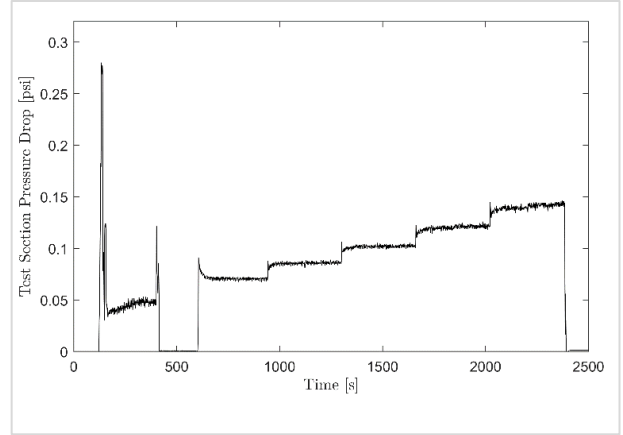
Figure B.2d: ΔP versus t plot for 50% DR.
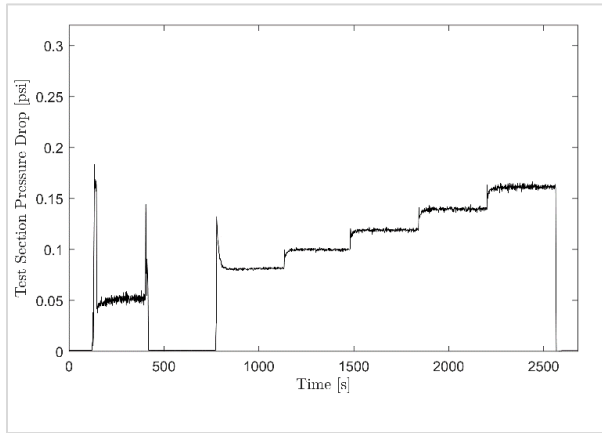
Figure B.2e: ΔP versus t plot for 40% DR.
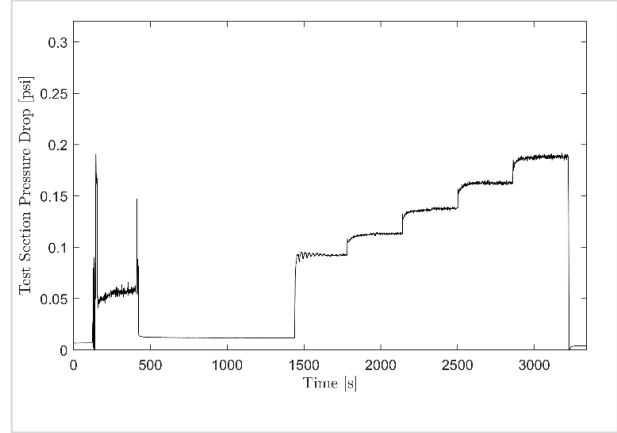
Figure B.2f: ΔP versus t plot for 30% DR.

Figure B.2g: ΔP versus t plot for 20% DR.

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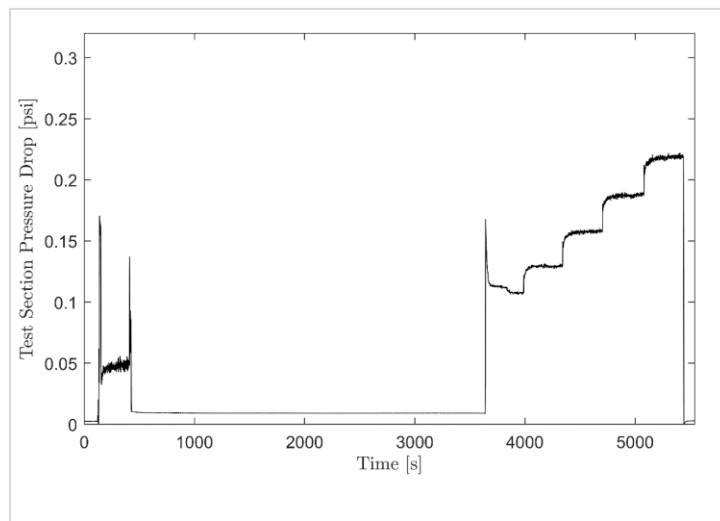
B.3 For test section with 2-inch ID
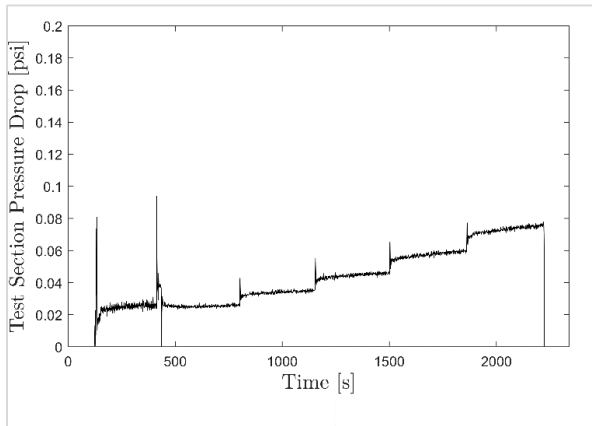
Figure B.3a: ΔP versus t plot for 60% DR.
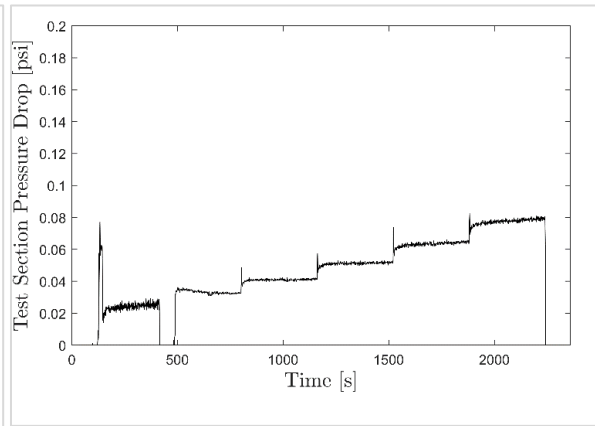
Figure B.3b: ΔP versus t plot for 50% DR.
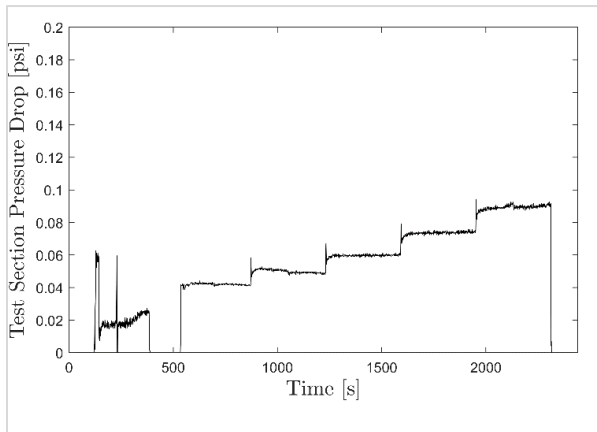
Figure B.3c: ΔP versus t plot for 40% DR.
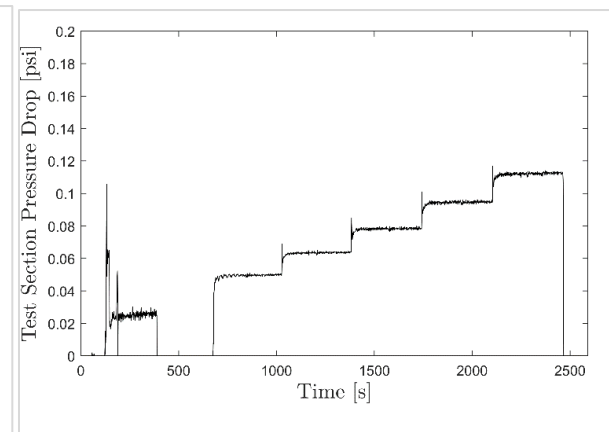
Figure B.3d: ΔP versus t plot for 30% DR.
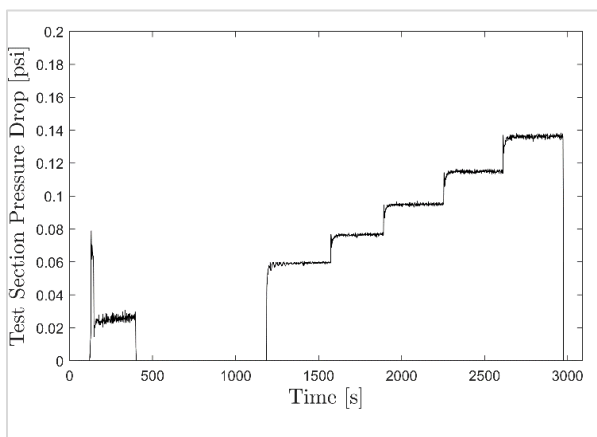
Figure B.3e: ΔP versus t plot for 15% DR.
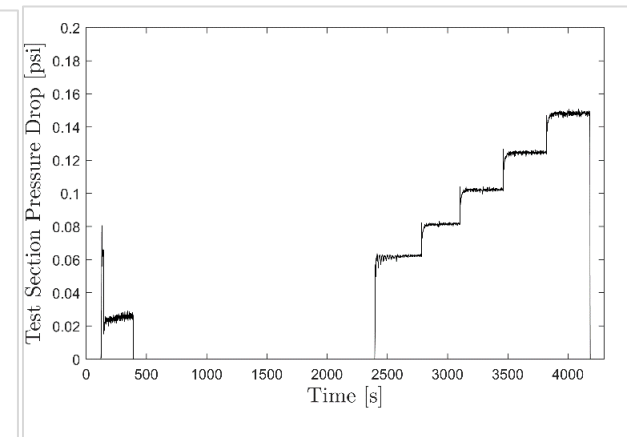
Figure B.3f: ΔP versus t plot for 10% DR.

Appendix C

Shear viscosity data

This section lists the data from the shear viscosity measurements as discussed in section 3.5. Each table provides the values for zero-rate viscosity (μ_0), infinite-rate viscosity (μ_∞), consistency (c) and rate index (n) for all five Re (60000, 70000, 80000, 90000, and 100000) for each %DR. The data is presented for all three test sections. This data was used to calculate the shear viscosity (μ_s) of the polymer solution, which was further utilized to obtain Re value for each sample as detailed in section 3.5.

C.1 For test section with 1–inch ID

76% DR

Data for 1-inch, 76% DR, Re: 60000
zero-rate viscosity: 1.47788e-3 Pa.s
infinite-rate viscosity: 1.16535e-3 Pa.s
consistency: 0.0371144 s
rate index: 0.852253
R²: 0.999609

Data for 1-inch, 76% DR, Re: 70000
zero-rate viscosity: 1.43593e-3 Pa.s
infinite-rate viscosity: 1.16585e-3 Pa.s
consistency: 0.0311286 s
rate index: 0.910882
R²: 0.999975

Data for 1-inch, 76% DR, Re: 80000
zero-rate viscosity: 1.43767e-3 Pa.s
infinite-rate viscosity: 1.12735e-3 Pa.s
consistency: 0.0373868 s
rate index: 0.746280
R²: 0.999882

Data for 1-inch, 76% DR, Re: 90000
zero-rate viscosity: 1.39574e-3 Pa.s
infinite-rate viscosity: 1.15050e-3 Pa.s
consistency: 0.0291223 s
rate index: 0.884987
R²: 0.999908

Data for 1-inch, 76% DR, Re: 100000
zero-rate viscosity: 1.37961e-3 Pa.s
infinite-rate viscosity: 1.15221e-3 Pa.s
consistency: 0.0272905 s
rate index: 0.907582
R²: 0.999909

70% DR

Data for 1-inch, 70% DR, Re: 60000
zero-rate viscosity: 1.45336e-3 Pa.s
infinite-rate viscosity: 1.14247e-3 Pa.s
consistency: 0.0338424 s
rate index: 0.733053
R²: 0.999759

Data for 1-inch, 70% DR, Re: 70000
zero-rate viscosity: 1.43556e-3 Pa.s
infinite-rate viscosity: 1.07410e-3 Pa.s
consistency: 0.0242955 s
rate index: 0.606596
R²: 0.999044

Data for 1-inch, 70% DR, Re: 80000
zero-rate viscosity: 1.41129e-3 Pa.s
infinite-rate viscosity: 1.14755e-3 Pa.s
consistency: 0.0283743 s
rate index: 0.799593
R²: 0.999729

Data for 1-inch, 70% DR, Re: 90000
zero-rate viscosity: 1.34483e-3 Pa.s
infinite-rate viscosity: 1.15559e-3 Pa.s
consistency: 0.0232656 s
rate index: 1.04150
R²: 0.999840

Data for 1-inch, 70% DR, Re: 100000
zero-rate viscosity: 1.30772e-3 Pa.s
infinite-rate viscosity: 1.13422e-3 Pa.s
consistency: 0.0224723 s
rate index: 1.03689
R²: 0.999773

65% DR

Data for 1-inch, 65% DR, Re: 60000
zero-rate viscosity: 1.32995e-3 Pa.s
infinite-rate viscosity: 1.13464e-3 Pa.s
consistency: 0.0224168 s
rate index: 0.901628
R²: 0.998197

Data for 1-inch, 65% DR, Re: 70000
zero-rate viscosity: 1.31819e-3 Pa.s
infinite-rate viscosity: 1.15460e-3 Pa.s
consistency: 0.0211985 s
rate index: 1.05122
R²: 0.998912

Data for 1-inch, 65% DR, Re: 80000
zero-rate viscosity: 1.31490e-3 Pa.s
infinite-rate viscosity: 1.13439e-3 Pa.s
consistency: 0.0223187 s
rate index: 0.880803
R²: 0.996175

Data for 1-inch, 65% DR, Re: 90000
zero-rate viscosity: 1.30039e-3 Pa.s
infinite-rate viscosity: 1.13809e-3 Pa.s
consistency: 0.0222117 s
rate index: 0.950678
R²: 0.995660

Data for 1-inch, 65% DR, Re: 100000
zero-rate viscosity: 1.26243e-3 Pa.s
infinite-rate viscosity: 1.14075e-3 Pa.s
consistency: 0.0188817 s
rate index: 1.24593
R²: 0.999448

	60% DR	50% DR	40% DR

60% DR

Data for 1-inch, 60% DR, Re: 60000
zero-rate viscosity: 1.32220e-3 Pa.s
infinite-rate viscosity: 1.11118e-3 Pa.s
consistency: 0.0252207 s
rate index: 0.653243
R^2: 0.999445

Data for 1-inch, 60% DR, Re: 70000
zero-rate viscosity: 1.28665e-3 Pa.s
infinite-rate viscosity: 1.12037e-3 Pa.s
consistency: 0.0207187 s
rate index: 0.801359
R^2: 0.999582

Data for 1-inch, 60% DR, Re: 80000
zero-rate viscosity: 1.27068e-3 Pa.s
infinite-rate viscosity: 1.12582e-3 Pa.s
consistency: 0.0209553 s
rate index: 0.893733
R^2: 0.999618

Data for 1-inch, 60% DR, Re: 90000
zero-rate viscosity: 1.26225e-3 Pa.s
infinite-rate viscosity: 1.12465e-3 Pa.s
consistency: 0.0190692 s
rate index: 0.895288
R^2: 0.999011

Data for 1-inch, 60% DR, Re: 100000
zero-rate viscosity: 1.24071e-3 Pa.s
infinite-rate viscosity: 1.12811e-3 Pa.s
consistency: 0.0180585 s
rate index: 1.07709
R^2: 0.999096

50% DR

Data for 1-inch, 50% DR, Re: 60000
zero-rate viscosity: 1.21893e-3 Pa.s
infinite-rate viscosity: 1.14288e-3 Pa.s
consistency: 0.0164962 s
rate index: 1.36994
R^2: 0.998178

Data for 1-inch, 50% DR, Re: 70000
zero-rate viscosity: 1.21072e-3 Pa.s
infinite-rate viscosity: 1.13362e-3 Pa.s
consistency: 0.0164958 s
rate index: 1.24524
R^2: 0.998450

Data for 1-inch, 50% DR, Re: 80000
zero-rate viscosity: 1.21229e-3 Pa.s
infinite-rate viscosity: 1.13632e-3 Pa.s
consistency: 0.0158272 s
rate index: 1.20453
R^2: 0.998342

Data for 1-inch, 50% DR, Re: 90000
zero-rate viscosity: 1.22044e-3 Pa.s
infinite-rate viscosity: 1.12914e-3 Pa.s
consistency: 0.0171295 s
rate index: 0.936512
R^2: 0.997968

Data for 1-inch, 50% DR, Re: 100000
zero-rate viscosity: 1.20837e-3 Pa.s
infinite-rate viscosity: 1.13738e-3 Pa.s
consistency: 0.0162727 s
rate index: 1.19510
R^2: 0.998970

40% DR

Data for 1-inch, 40% DR, Re: 60000
zero-rate viscosity: 1.22019e-3 Pa.s
infinite-rate viscosity: 1.09985e-3 Pa.s
consistency: 0.0143782 s
rate index: 0.519139
R^2: 0.996537

Data for 1-inch, 40% DR, Re: 70000
zero-rate viscosity: 1.17546e-3 Pa.s
infinite-rate viscosity: 1.10208e-3 Pa.s
consistency: 0.0110345 s
rate index: 0.780116
R^2: 0.991262

Data for 1-inch, 40% DR, Re: 80000
zero-rate viscosity: 1.17590e-3 Pa.s
infinite-rate viscosity: 1.12117e-3 Pa.s
consistency: 0.0140380 s
rate index: 1.08432
R^2: 0.999633

Data for 1-inch, 40% DR, Re: 90000
zero-rate viscosity: 1.17661e-3 Pa.s
infinite-rate viscosity: 1.13328e-3 Pa.s
consistency: 0.0149413 s
rate index: 1.43389
R^2: 0.988000

Data for 1-inch, 40% DR, Re: 100000
zero-rate viscosity: 1.17310e-3 Pa.s
infinite-rate viscosity: 1.12575e-3 Pa.s
consistency: 0.0152374 s
rate index: 1.22032
R^2: 0.995489

30% DR	20% DR

Data for 1-inch, 30% DR, Re: 60000
zero-rate viscosity: 1.13995e-3 Pa.s
infinite-rate viscosity: 1.12240e-3 Pa.s
consistency: 0.0195278 s
rate index: 1.41203
R²: 0.962368

Data for 1-inch, 20% DR, Re: 60000
zero-rate viscosity: 1.17093e-3 Pa.s
infinite-rate viscosity: 1.11293e-3 Pa.s
consistency: 0.489228 s
rate index: 1.03814
R²: 0.947080

Data for 1-inch, 30% DR, Re: 70000
zero-rate viscosity: 1.13935e-3 Pa.s
infinite-rate viscosity: 1.10487e-3 Pa.s
consistency: 0.0352595 s
rate index: 0.660233
R²: 0.991625

Data for 1-inch, 20% DR, Re: 70000
zero-rate viscosity: 1.10437e-3 Pa.s
infinite-rate viscosity: 1.09966e-3 Pa.s
consistency: 0.0333496 s
rate index: 3.26449
R²: 0.891054

Data for 1-inch, 30% DR, Re: 80000
zero-rate viscosity: 1.12621e-3 Pa.s
infinite-rate viscosity: 1.10770e-3 Pa.s
consistency: 0.0247067 s
rate index: 1.14816
R²: 0.997435

Data for 1-inch, 20% DR, Re: 80000
zero-rate viscosity: 1.11281e-3 Pa.s
infinite-rate viscosity: 1.10924e-3 Pa.s
consistency: 0.0281452 s
rate index: 4.63918
R²: 0.872457

Data for 1-inch, 30% DR, Re: 90000
zero-rate viscosity: 1.13439e-3 Pa.s
infinite-rate viscosity: 1.11411e-3 Pa.s
consistency: 0.0255277 s
rate index: 0.994692
R²: 0.987821

Data for 1-inch, 20% DR, Re: 90000
zero-rate viscosity: 1.11064e-3 Pa.s
infinite-rate viscosity: 1.09978e-3 Pa.s
consistency: 0.0922346 s
rate index: 1.81400
R²: 0.917117

Data for 1-inch, 30% DR, Re: 100000
zero-rate viscosity: 1.11598e-3 Pa.s
infinite-rate viscosity: 1.10022e-3 Pa.s
consistency: 0.0204221 s
rate index: 1.57939
R²: 0.998471

Data for 1-inch, 20% DR, Re: 100000
zero-rate viscosity: 1.11858e-3 Pa.s
infinite-rate viscosity: 1.10163e-3 Pa.s
consistency: 0.132657 s
rate index: 2.03047
R²: 0.942423

C.2 For test section with 1.5–inch ID

70% DR	65% DR	60% DR

Data for 1.5-inch, 70% DR, Re: 60000
zero-rate viscosity: 1.78010e-3 Pa.s
infinite-rate viscosity: 1.20873e-3 Pa.s
consistency: 0.0708401 s
rate index: 0.711454
R²: 0.999836

Data for 1.5-inch, 65% DR, Re: 60000
zero-rate viscosity: 1.47113e-3 Pa.s
infinite-rate viscosity: 1.17612e-3 Pa.s
consistency: 0.0276905 s
rate index: 0.950123
R²: 0.999439

Data for 1.5-inch, 60% DR, Re: 60000
zero-rate viscosity: 1.45679e-3 Pa.s
infinite-rate viscosity: 1.16362e-3 Pa.s
consistency: 0.0257490 s
rate index: 0.853403
R²: 0.999433

Data for 1.5-inch, 70% DR, Re: 70000
zero-rate viscosity: 1.80153e-3 Pa.s
infinite-rate viscosity: 1.18892e-3 Pa.s
consistency: 0.0814663 s
rate index: 0.639151
R²: 0.999051

Data for 1.5-inch, 65% DR, Re: 70000
zero-rate viscosity: 1.46281e-3 Pa.s
infinite-rate viscosity: 1.16685e-3 Pa.s
consistency: 0.0275963 s
rate index: 0.906429
R²: 0.999951

Data for 1.5-inch, 60% DR, Re: 70000
zero-rate viscosity: 1.44761e-3 Pa.s
infinite-rate viscosity: 1.17041e-3 Pa.s
consistency: 0.0239175 s
rate index: 0.886445
R²: 0.999769

Data for 1.5-inch, 70% DR, Re: 80000
zero-rate viscosity: 1.69759e-3 Pa.s
infinite-rate viscosity: 1.17247e-3 Pa.s
consistency: 0.0571250 s
rate index: 0.663788
R²: 0.999729

Data for 1.5-inch, 65% DR, Re: 80000
zero-rate viscosity: 1.44654e-3 Pa.s
infinite-rate viscosity: 1.18384e-3 Pa.s
consistency: 0.0243759 s
rate index: 1.00077
R²: 0.999497

Data for 1.5-inch, 60% DR, Re: 80000
zero-rate viscosity: 1.45309e-3 Pa.s
infinite-rate viscosity: 1.14745e-3 Pa.s
consistency: 0.0249090 s
rate index: 0.750873
R²: 0.999444

Data for 1.5-inch, 70% DR, Re: 90000
zero-rate viscosity: 1.64037e-3 Pa.s
infinite-rate viscosity: 1.18392e-3 Pa.s
consistency: 0.0478388 s
rate index: 0.736269
R²: 0.999424

Data for 1.5-inch, 65% DR, Re: 90000
zero-rate viscosity: 1.43926e-3 Pa.s
infinite-rate viscosity: 1.16639e-3 Pa.s
consistency: 0.0260826 s
rate index: 0.908869
R²: 0.999836

Data for 1.5-inch, 60% DR, Re: 90000
zero-rate viscosity: 1.40258e-3 Pa.s
infinite-rate viscosity: 1.18022e-3 Pa.s
consistency: 0.0225398 s
rate index: 1.04575
R²: 0.995010

Data for 1.5-inch, 70% DR, Re: 100000
zero-rate viscosity: 1.54960e-3 Pa.s
infinite-rate viscosity: 1.20164e-3 Pa.s
consistency: 0.0334736 s
rate index: 0.899984
R²: 0.999895

Data for 1.5-inch, 65% DR, Re: 100000
zero-rate viscosity: 1.41992e-3 Pa.s
infinite-rate viscosity: 1.16463e-3 Pa.s
consistency: 0.0243763 s
rate index: 0.928607
R²: 0.999857

Data for 1.5-inch, 60% DR, Re: 100000
zero-rate viscosity: 1.40457e-3 Pa.s
infinite-rate viscosity: 1.14032e-3 Pa.s
consistency: 0.0211343 s
rate index: 0.789359
R²: 0.999651

	50% DR	40% DR	30% DR

Data for 1.5-inch, 50% DR, Re: 60000
zero-rate viscosity: 1.35715e-3 Pa.s
infinite-rate viscosity: 1.15350e-3 Pa.s
consistency: 0.0204247 s
rate index: 0.903157
R²: 0.996260

Data for 1.5-inch, 40% DR, Re: 60000
zero-rate viscosity: 1.27905e-3 Pa.s
infinite-rate viscosity: 1.14581e-3 Pa.s
consistency: 0.0157306 s
rate index: 1.00323
R²: 0.994968

Data for 1.5-inch, 30% DR, Re: 60000
zero-rate viscosity: 1.20564e-3 Pa.s
infinite-rate viscosity: 1.14736e-3 Pa.s
consistency: 0.0146037 s
rate index: 1.61385
R²: 0.997289

Data for 1.5-inch, 50% DR, Re: 70000
zero-rate viscosity: 1.33841e-3 Pa.s
infinite-rate viscosity: 1.11715e-3 Pa.s
consistency: 0.0180445 s
rate index: 0.767926
R²: 0.998926

Data for 1.5-inch, 40% DR, Re: 70000
zero-rate viscosity: 1.27014e-3 Pa.s
infinite-rate viscosity: 1.16483e-3 Pa.s
consistency: 0.0159549 s
rate index: 1.32335
R²: 0.998420

Data for 1.5-inch, 30% DR, Re: 70000
zero-rate viscosity: 1.22565e-3 Pa.s
infinite-rate viscosity: 1.14520e-3 Pa.s
consistency: 0.0126141 s
rate index: 1.06566
R²: 0.993023

Data for 1.5-inch, 50% DR, Re: 80000
zero-rate viscosity: 1.31094e-3 Pa.s
infinite-rate viscosity: 1.16361e-3 Pa.s
consistency: 0.0197334 s
rate index: 1.26998
R²: 0.993929

Data for 1.5-inch, 40% DR, Re: 80000
zero-rate viscosity: 1.29757e-3 Pa.s
infinite-rate viscosity: 1.12037e-3 Pa.s
consistency: 0.0123914 s
rate index: 0.699203
R²: 0.994795

Data for 1.5-inch, 30% DR, Re: 80000
zero-rate viscosity: 1.20372e-3 Pa.s
infinite-rate viscosity: 1.13991e-3 Pa.s
consistency: 0.0141781 s
rate index: 1.38662
R²: 0.998309

Data for 1.5-inch, 50% DR, Re: 90000
zero-rate viscosity: 1.31656e-3 Pa.s
infinite-rate viscosity: 1.15177e-3 Pa.s
consistency: 0.0183875 s
rate index: 1.05058
R²: 0.999826

Data for 1.5-inch, 40% DR, Re: 90000
zero-rate viscosity: 1.25805e-3 Pa.s
infinite-rate viscosity: 1.17280e-3 Pa.s
consistency: 0.0171194 s
rate index: 1.68898
R²: 0.974303

Data for 1.5-inch, 30% DR, Re: 90000
zero-rate viscosity: 1.22025e-3 Pa.s
infinite-rate viscosity: 1.12160e-3 Pa.s
consistency: 0.0136724 s
rate index: 0.805431
R²: 0.998150

Data for 1.5-inch, 50% DR, Re: 100000
zero-rate viscosity: 1.31686e-3 Pa.s
infinite-rate viscosity: 1.18204e-3 Pa.s
consistency: 0.0178393 s
rate index: 1.34776
R²: 0.996007

Data for 1.5-inch, 40% DR, Re: 100000
zero-rate viscosity: 1.26384e-3 Pa.s
infinite-rate viscosity: 1.13514e-3 Pa.s
consistency: 0.0142319 s
rate index: 0.942231
R²: 0.997345

Data for 1.5-inch, 30% DR, Re: 100000
zero-rate viscosity: 1.19667e-3 Pa.s
infinite-rate viscosity: 1.13072e-3 Pa.s
consistency: 0.0135764 s
rate index: 1.22993
R²: 0.999728

20% DR

Data for 1.5-inch, 20% DR, Re: 60000
zero-rate viscosity: 1.14992e-3 Pa.s
infinite-rate viscosity: 1.12939e-3 Pa.s
consistency: 0.0140900 s
rate index: 1.69378
R²: 0.957775

Data for 1.5-inch, 20% DR, Re: 70000
zero-rate viscosity: 1.14943e-3 Pa.s
infinite-rate viscosity: 1.12736e-3 Pa.s
consistency: 0.0155893 s
rate index: 1.52734
R²: 0.993572

Data for 1.5-inch, 20% DR, Re: 80000
zero-rate viscosity: 1.14974e-3 Pa.s
infinite-rate viscosity: 1.12568e-3 Pa.s
consistency: 0.0147729 s
rate index: 1.35398
R²: 0.993174

Data for 1.5-inch, 20% DR, Re: 90000
zero-rate viscosity: 1.14650e-3 Pa.s
infinite-rate viscosity: 1.12905e-3 Pa.s
consistency: 0.0160059 s
rate index: 1.94179
R²: 0.977152

Data for 1.5-inch, 20% DR, Re: 100000
zero-rate viscosity: 1.15575e-3 Pa.s
infinite-rate viscosity: 1.13119e-3 Pa.s
consistency: 0.0140441 s
rate index: 1.27562
R²: 0.994392

C.3 For test section with 2–inch ID

65% DR

Data for 2-inch, 65% DR, Re: 60000
zero-rate viscosity: 1.49059e-3 Pa.s
infinite-rate viscosity: 1.18335e-3 Pa.s
consistency: 0.0335858 s
rate index: 0.901018
R²: 0.999888

Data for 2-inch, 65% DR, Re: 70000
zero-rate viscosity: 1.40738e-3 Pa.s
infinite-rate viscosity: 1.16764e-3 Pa.s
consistency: 0.0268196 s
rate index: 1.06343
R²: 0.999617

Data for 2-inch, 65% DR, Re: 80000
zero-rate viscosity: 1.42903e-3 Pa.s
infinite-rate viscosity: 1.15162e-3 Pa.s
consistency: 0.0299945 s
rate index: 0.839125
R²: 0.999813

Data for 2-inch, 65% DR, Re: 90000
zero-rate viscosity: 1.40489e-3 Pa.s
infinite-rate viscosity: 1.14281e-3 Pa.s
consistency: 0.0282386 s
rate index: 0.810092
R²: 0.999938

Data for 2-inch, 65% DR, Re: 100000
zero-rate viscosity: 1.35277e-3 Pa.s
infinite-rate viscosity: 1.14682e-3 Pa.s
consistency: 0.0233754 s
rate index: 0.953702
R²: 0.999733

50% DR

Data for 2-inch, 50% DR, Re: 60000
zero-rate viscosity: 1.43083e-3 Pa.s
infinite-rate viscosity: 1.14956e-3 Pa.s
consistency: 0.0295580 s
rate index: 0.833624
R²: 0.999857

Data for 2-inch, 50% DR, Re: 70000
zero-rate viscosity: 1.42125e-3 Pa.s
infinite-rate viscosity: 1.13315e-3 Pa.s
consistency: 0.0316054 s
rate index: 0.774617
R²: 0.999749

Data for 2-inch, 50% DR, Re: 80000
zero-rate viscosity: 1.43543e-3 Pa.s
infinite-rate viscosity: 1.13940e-3 Pa.s
consistency: 0.0311618 s
rate index: 0.720296
R²: 0.999620

Data for 2-inch, 50% DR, Re: 90000
zero-rate viscosity: 1.35563e-3 Pa.s
infinite-rate viscosity: 1.14590e-3 Pa.s
consistency: 0.0231072 s
rate index: 0.950430
R²: 0.999776

Data for 2-inch, 50% DR, Re: 100000
zero-rate viscosity: 1.34767e-3 Pa.s
infinite-rate viscosity: 1.14098e-3 Pa.s
consistency: 0.0232822 s
rate index: 0.899845
R²: 0.997840

40% DR

Data for 2-inch, 40% DR, Re: 60000
zero-rate viscosity: 1.29052e-3 Pa.s
infinite-rate viscosity: 1.15033e-3 Pa.s
consistency: 0.0189633 s
rate index: 1.14746
R²: 0.999799

Data for 2-inch, 40% DR, Re: 70000
zero-rate viscosity: 1.29079e-3 Pa.s
infinite-rate viscosity: 1.13826e-3 Pa.s
consistency: 0.0200980 s
rate index: 0.986483
R²: 0.999643

Data for 2-inch, 40% DR, Re: 80000
zero-rate viscosity: 1.29487e-3 Pa.s
infinite-rate viscosity: 1.13926e-3 Pa.s
consistency: 0.0188249 s
rate index: 0.921381
R²: 0.998493

Data for 2-inch, 40% DR, Re: 90000
zero-rate viscosity: 1.28542e-3 Pa.s
infinite-rate viscosity: 1.13453e-3 Pa.s
consistency: 0.0193912 s
rate index: 0.911003
R²: 0.999826

Data for 2-inch, 40% DR, Re: 100000
zero-rate viscosity: 1.27486e-3 Pa.s
infinite-rate viscosity: 1.13246e-3 Pa.s
consistency: 0.0189322 s
rate index: 0.915976
R²: 0.999850

30% DR	**20% DR**	**10% DR**

Data for 2-inch, 30% DR, Re: 60000	Data for 2-inch, 20% DR, Re: 60000	Data for 2-inch, 10% DR, Re: 60000
zero-rate viscosity: 1.25902e-3 Pa.s	zero-rate viscosity: 1.17692e-3 Pa.s	zero-rate viscosity: 1.13683e-3 Pa.s
infinite-rate viscosity: 1.11652e-3 Pa.s	infinite-rate viscosity: 1.12468e-3 Pa.s	infinite-rate viscosity: 1.10789e-3 Pa.s
consistency: 0.0146857 s	consistency: 0.0139004 s	consistency: 0.0240053 s
rate index: 0.771238	rate index: 1.15686	rate index: 0.747201
R²: 0.988245	R²: 0.998787	R²: 0.982033

Data for 2-inch, 30% DR, Re: 70000	Data for 2-inch, 20% DR, Re: 70000	Data for 2-inch, 10% DR, Re: 70000
zero-rate viscosity: 1.22958e-3 Pa.s	zero-rate viscosity: 1.17688e-3 Pa.s	zero-rate viscosity: 1.12737e-3 Pa.s
infinite-rate viscosity: 1.14019e-3 Pa.s	infinite-rate viscosity: 1.13244e-3 Pa.s	infinite-rate viscosity: 1.10984e-3 Pa.s
consistency: 0.0157253 s	consistency: 0.0138697 s	consistency: 0.0188864 s
rate index: 1.27864	rate index: 1.33368	rate index: 1.18383
R²: 0.999409	R²: 0.999548	R²: 0.997250

Data for 2-inch, 30% DR, Re: 80000	Data for 2-inch, 20% DR, Re: 80000	Data for 2-inch, 10% DR, Re: 80000
zero-rate viscosity: 1.21247e-3 Pa.s	zero-rate viscosity: 1.19307e-3 Pa.s	zero-rate viscosity: 1.13299e-3 Pa.s
infinite-rate viscosity: 1.12295e-3 Pa.s	infinite-rate viscosity: 1.10675e-3 Pa.s	infinite-rate viscosity: 1.12060e-3 Pa.s
consistency: 0.0156216 s	consistency: 0.0193986 s	consistency: 0.0171093 s
rate index: 1.14836	rate index: 0.639515	rate index: 1.84523
R²: 0.998525	R²: 0.997646	R²: 0.956678

Data for 2-inch, 30% DR, Re: 90000	Data for 2-inch, 20% DR, Re: 90000	Data for 2-inch, 10% DR, Re: 90000
zero-rate viscosity: 1.21700e-3 Pa.s	zero-rate viscosity: 1.18492e-3 Pa.s	zero-rate viscosity: 1.13570e-3 Pa.s
infinite-rate viscosity: 1.14172e-3 Pa.s	infinite-rate viscosity: 1.09913e-3 Pa.s	infinite-rate viscosity: 1.10317e-3 Pa.s
consistency: 0.0156393 s	consistency: 0.0140235 s	consistency: 0.0162314 s
rate index: 1.40456	rate index: 0.585523	rate index: 0.528652
R²: 0.999000	R²: 0.995541	R²: 0.985714

Data for 2-inch, 30% DR, Re: 100000	Data for 2-inch, 20% DR, Re: 100000	Data for 2-inch, 10% DR, Re: 100000
zero-rate viscosity: 1.20358e-3 Pa.s	zero-rate viscosity: 1.16876e-3 Pa.s	zero-rate viscosity: 1.12522e-3 Pa.s
infinite-rate viscosity: 1.13526e-3 Pa.s	infinite-rate viscosity: 1.12169e-3 Pa.s	infinite-rate viscosity: 1.11109e-3 Pa.s
consistency: 0.0154643 s	consistency: 0.0149370 s	consistency: 0.0210032 s
rate index: 1.46943	rate index: 1.09759	rate index: 1.28382
R²: 0.998421	R²: 0.998125	R²: 0.903394

Appendix D

Extensional viscosity data

This section presents the plots for the extensional viscosity measurements (detailed in section 3.6), mapping the normalized minimum diameter of the extensional filament (D/D_0) versus time (t), showing three measurements (represented by color blue, orange and yellow) for each of the five Re (60000, 70000, 80000, 90000, and 100000) for each %DR. The data is presented for all three test sections. Each plot shows the relaxation time (t_r) value calculated using equation 29, for the 3-readings and their average.

D.1 (D/D_0) versus time (t) plots for test section with 1-inch ID

D.1.1 Plots for 76% DR (data acquisition rate: 4000 fps)
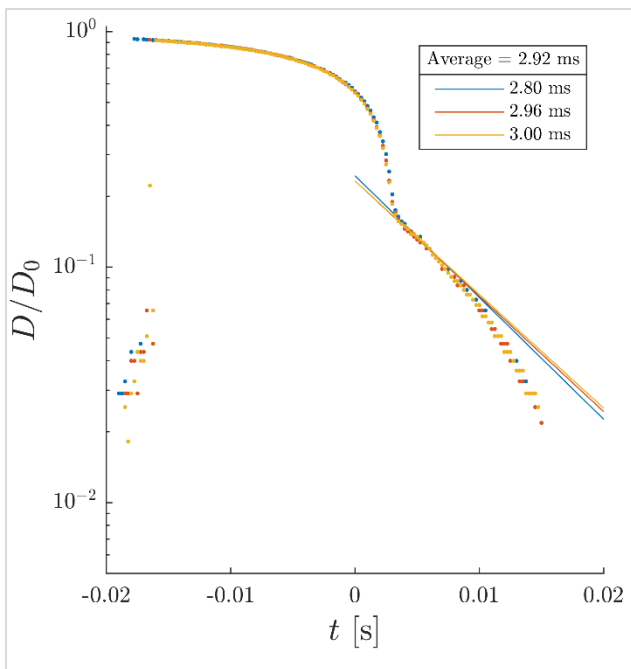
Figure D.1.1a: *D/D₀* versus *t* plot for 76% DR, Re: 60000. Figure D.1.1b: *D/D₀* versus *t* plot for 76% DR, Re: 70000.
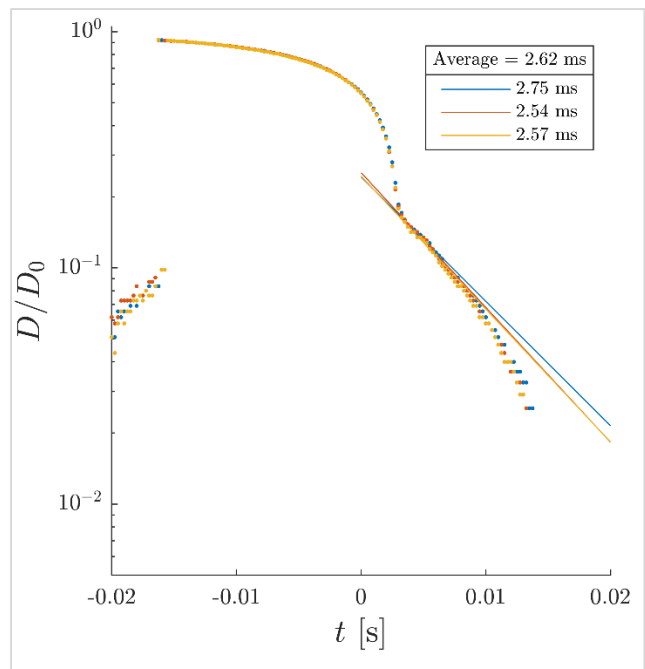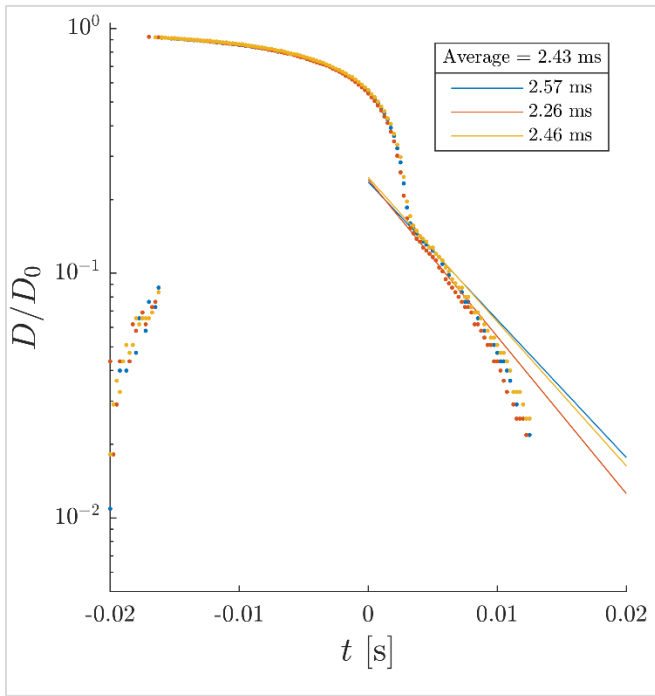
Figure D.1.1c: D/D_0 versus t plot for 76% DR, Re: 80000.
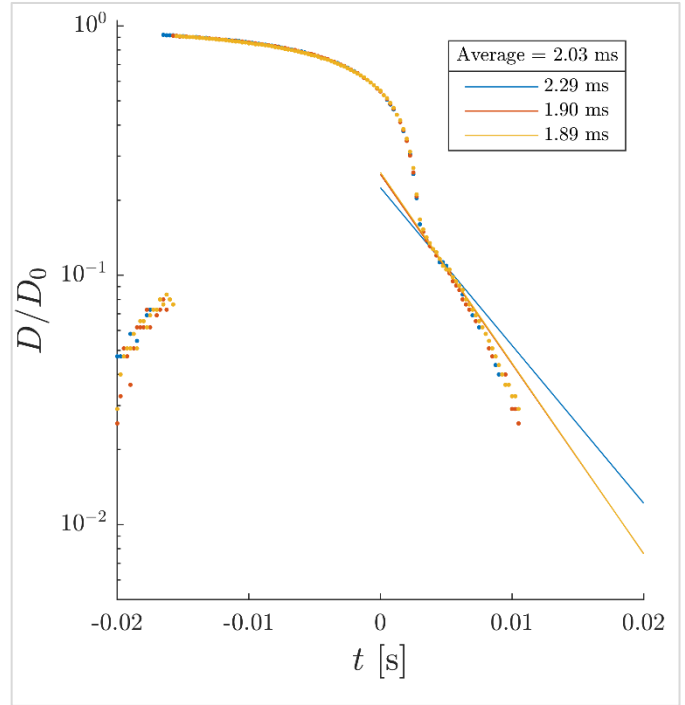
Figure D.1.1d: D/D_0 versus t plot for 76% DR, Re: 90000.
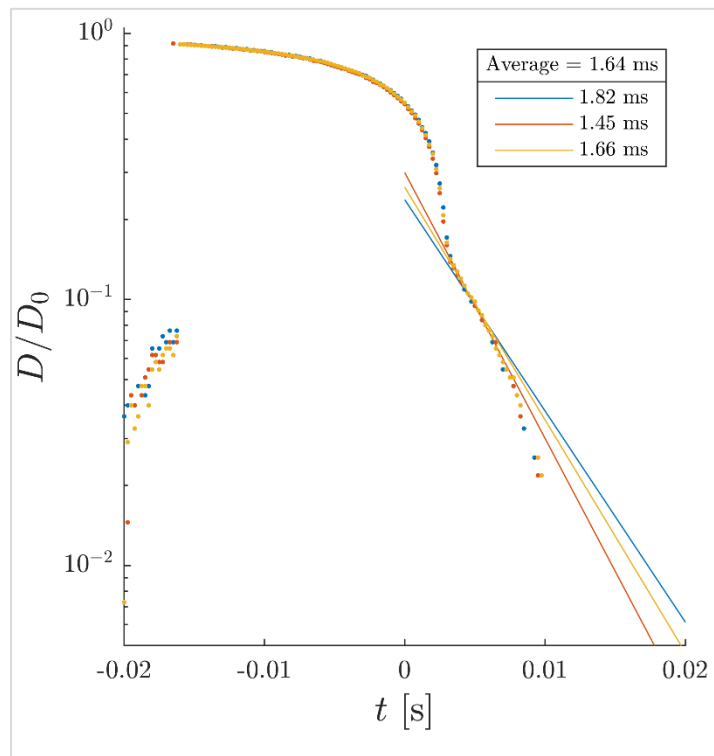
Figure D.1.1e: D/D_0 versus t plot for 76% DR, Re: 100000.

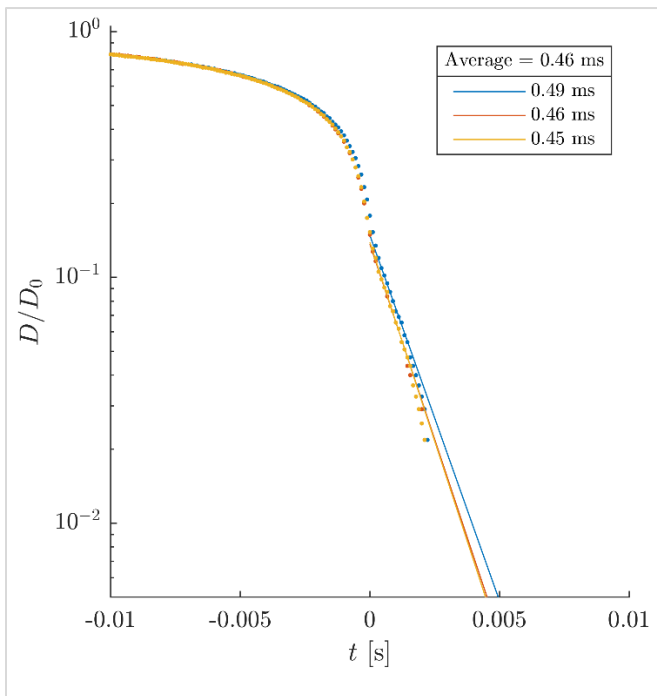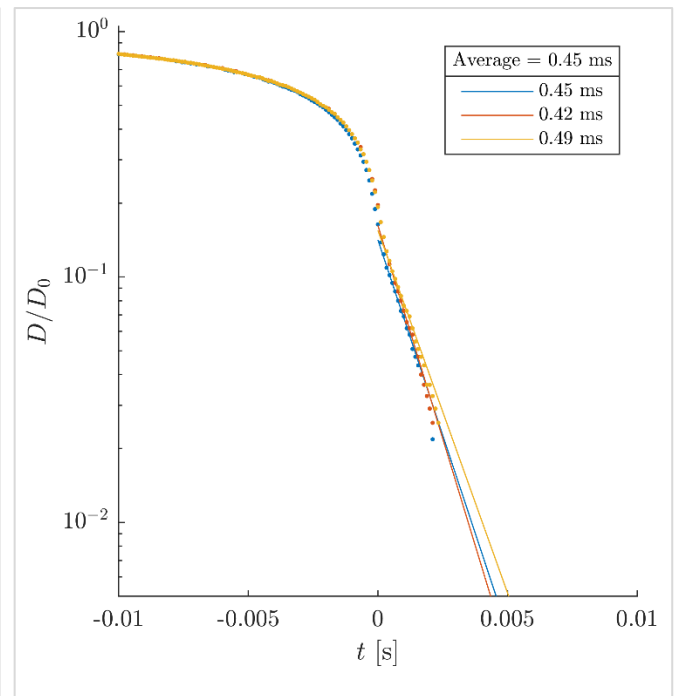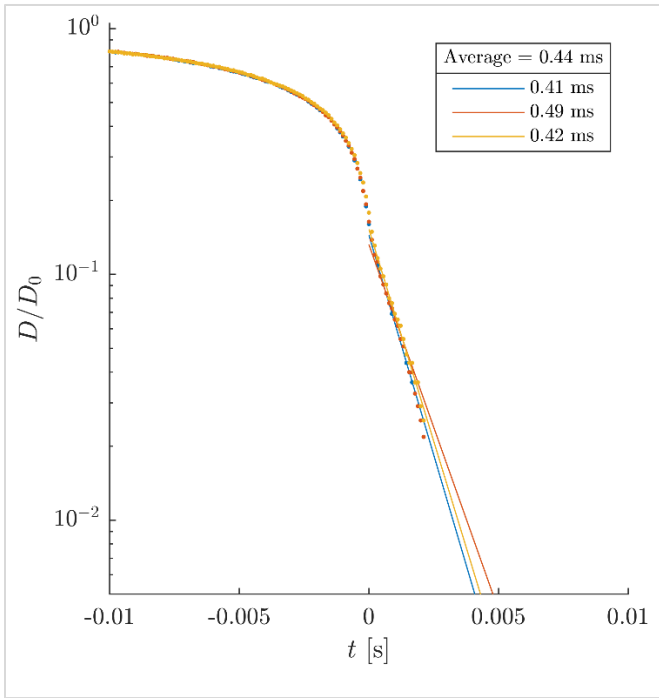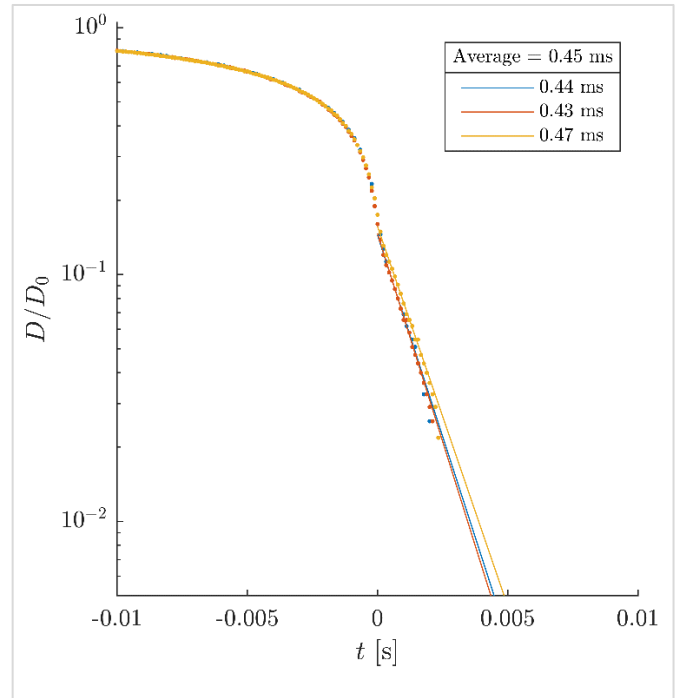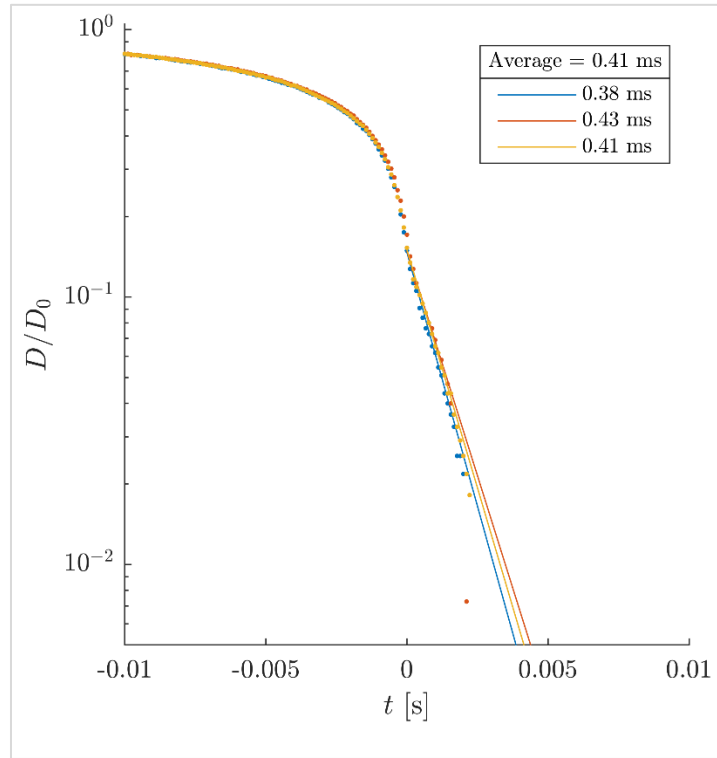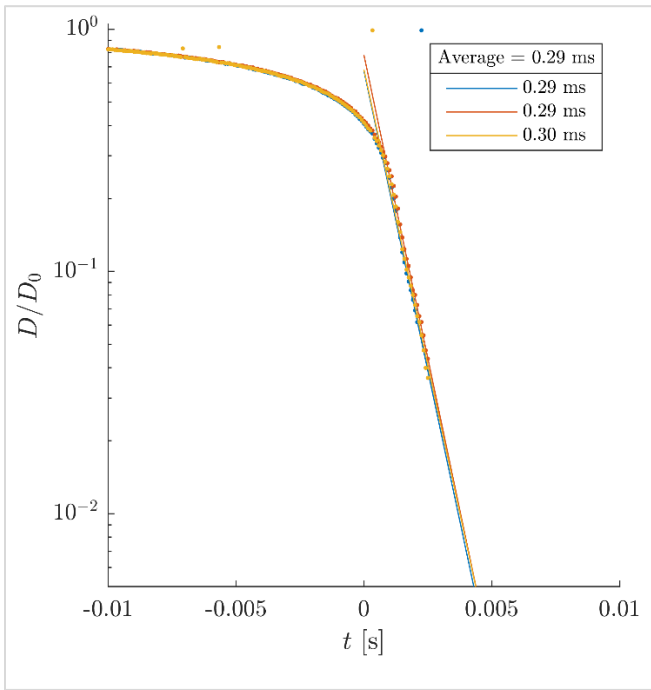## D.1.2 Plots for 70% DR (data acquisition rate: 4000 fps)
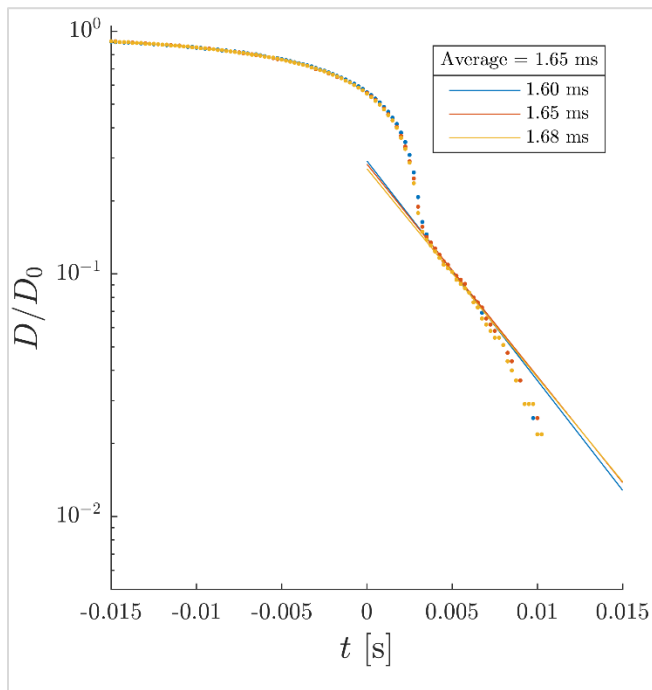
Figure D.1.2a: *D/D₀* versus *t* plot for 70% DR, Re: 60000.
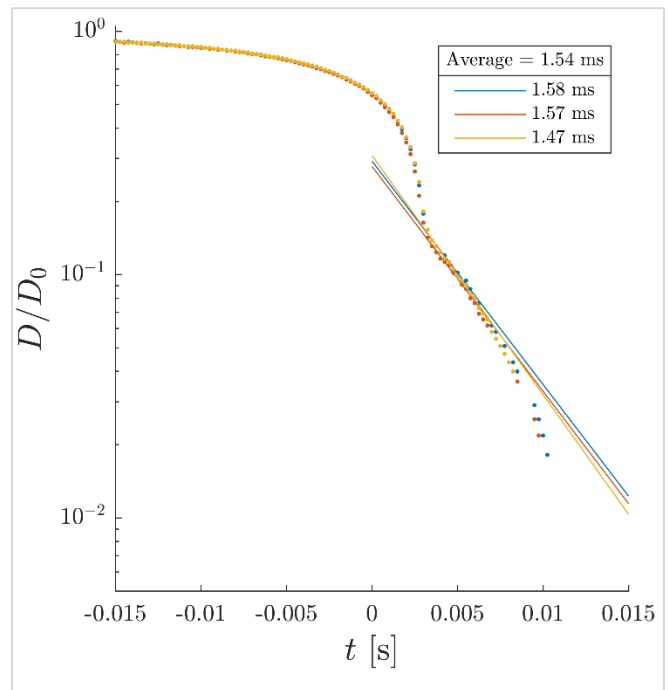
Figure D.1.2b: *D/D₀* versus *t* plot for 70% DR, Re: 70000.
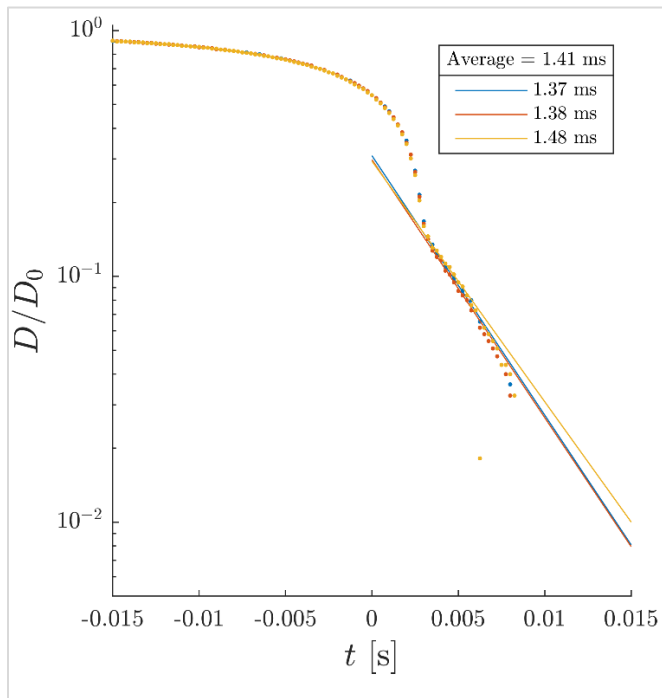
Figure D.1.2c: *D/D₀* versus *t* plot for 70% DR, Re: 80000.
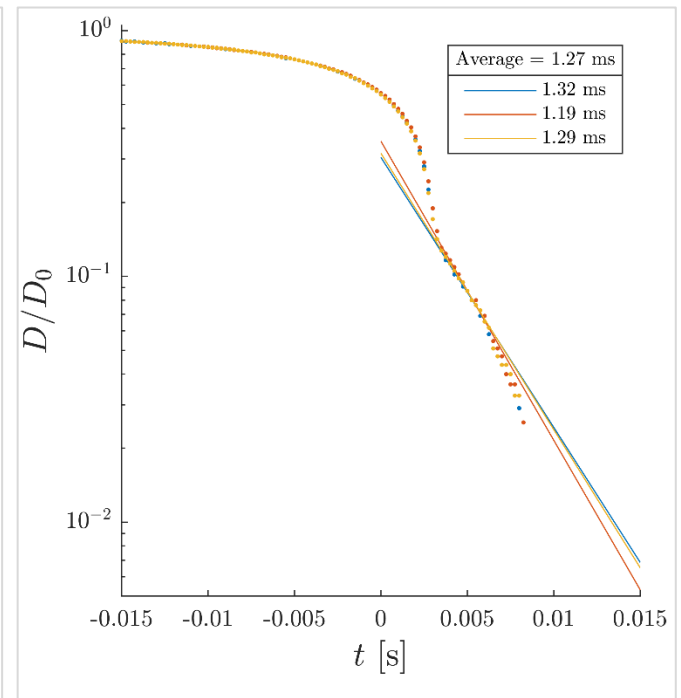
Figure D.1.2d: *D/D₀* versus *t* plot for 70% DR, Re: 90000.
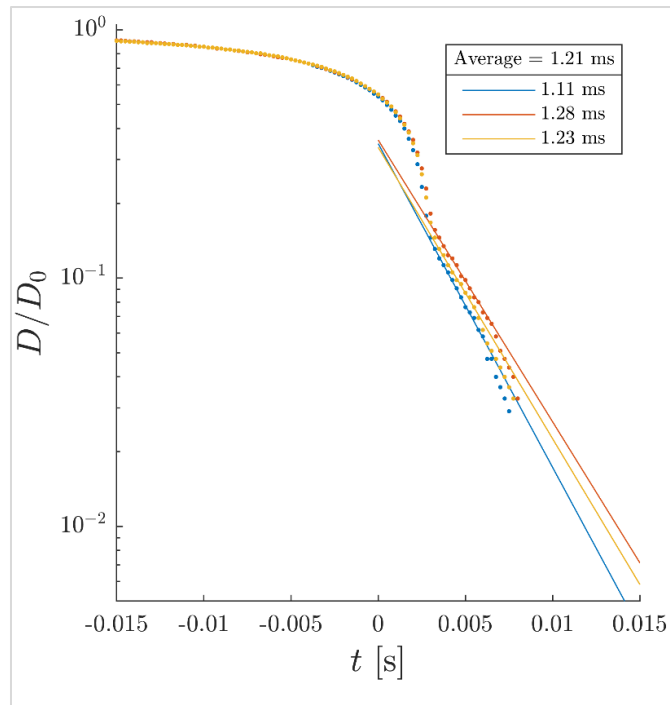
Figure D.1.2e: *D/D₀* versus *t* plot for 70% DR, Re: 100000.

D.1.3 Plots for 65% DR (data acquisition rate: 4000 fps)
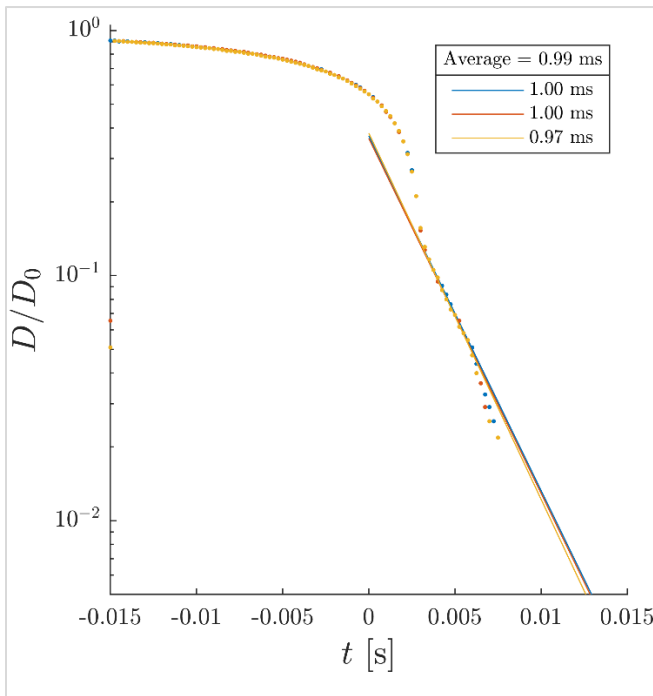
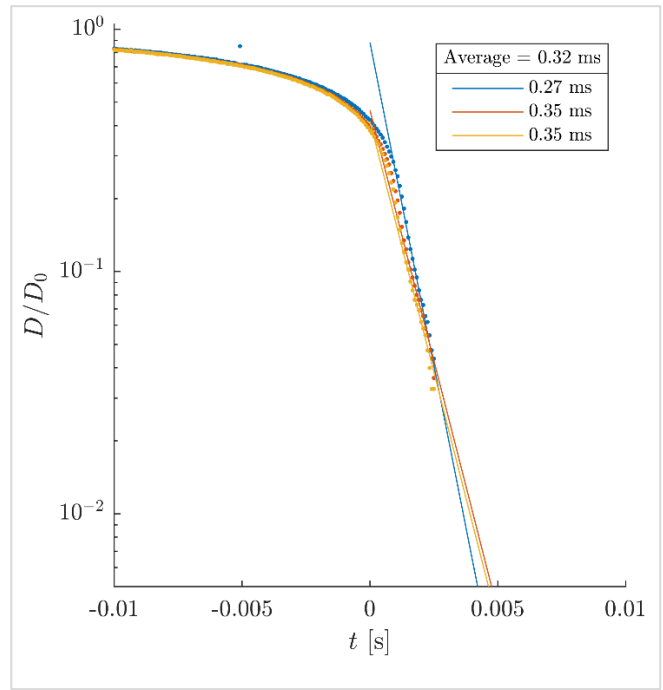Figure D.1.3a: *D/D₀* versus *t* plot for 65% DR, Re: 60000.
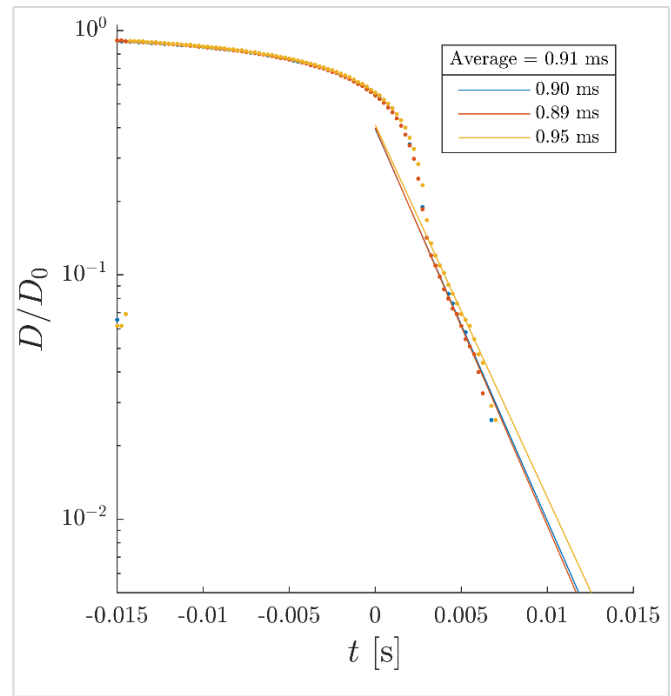
Figure D.1.3b: *D/D₀* versus *t* plot for 65% DR, Re: 70000.
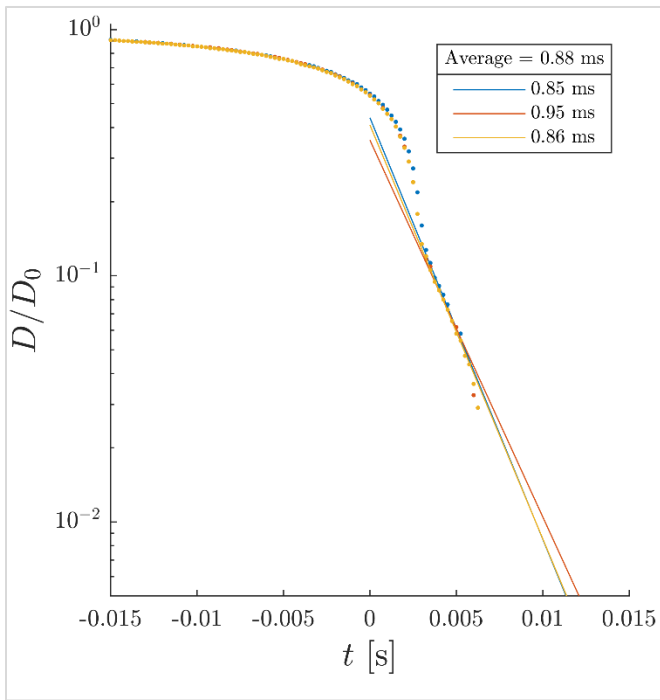
Figure D.1.3c: *D/D₀* versus *t* plot for 65% DR, Re: 80000.
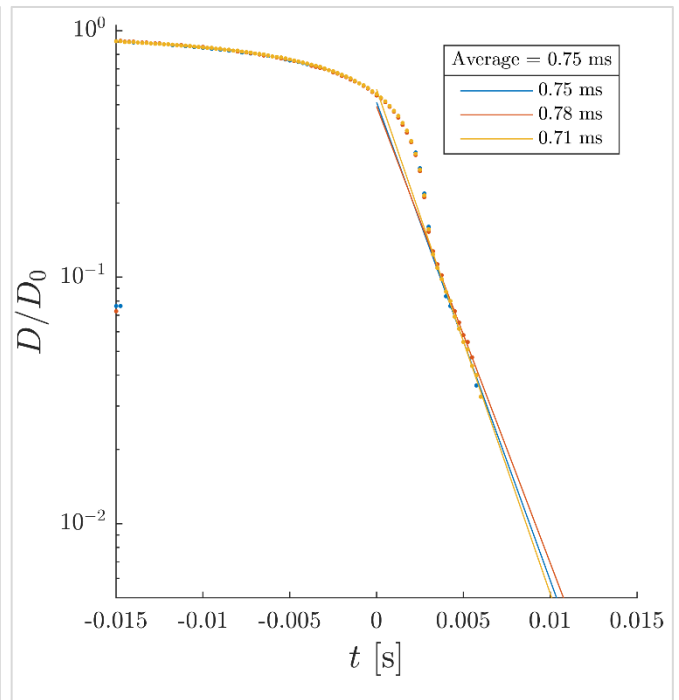
Figure D.1.3d: *D/D₀* versus *t* plot for 65% DR, Re: 90000.
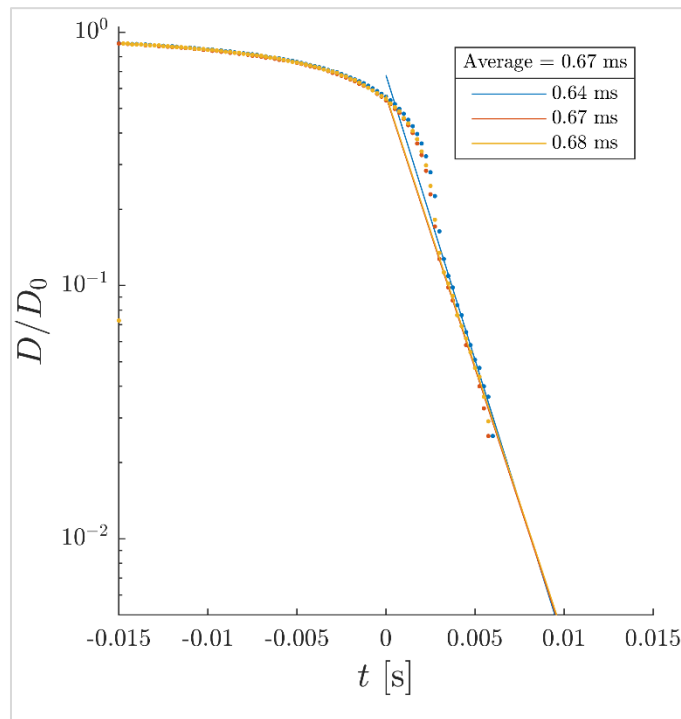
Figure D.1.3e: *D/D₀* versus *t* plot for 65% DR, Re: 100000.

D.1.4 Plots for 60% DR (data acquisition rate: 4000 fps)
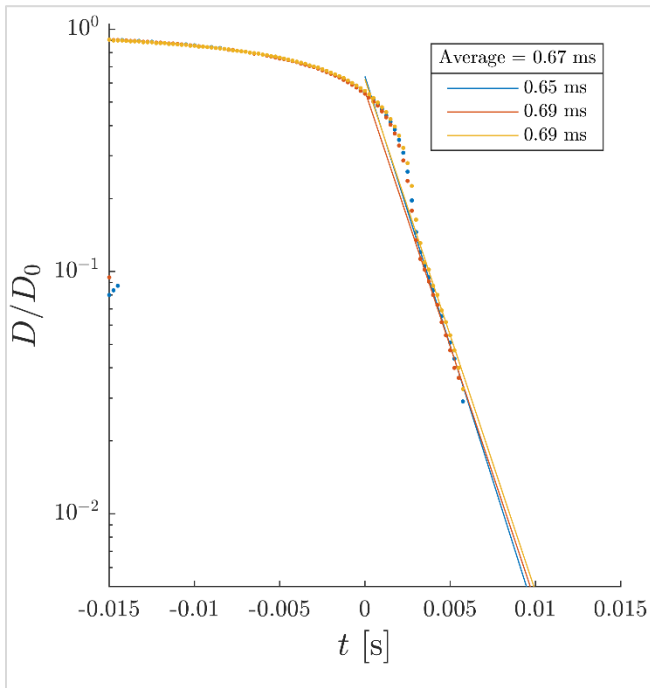
Figure D.1.4a: *D/D₀* versus *t* plot for 60% DR, Re: 60000.
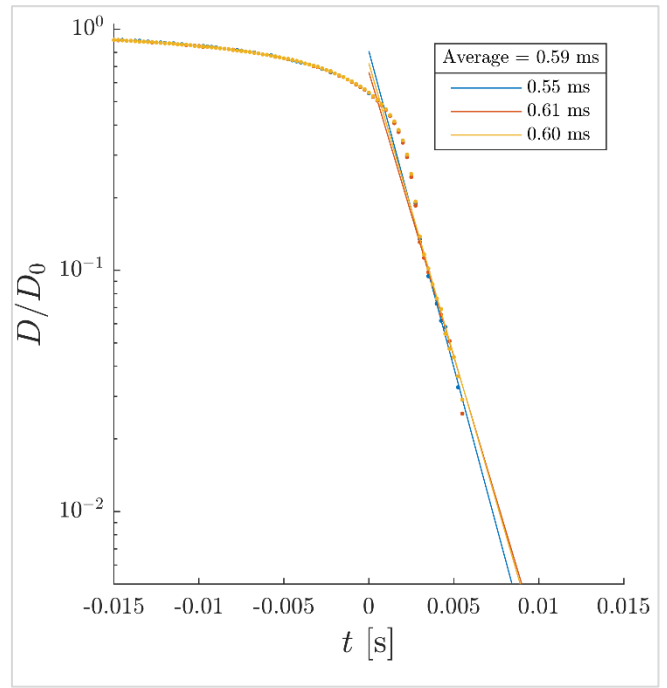
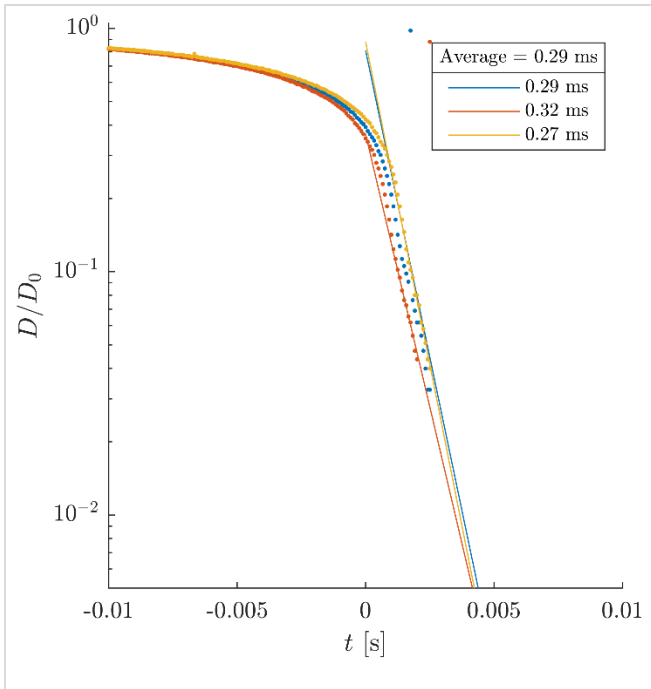Figure D.1.4b: *D/D₀* versus *t* plot for 60% DR, Re: 70000.
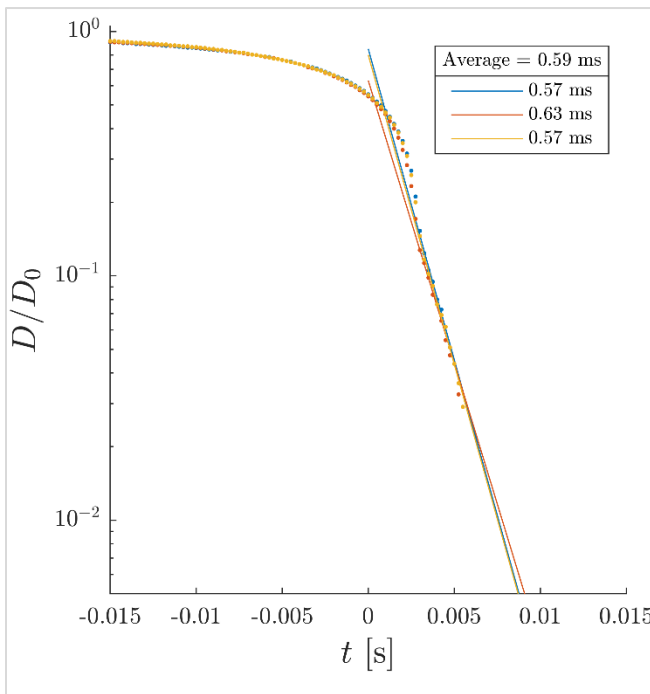
Figure D.1.4c: *D/D₀* versus *t* plot for 60% DR, Re: 80000.
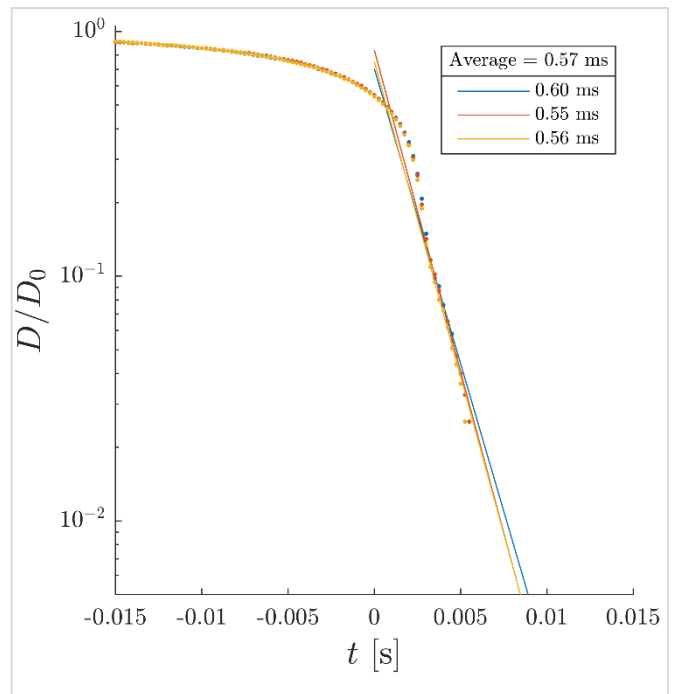
Figure D.1.4d: *D/D₀* versus *t* plot for 60% DR, Re: 90000.
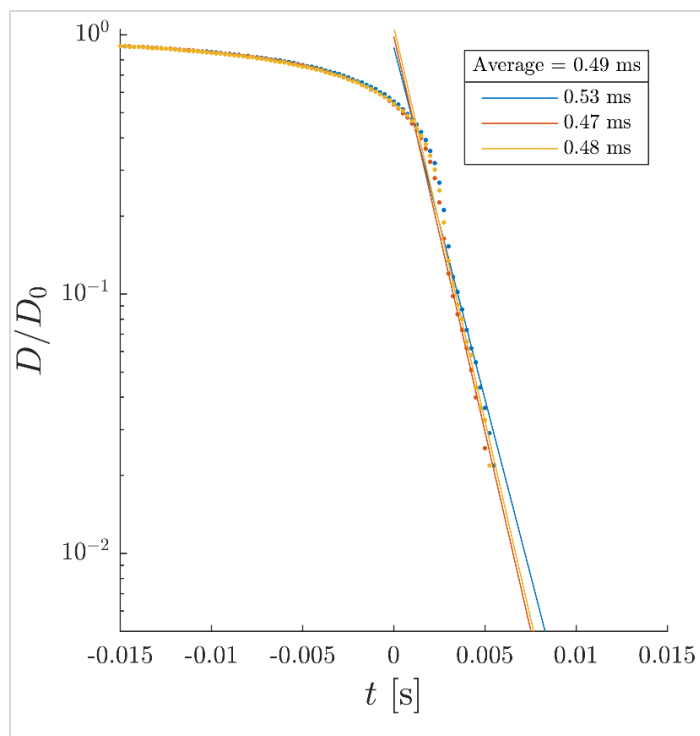
Figure D.1.4e: *D/D₀* versus *t* plot for 60% DR, Re: 100000.

D.1.5 Plots for 50% DR (data acquisition rate: 4000 fps)
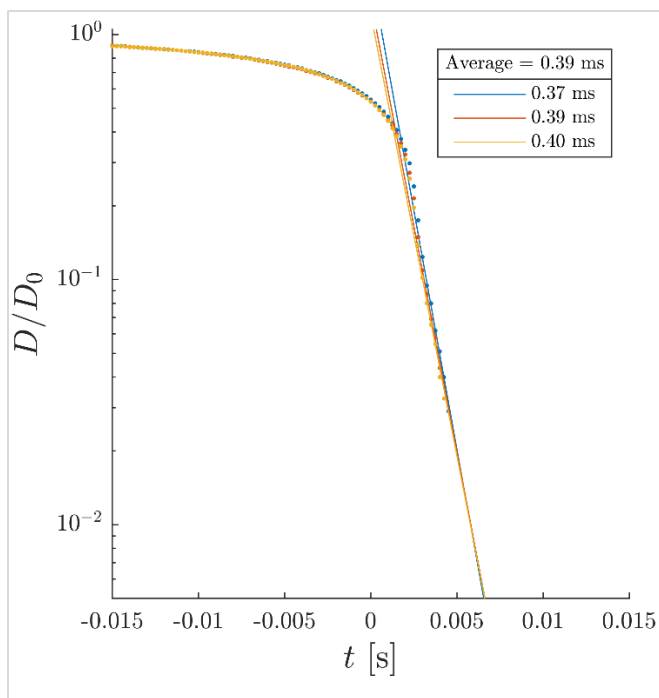
Figure D.1.5a: *D/D₀* versus *t* plot for 50% DR, Re: 60000.
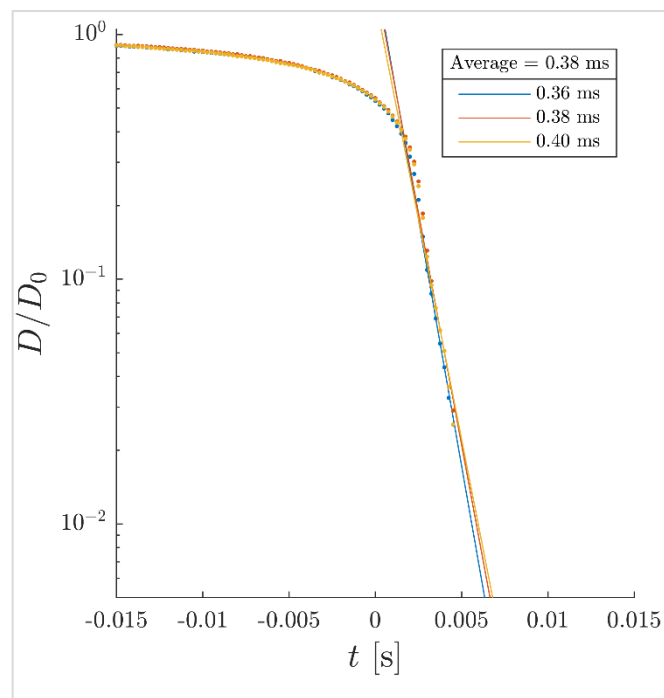
Figure D.1.5b: *D/D₀* versus *t* plot for 50% DR, Re: 70000.
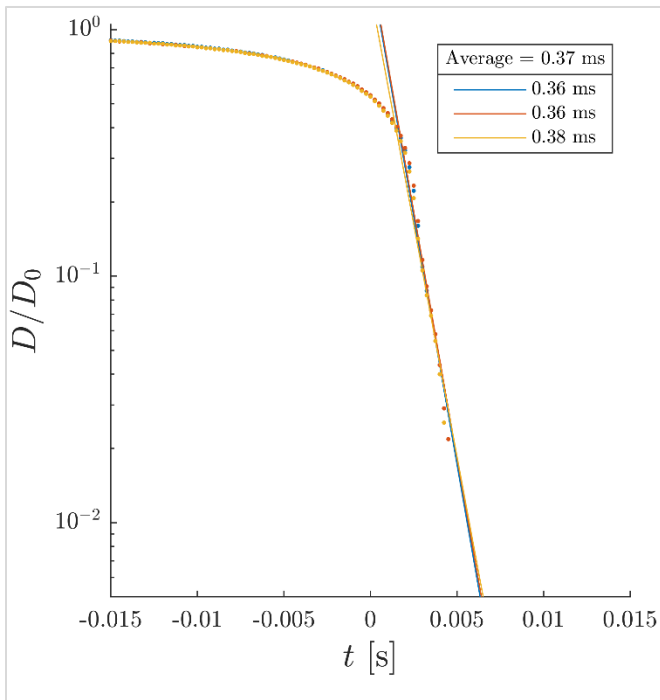
Figure D.1.5c: D/D_0 versus t plot for 50% DR, Re: 80000.
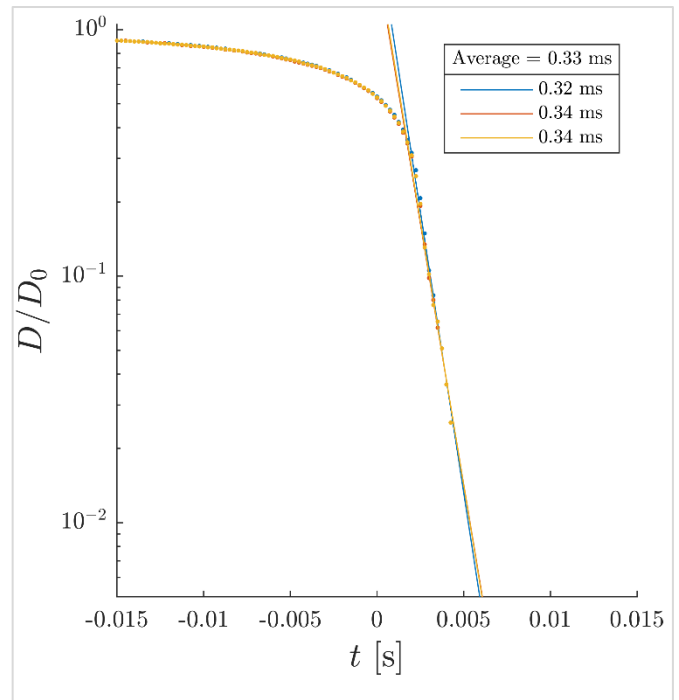
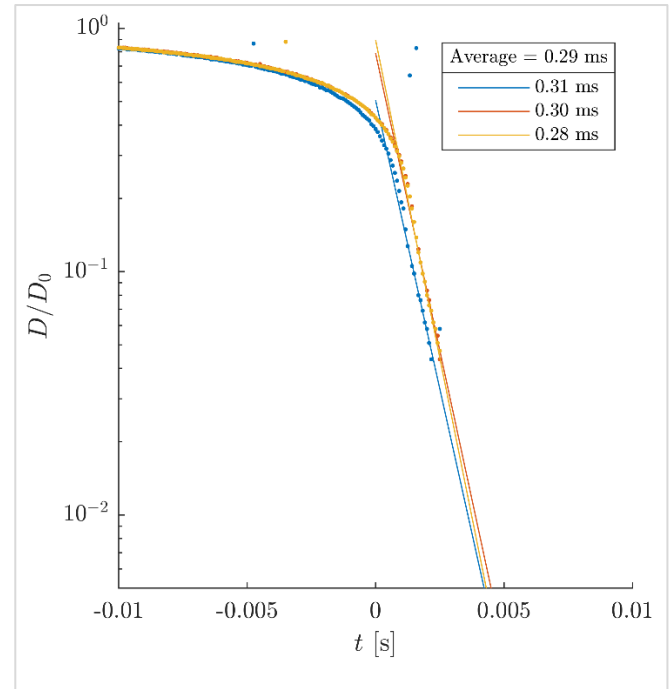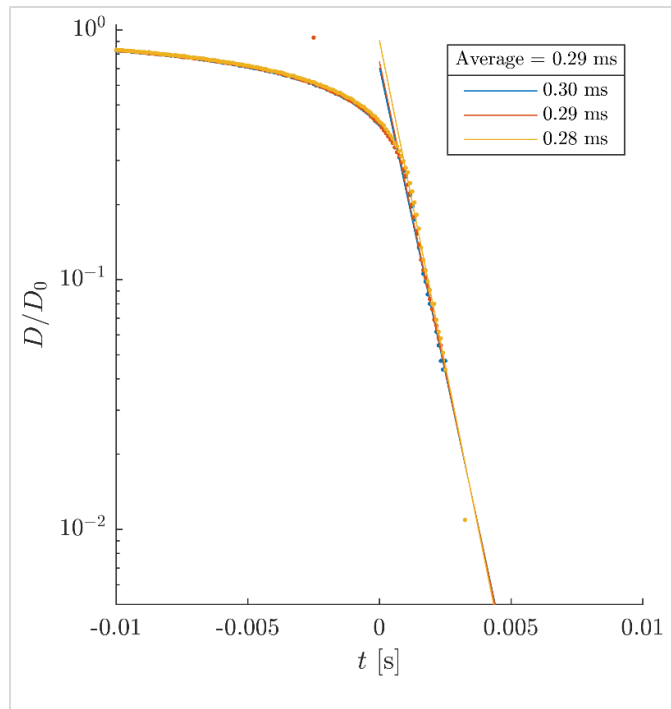Figure D.1.5d: D/D_0 versus t plot for 50% DR, Re: 90000.
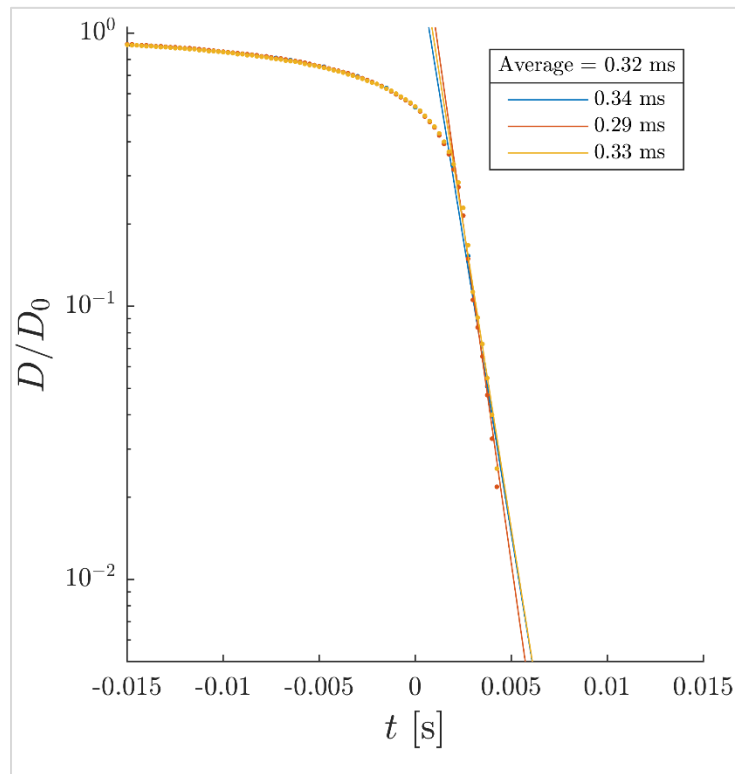
Figure D.1.5e: D/D_0 versus t plot for 50% DR, Re: 100000.

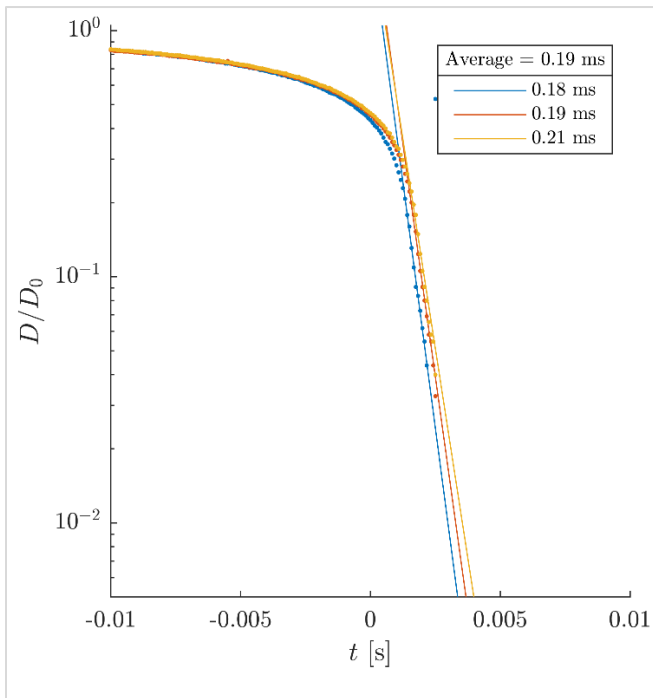## D.1.6 Plots for 40% DR (data acquisition rate: 9000 fps)
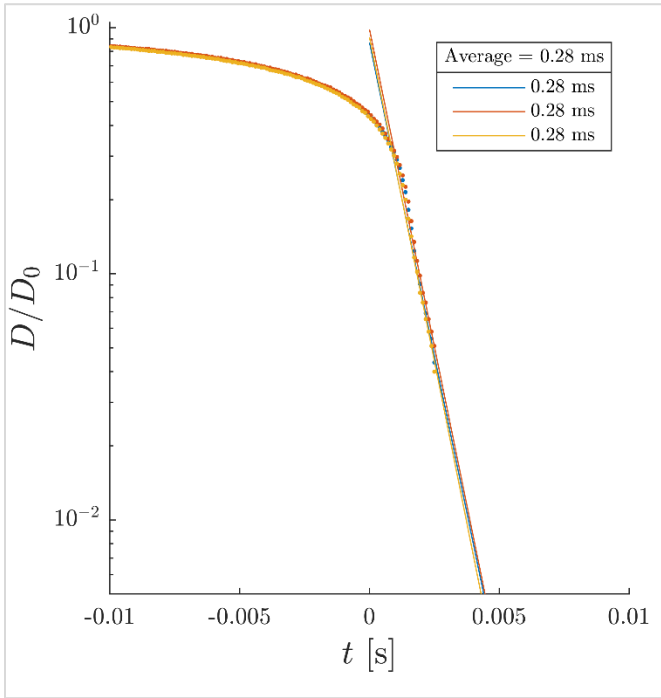
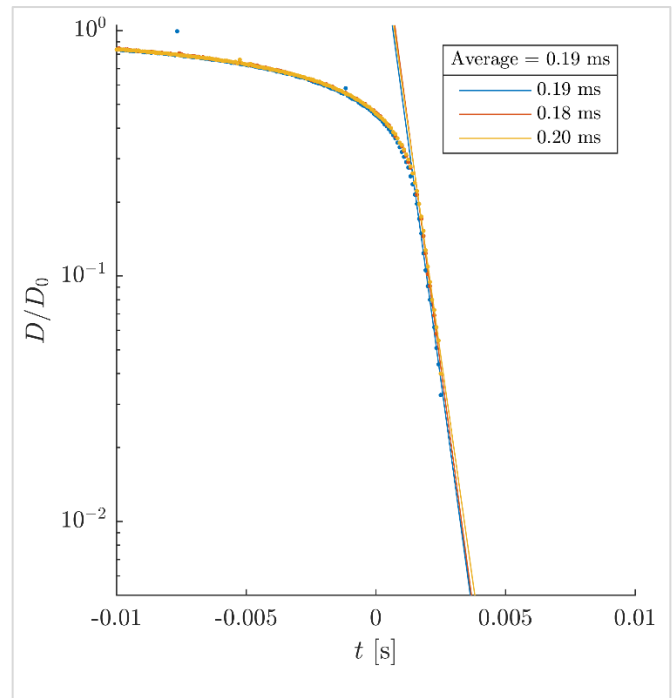Figure D.1.6a: D/D_0 versus t plot for 40% DR, Re: 60000.
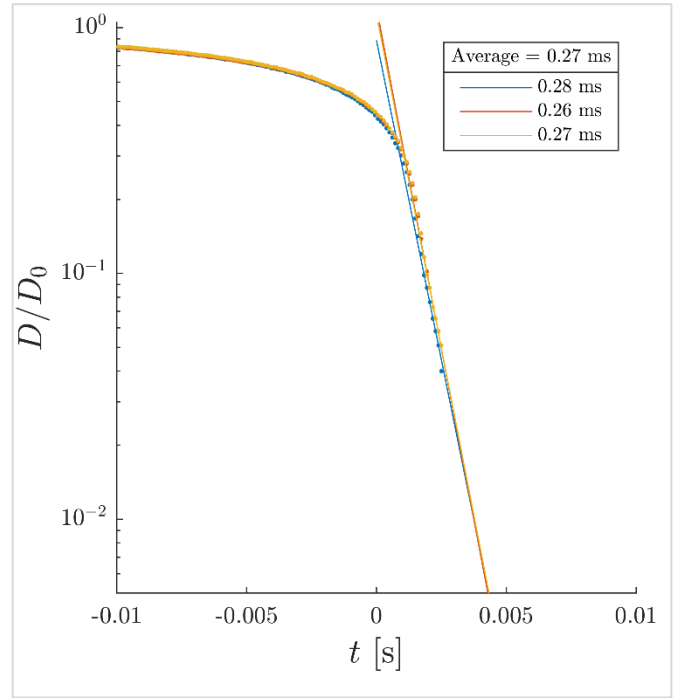
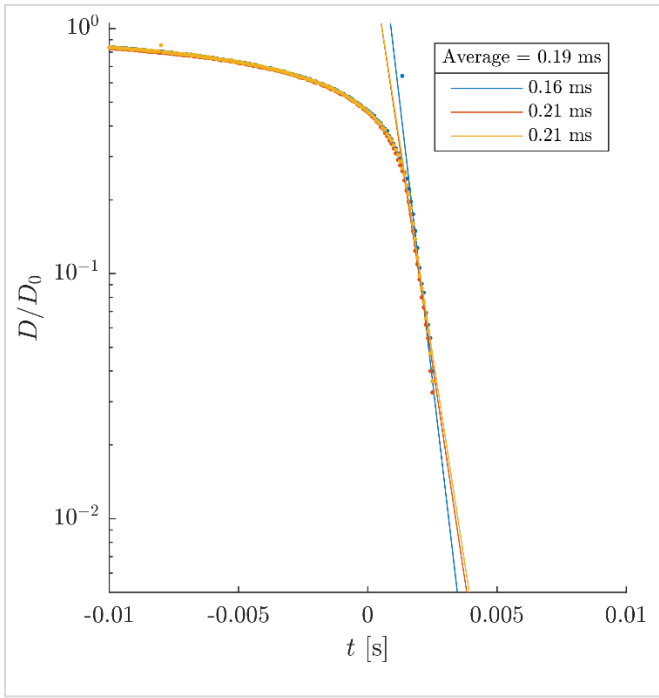Figure D.1.6b: D/D_0 versus t plot for 40% DR, Re: 70000.
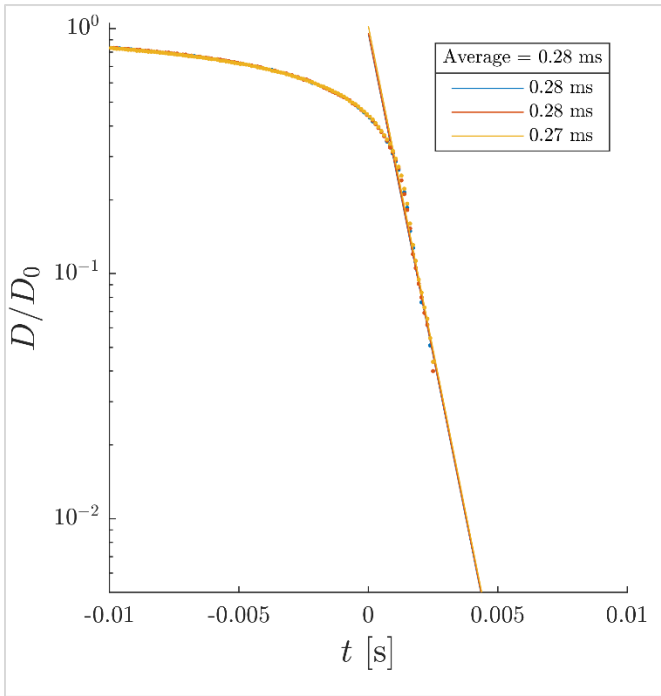
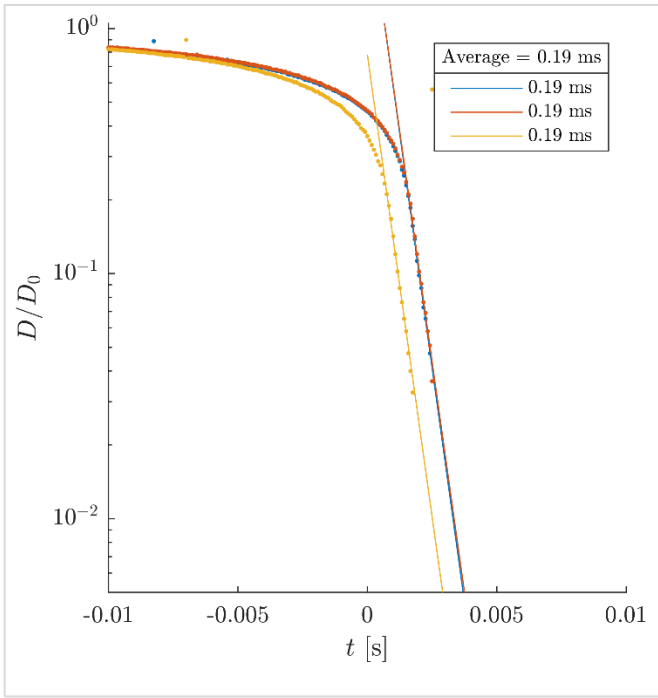Figure D.1.6c: D/D_0 versus t plot for 40% DR, Re: 80000.
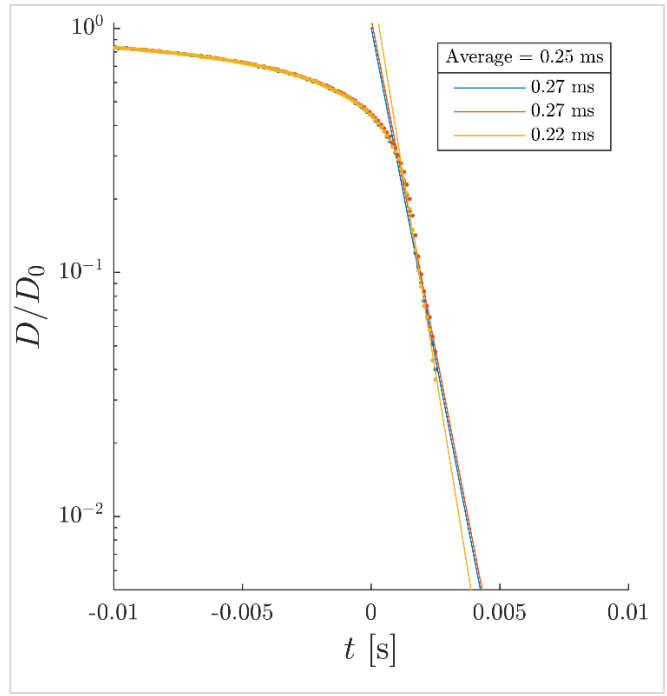
Figure D.1.6d: D/D_0 versus t plot for 40% DR, Re: 90000.
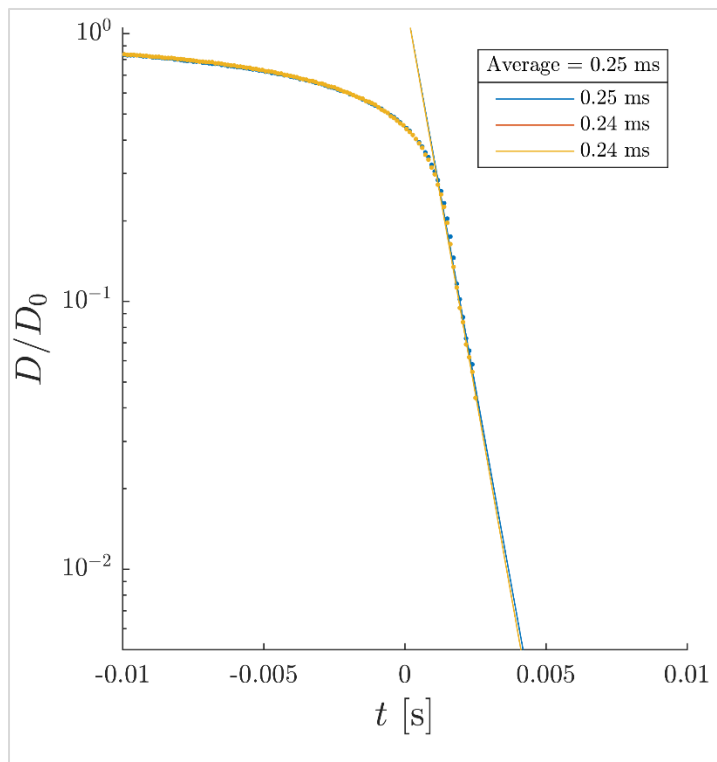
Figure D.1.6e: *D/D₀* versus *t* plot for 40% DR, Re: 100000.

D.1.7 Plots for 30% DR (data acquisition rate: 12000 fps)
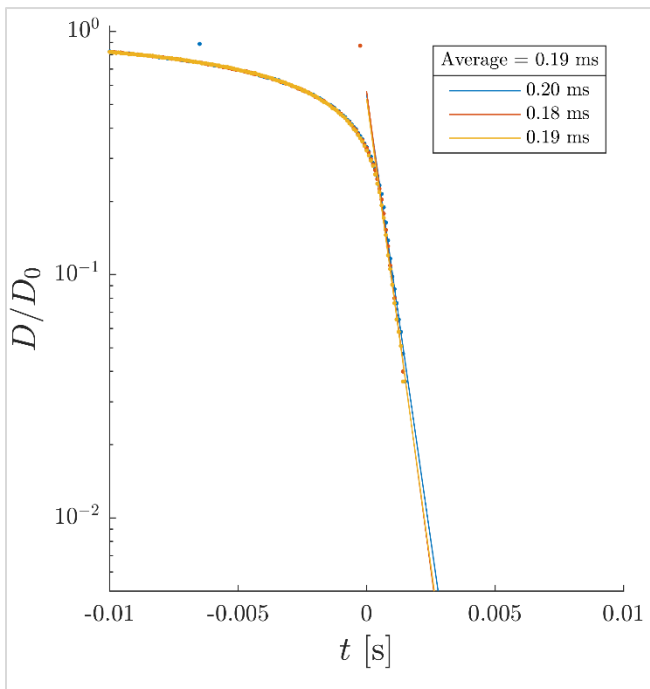
Figure D.1.7a: *D/D₀* versus *t* plot for 30% DR, Re: 60000.
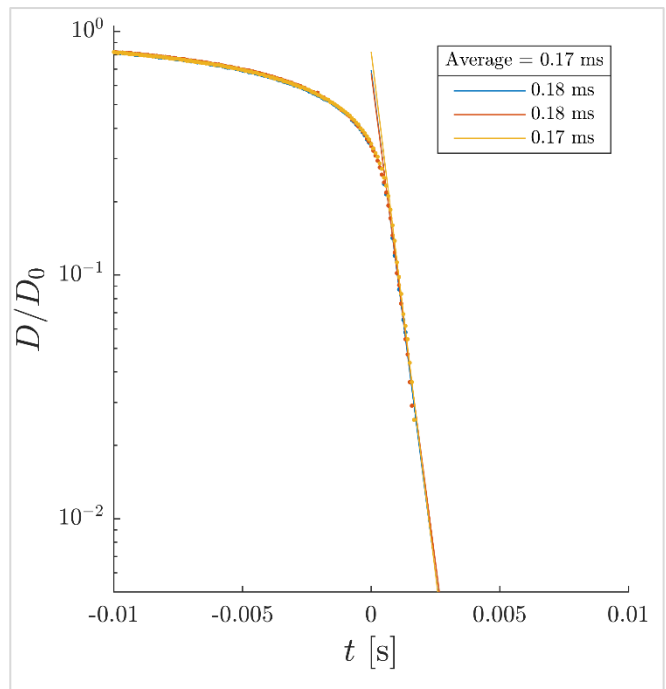
Figure D.1.7b: *D/D₀* versus *t* plot for 30% DR, Re: 70000.
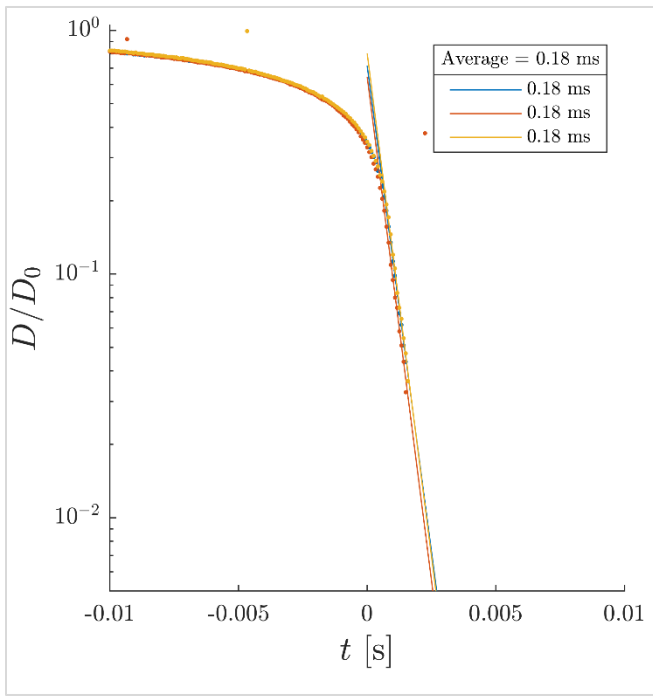
Figure D.1.7c: *D/D₀* versus *t* plot for 30% DR, Re: 80000.
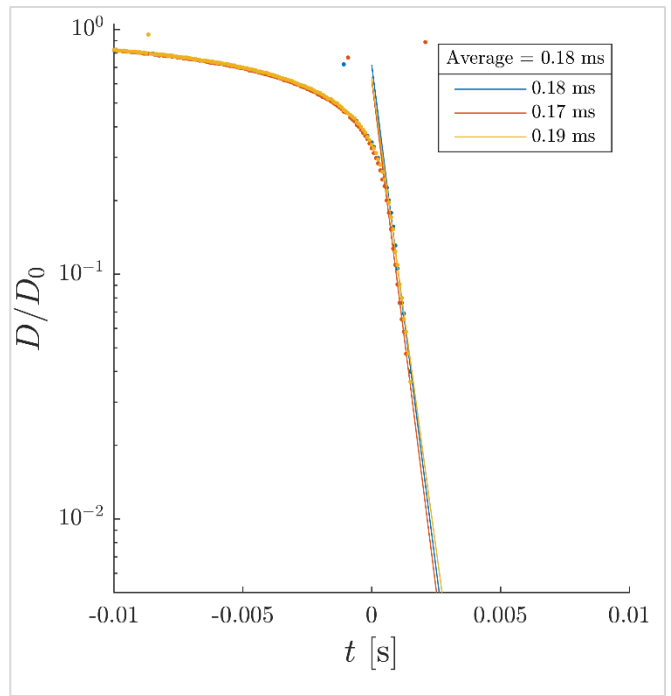
Figure D.1.7d: *D/D₀* versus *t* plot for 30% DR, Re: 90000.
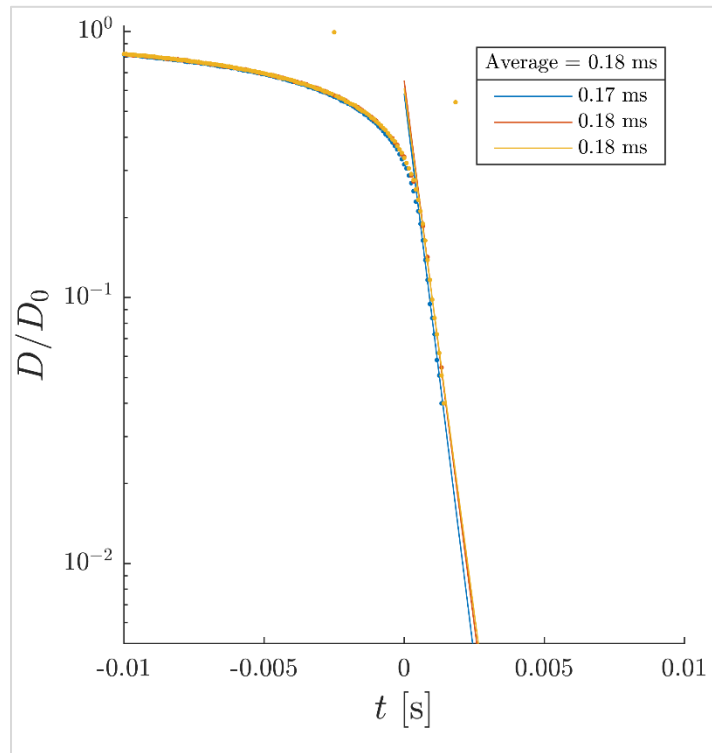
Figure D.1.7e: *D/D₀* versus *t* plot for 30% DR, Re: 100000.

D.1.8 Plots for 20% DR (data acquisition rate: 12000 fps)
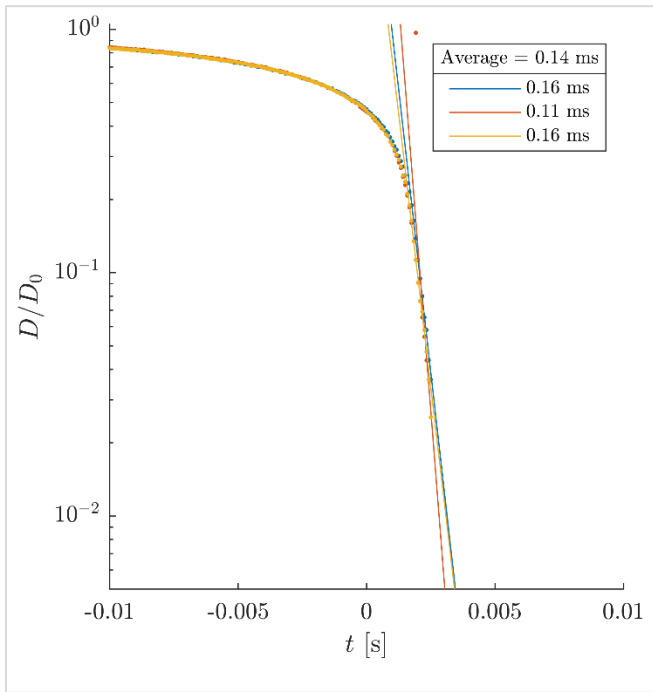
Figure D.1.8a: *D/D₀* versus *t* plot for 20% DR, Re: 60000.
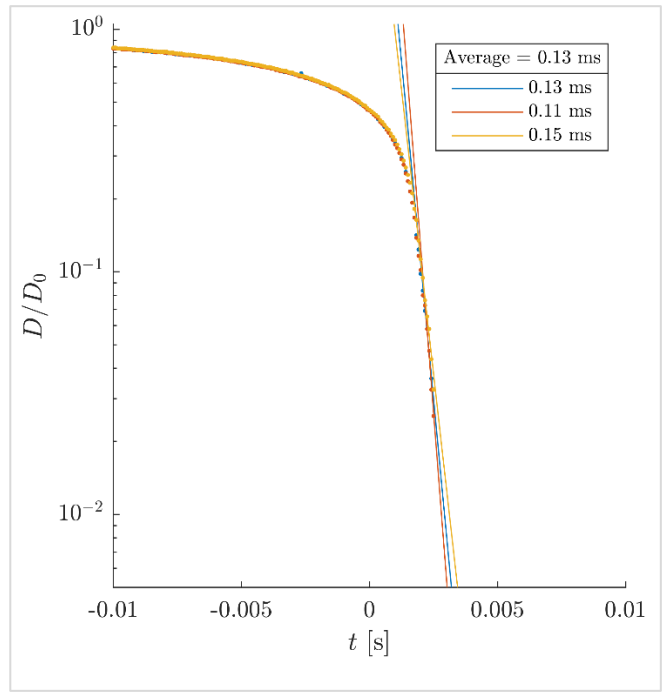
Figure D.1.8b: *D/D₀* versus *t* plot for 20% DR, Re: 70000.
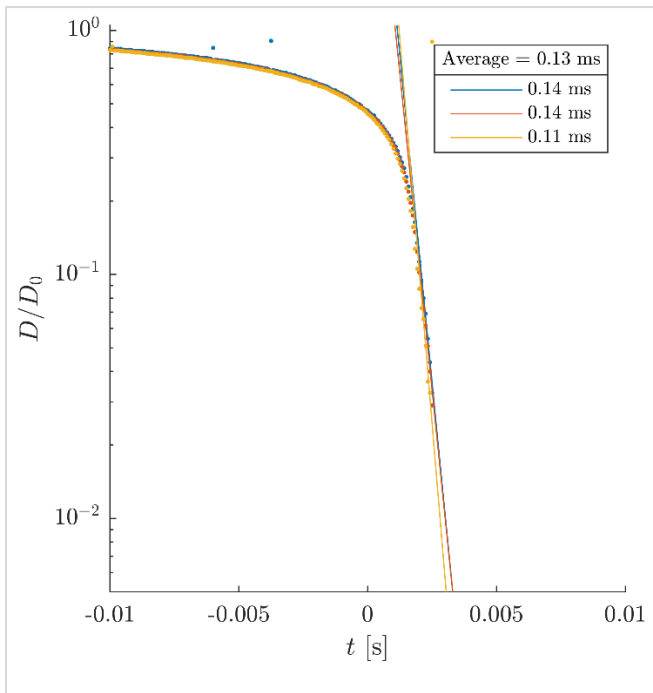
Figure D.1.8c: *D/D₀* versus *t* plot for 20% DR, Re: 80000.
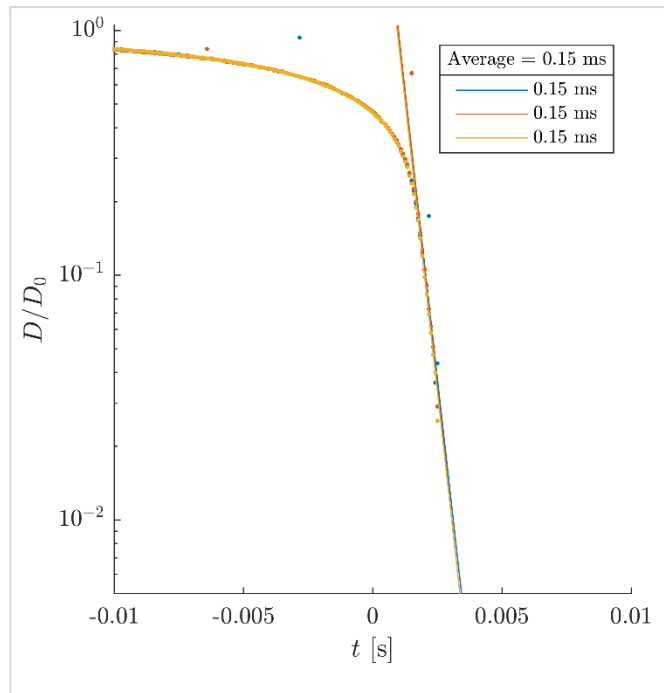
Figure D.1.8d: *D/D₀* versus *t* plot for 20% DR, Re: 90000.
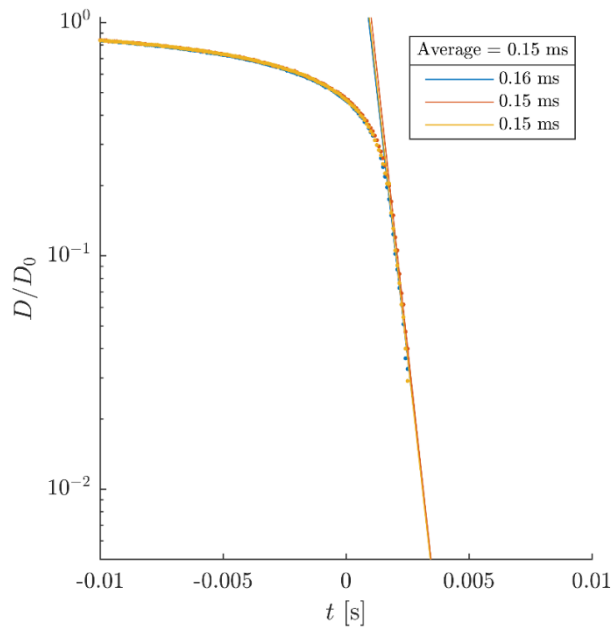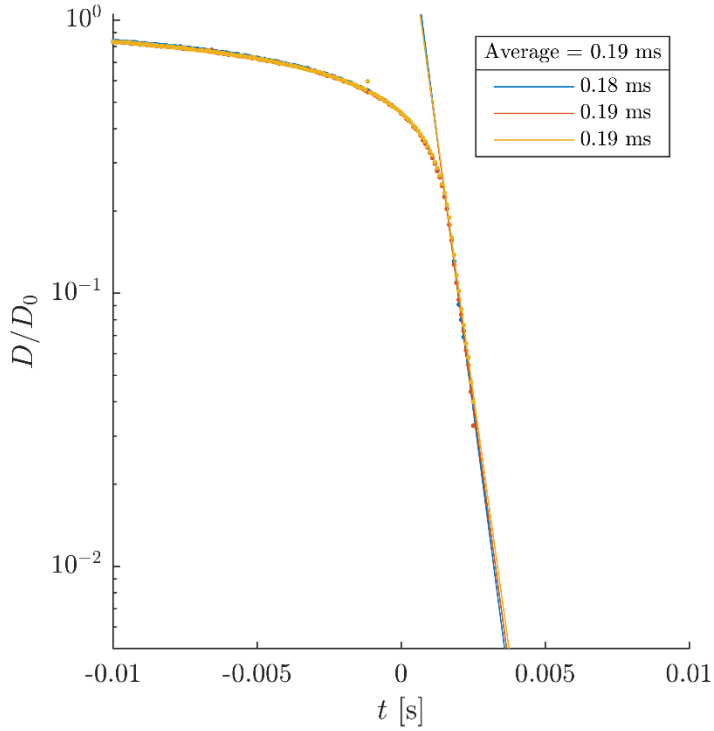
Figure D.1.8e: *D/D₀* versus *t* plot for 20% DR, Re: 100000.

D.2 (*D/D₀*) versus time (*t*) plots for test section with 1.5-inch ID

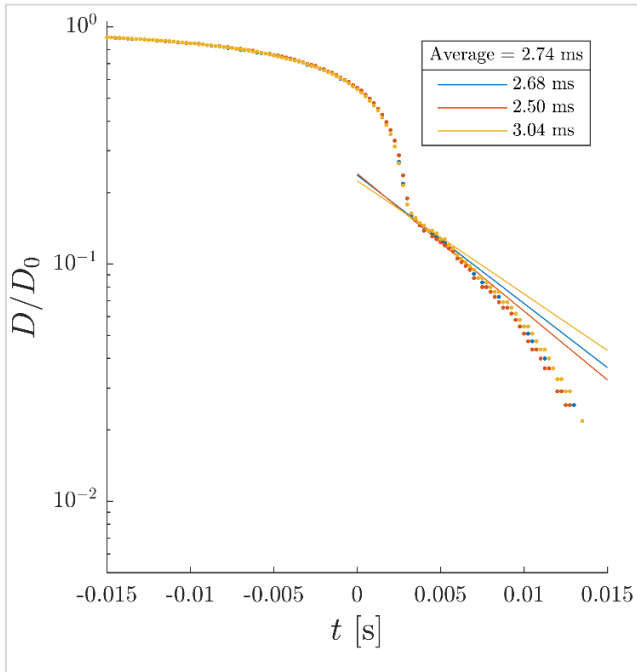### D.2.1 Plots for 70% DR (data acquisition rate: 4000 fps)
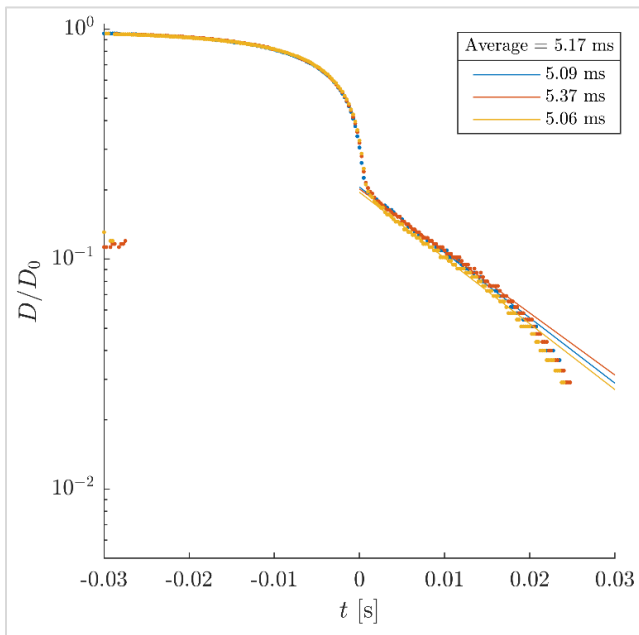
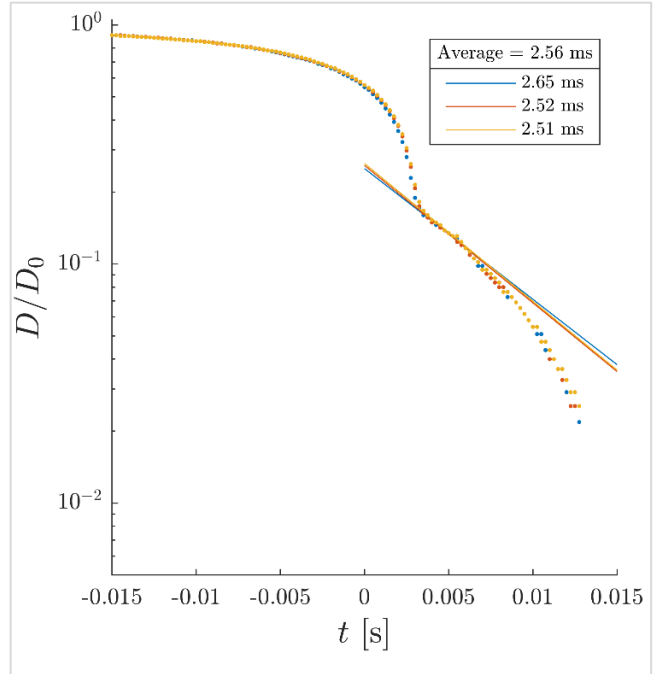Figure D.2.1a: *D/D₀* versus *t* plot for 70% DR, Re: 60000.
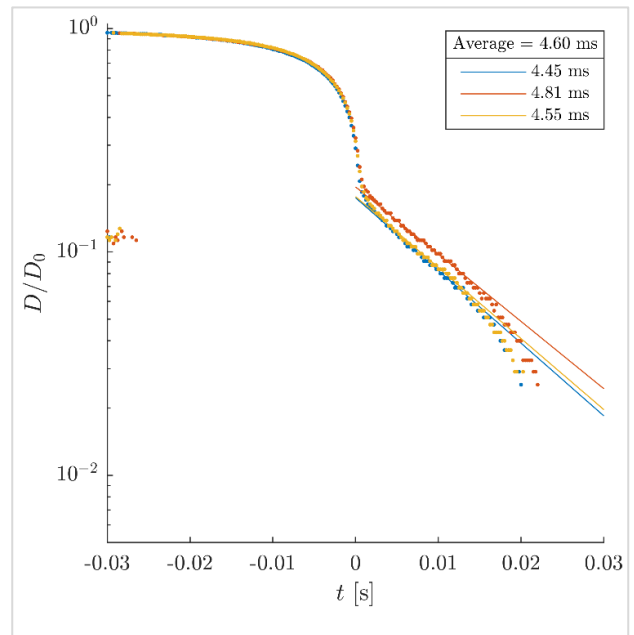
Figure D.2.1b: *D/D₀* versus *t* plot for 70% DR, Re: 70000.
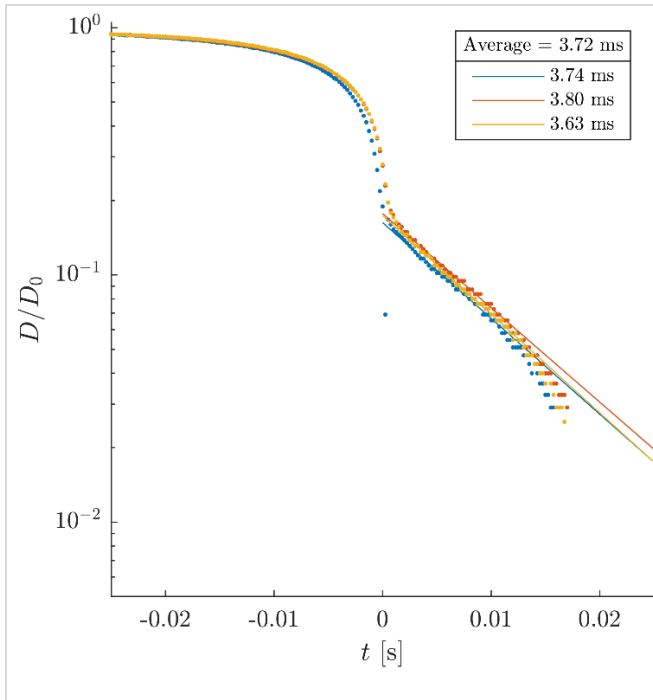
Figure D.2.1c: *D/D₀* versus *t* plot for 70% DR, Re: 80000.
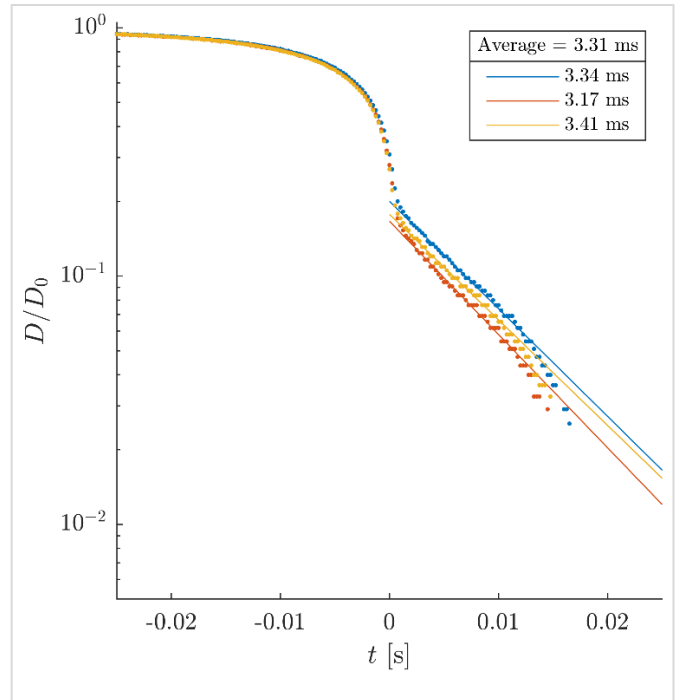
Figure D.2.1d: *D/D₀* versus *t* plot for 70% DR, Re: 90000.
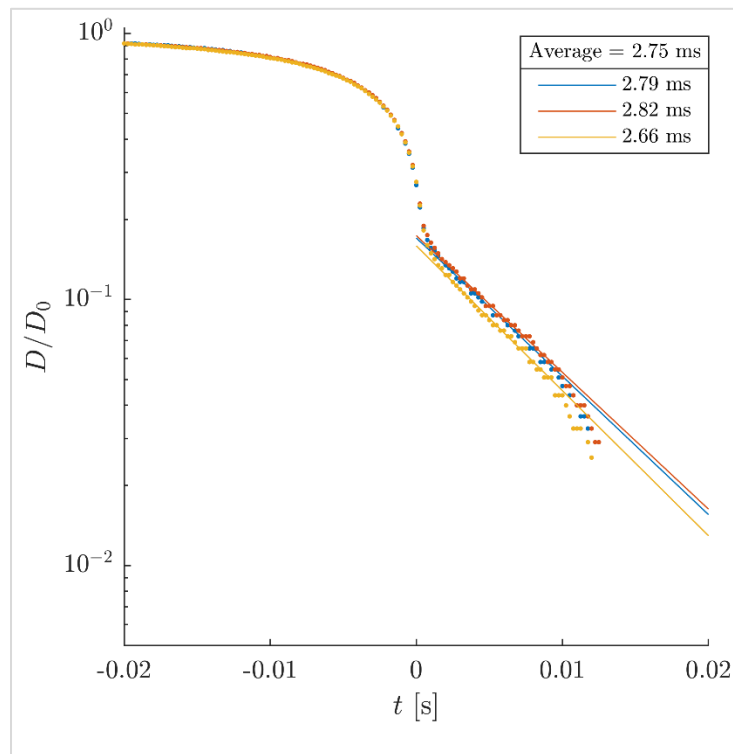
Figure D.2.1e: *D/D₀* versus *t* plot for 70% DR, Re: 100000.

D.2.2 Plots for 65% DR (data acquisition rate: 4000 fps)
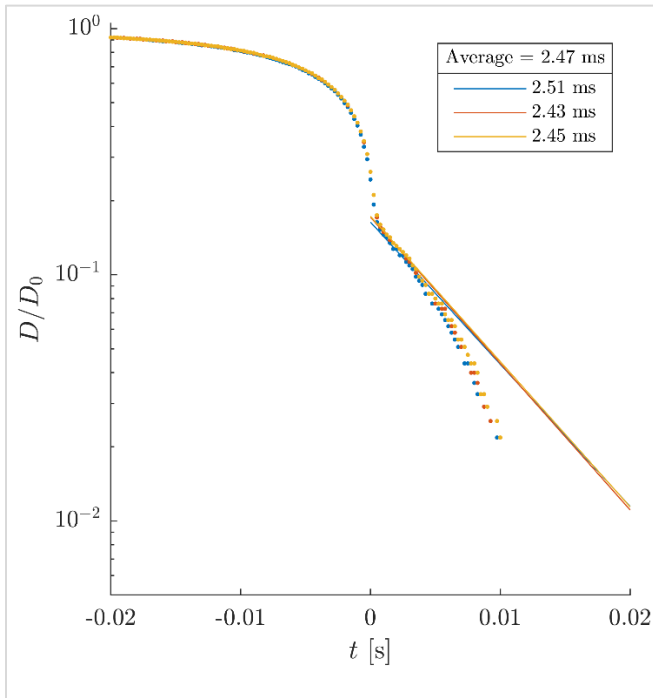
Figure D.2.2a: D/D_0 versus t plot for 65% DR, Re: 60000.
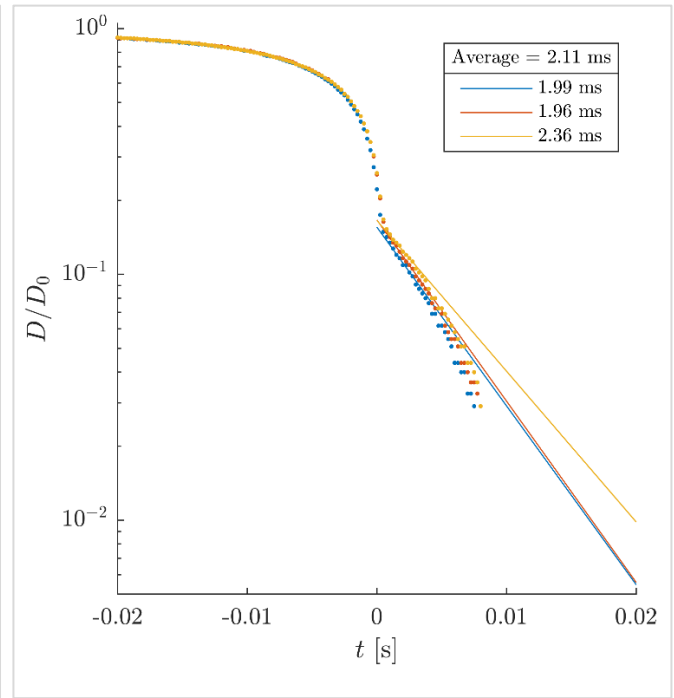
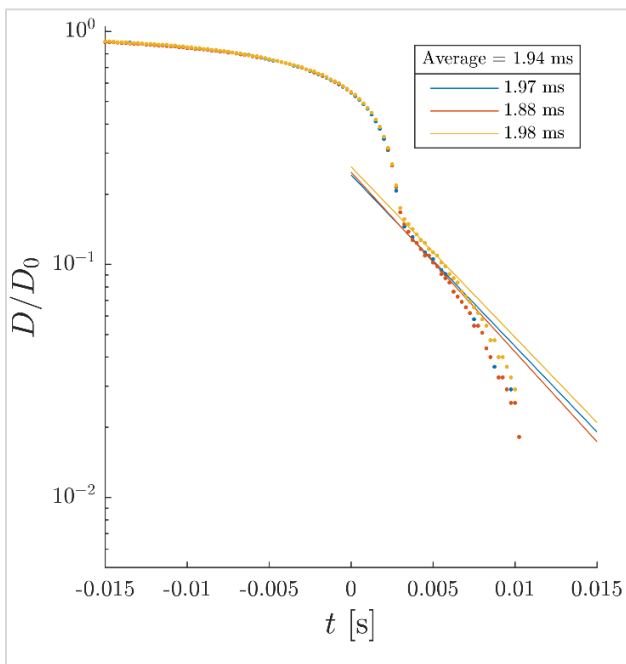Figure D.2.2b: D/D_0 versus t plot for 65% DR, Re: 70000.
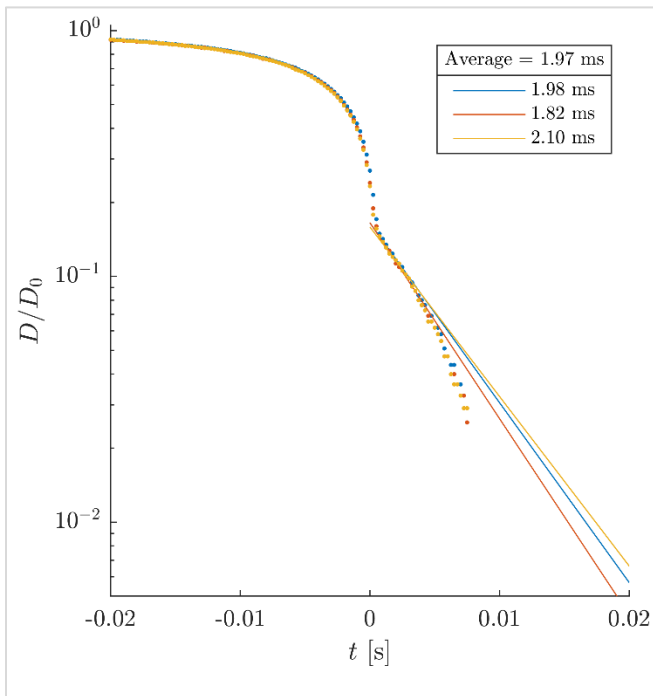
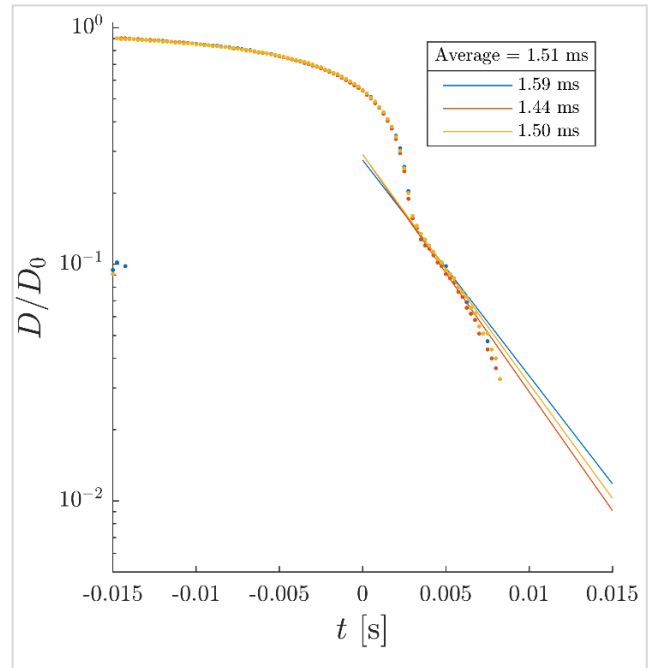Figure D.2.2c: D/D_0 versus t plot for 65% DR, Re: 80000.
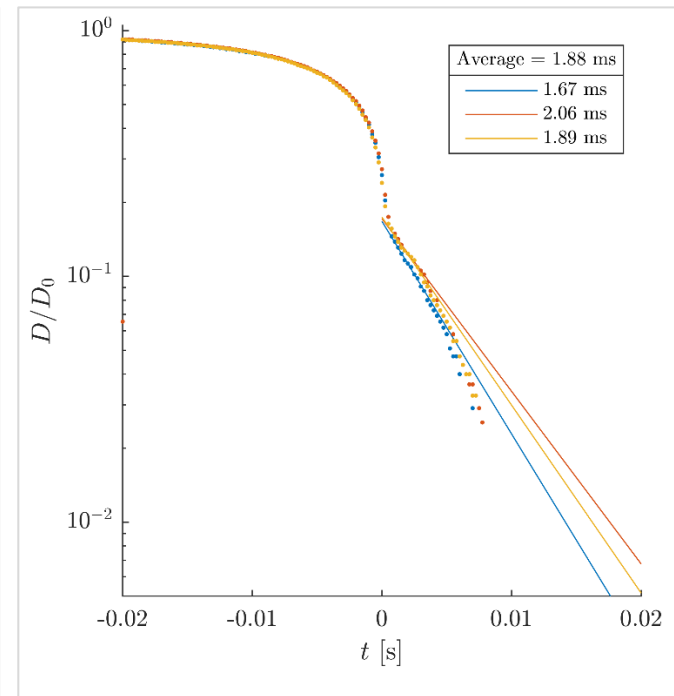
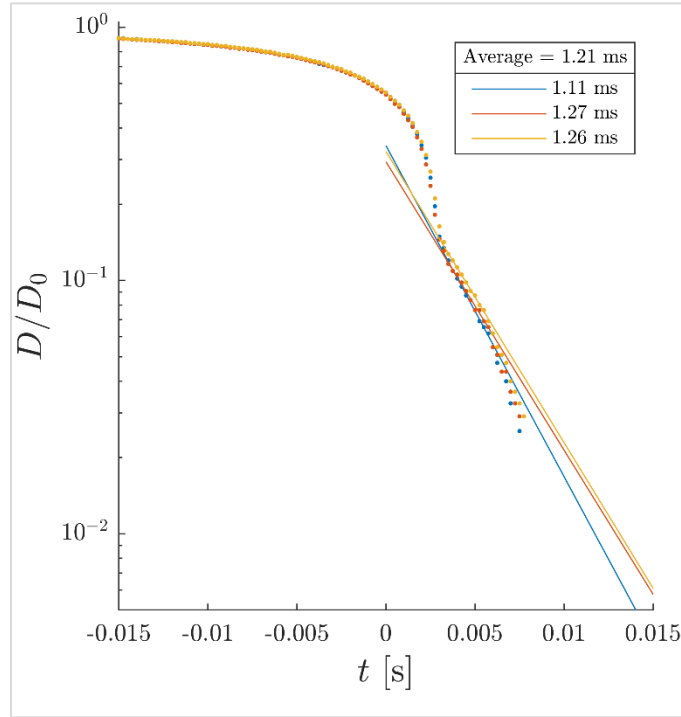Figure D.2.2d: D/D_0 versus t plot for 65% DR, Re: 90000.
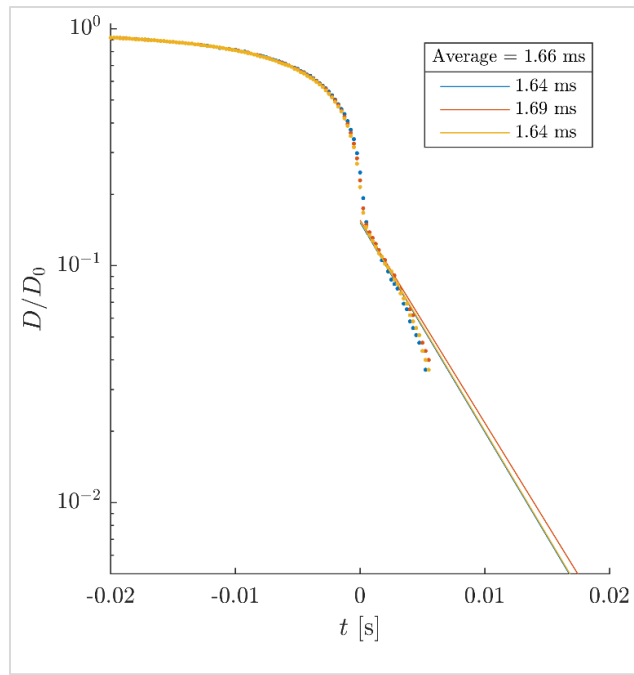
Figure D.2.2e: D/D_0 versus t plot for 65% DR, Re: 100000.

D.2.3 Plots for 60% DR (data acquisition rate: 4000 fps)
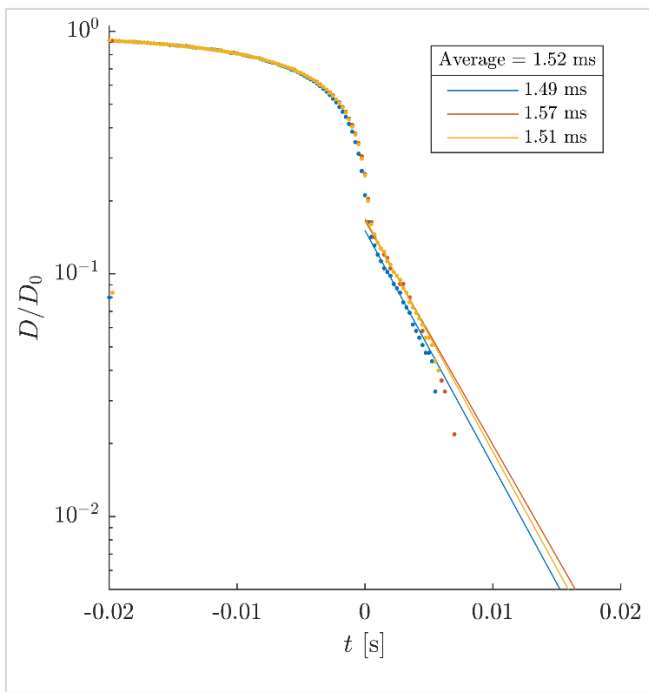
Figure D.2.3a: D/D_0 versus t plot for 60% DR, Re: 60000.
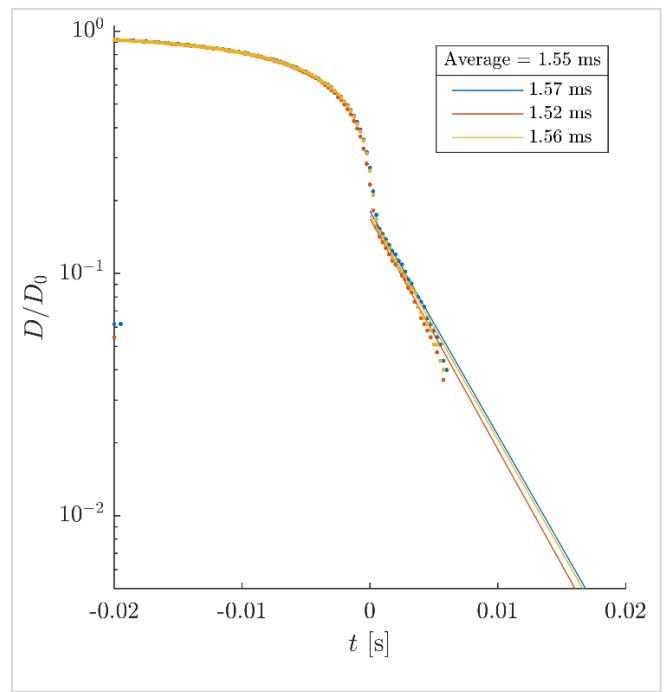
Figure D.2.3b: D/D_0 versus t plot for 60% DR, Re: 70000.
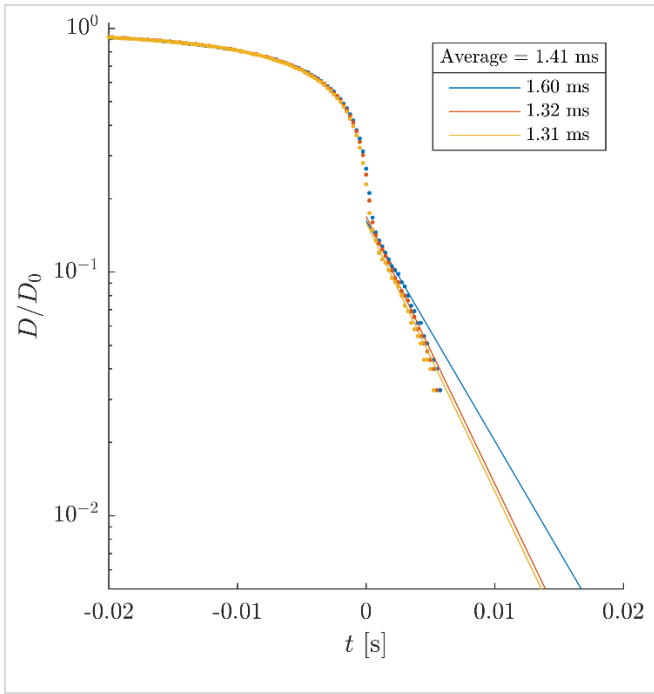
Figure D.2.3c: *D/D₀* versus *t* plot for 60% DR, Re: 80000.
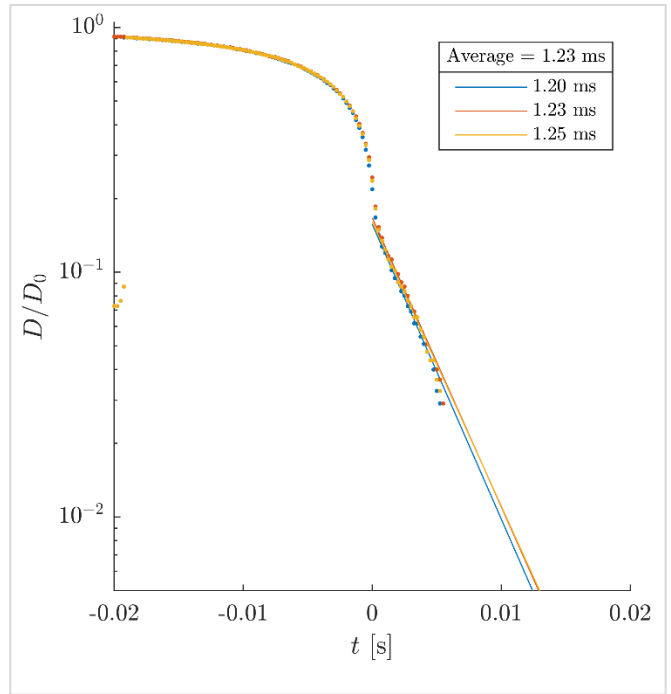
Figure D.2.3d: *D/D₀* versus *t* plot for 60% DR, Re: 90000.
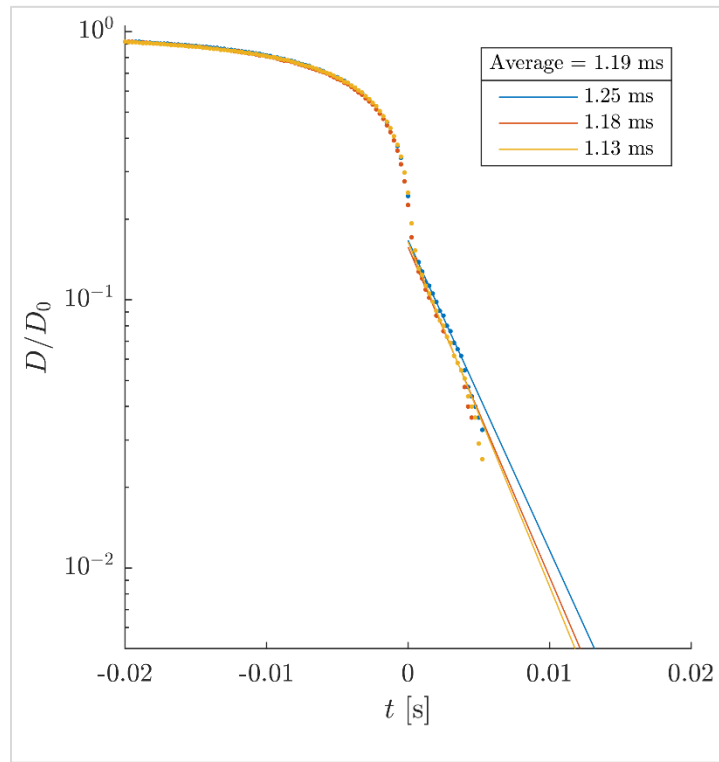
Figure D.2.3e: *D/D₀* versus *t* plot for 60% DR, Re: 100000.

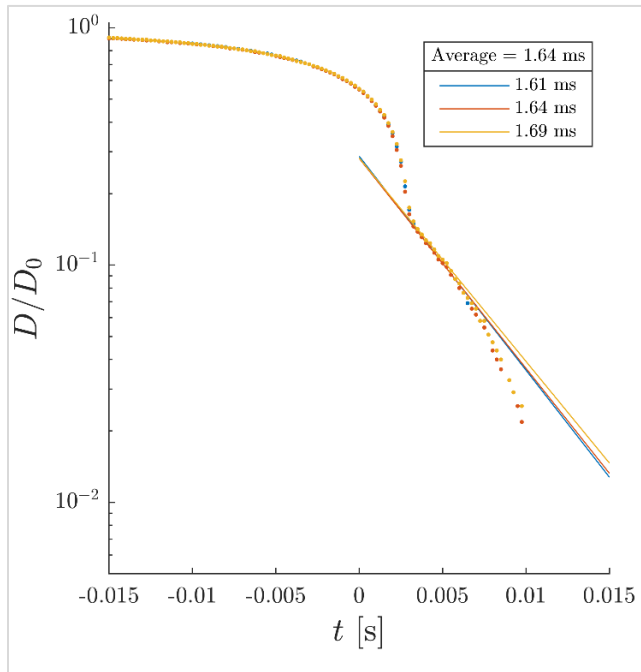## D.2.4 Plots for 50% DR (data acquisition rate: 4000 fps)
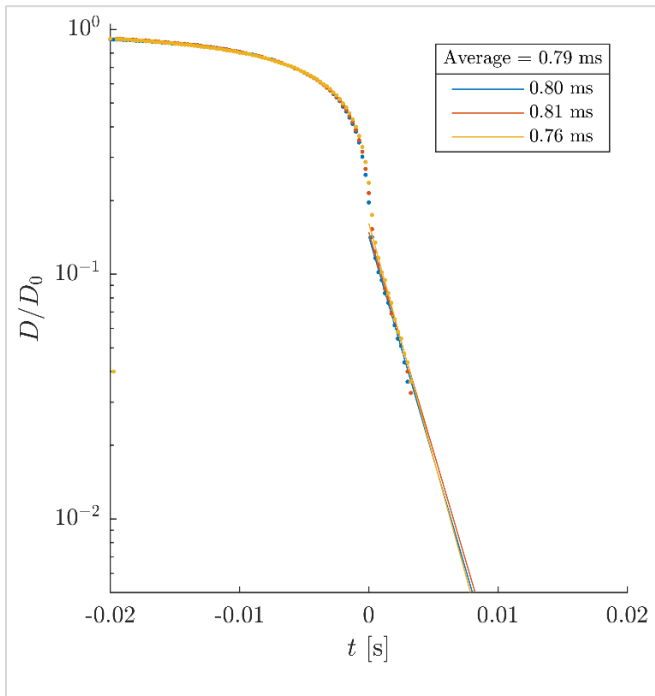
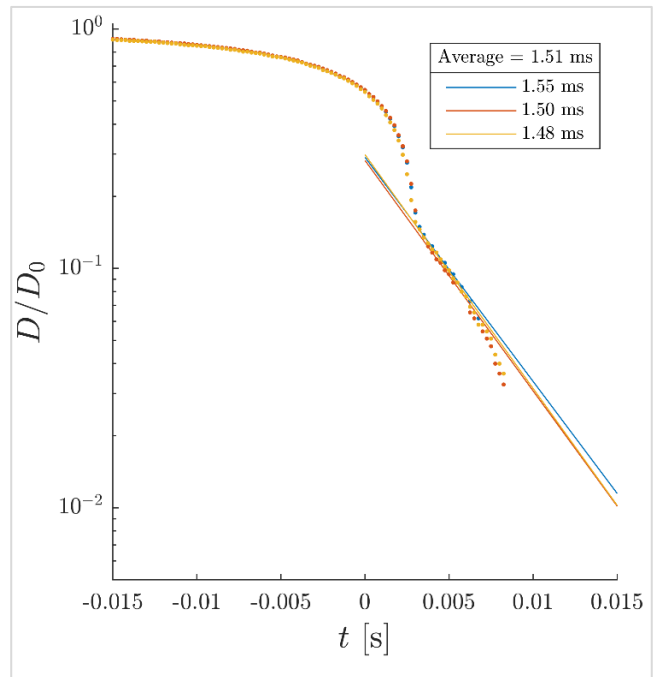Figure D.2.4a: D/D_0 versus t plot for 50% DR, Re: 60000.
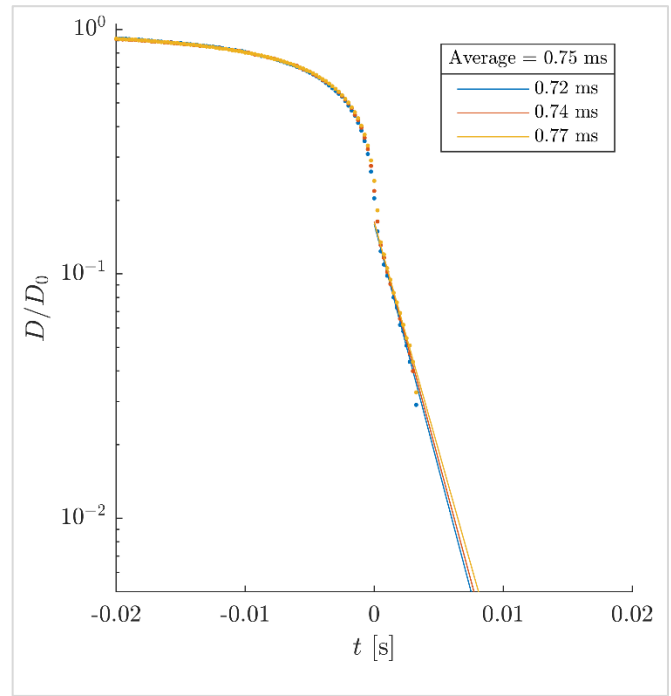
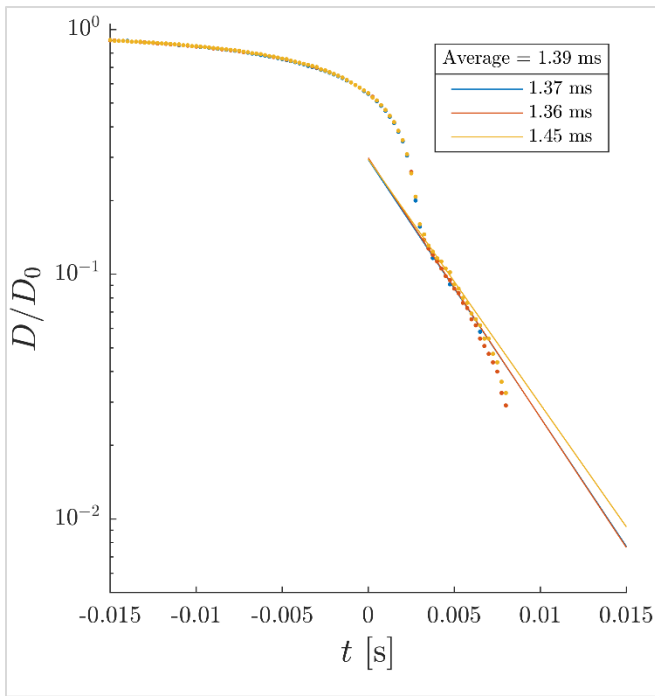Figure D.2.4b: D/D_0 versus t plot for 50% DR, Re: 70000.
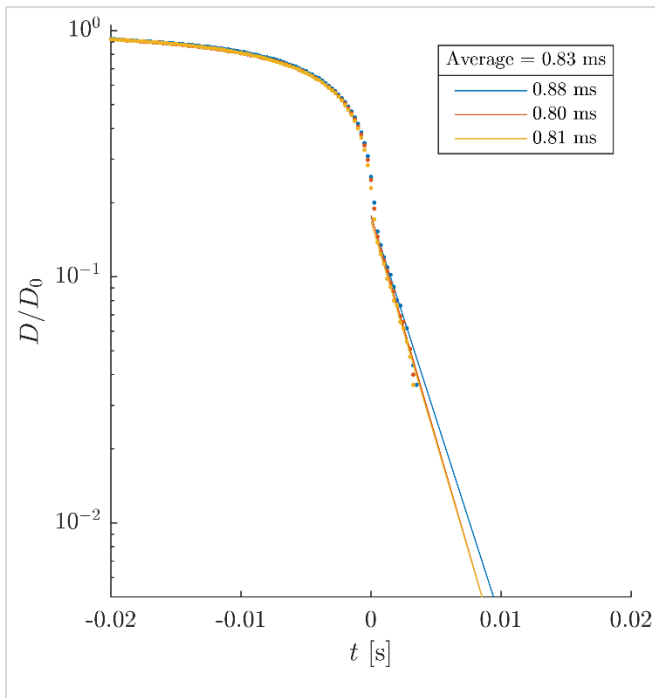
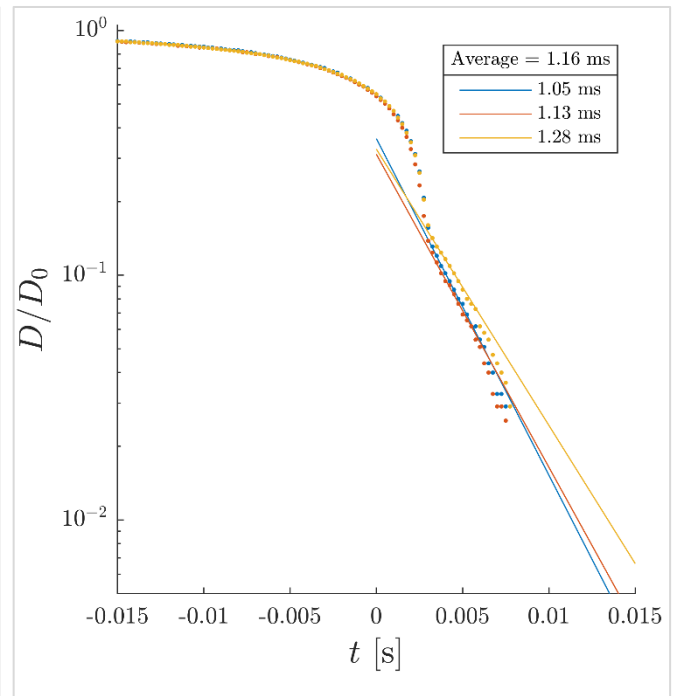Figure D.2.4c: D/D_0 versus t plot for 50% DR, Re: 80000.
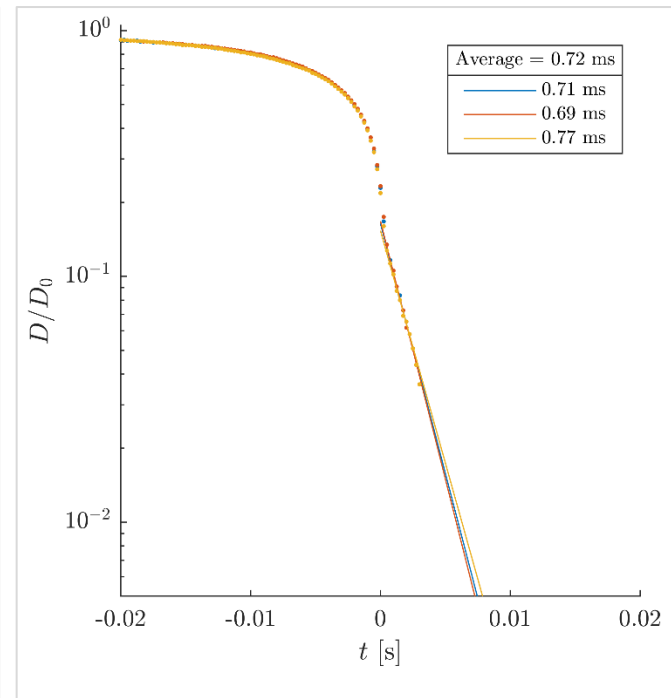
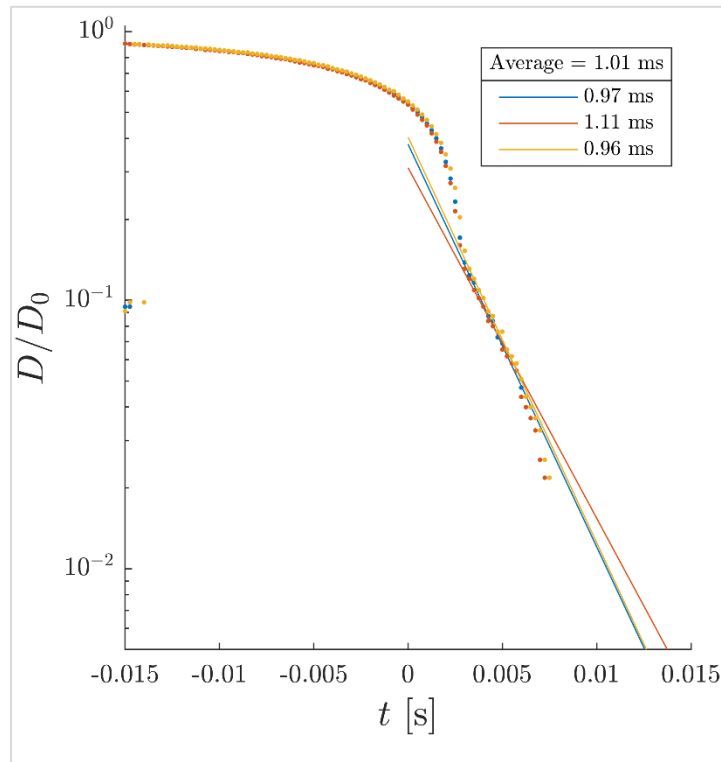Figure D.2.4d: D/D_0 versus t plot for 50% DR, Re: 90000.
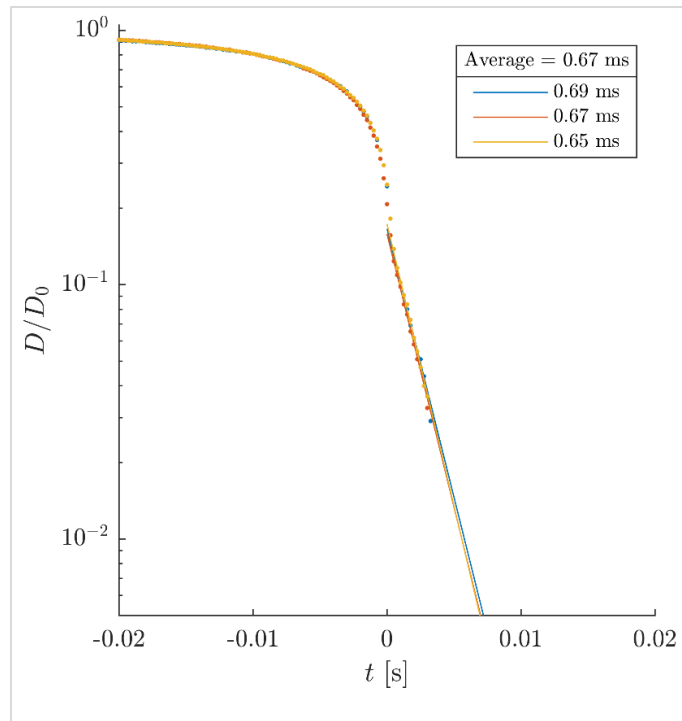
Figure D.2.4e: D/D_0 versus t plot for 50% DR, Re: 100000.

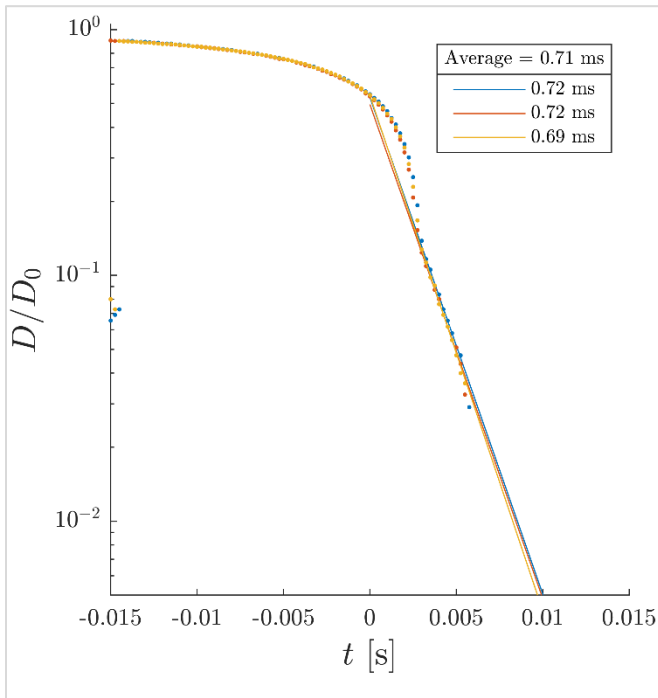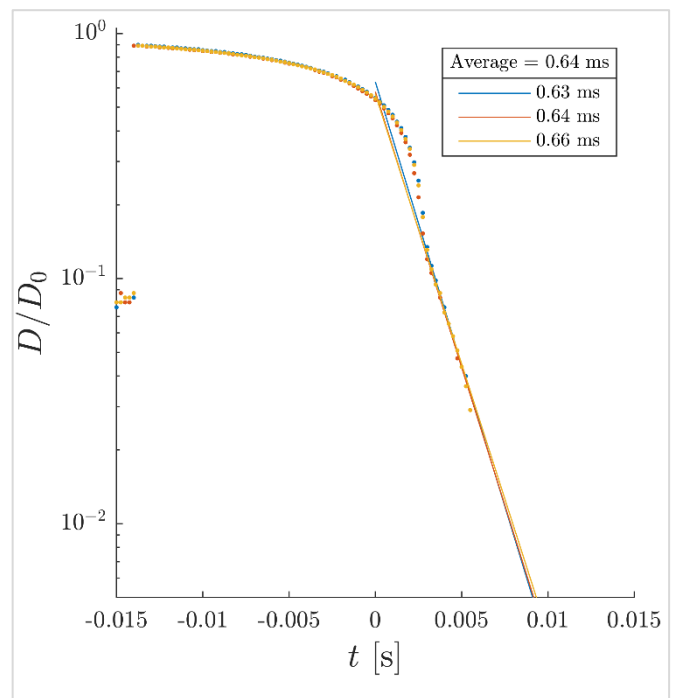## D.2.5 Plots for 40% DR (data acquisition rate: 9000 fps)

Figure D.2.5a: D/D_0 versus t plot for 40% DR, Re: 60000.

Figure D.2.5b: D/D_0 versus t plot for 40% DR, Re: 70000.

Figure D.2.5c: *D/D₀* versus *t* plot for 40% DR, Re: 80000.

Figure D.2.5d: *D/D₀* versus *t* plot for 40% DR, Re: 90000.

Figure D.2.5e: *D/D₀* versus *t* plot for 40% DR, Re: 100000.

D.2.6 Plots for 30% DR (data acquisition rate: 12000 fps)

Figure D.2.6a: *D/D₀* versus *t* plot for 30% DR, Re: 60000.

Figure D.2.6b: *D/D₀* versus *t* plot for 30% DR, Re: 70000.

Figure D.2.6c: *D/D₀* versus *t* plot for 30% DR, Re: 80000.

Figure D.2.6d: *D/D₀* versus *t* plot for 30% DR, Re: 90000.

Figure D.2.6e: *D/D₀* versus *t* plot for 30% DR, Re: 100000.

D.2.7 Plots for 20% DR (data acquisition rate: 12000 fps)

Figure D.2.7a: *D/D₀* versus *t* plot for 20% DR, Re: 60000.

Figure D.2.7b: *D/D₀* versus *t* plot for 20% DR, Re: 70000.

Figure D.2.7c: *D/D₀* versus *t* plot for 20% DR, Re: 80000.

Figure D.2.7d: *D/D₀* versus *t* plot for 20% DR, Re: 90000.

Figure D.2.7e: *D/D₀* versus *t* plot for 20% DR, Re: 100000.

D.3 (D/D_0) versus time (t) plots for test section with 2-inch ID

D.3.1 Plots for 60% DR (data acquisition rate: 4000 fps)

Figure D.3.1a: D/D_0 versus t plot for 60% DR, Re: 60000.

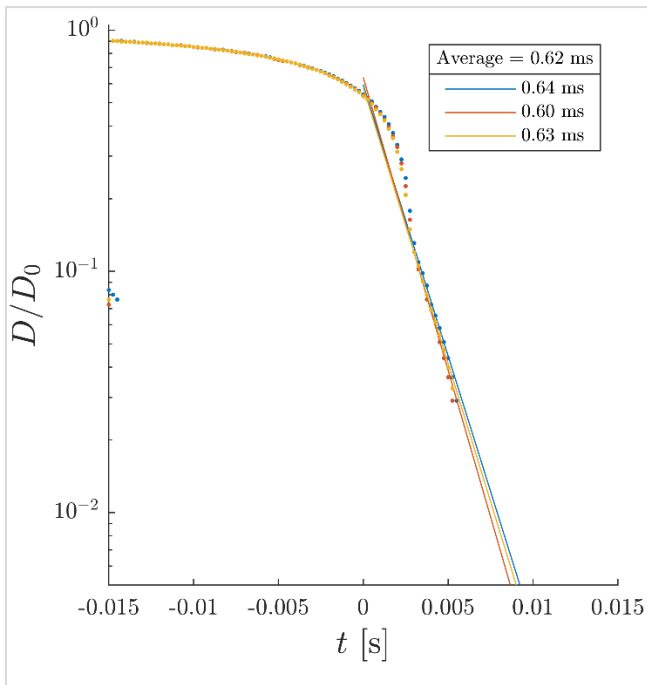Figure D.3.1b: D/D_0 versus t plot for 60% DR, Re: 70000.

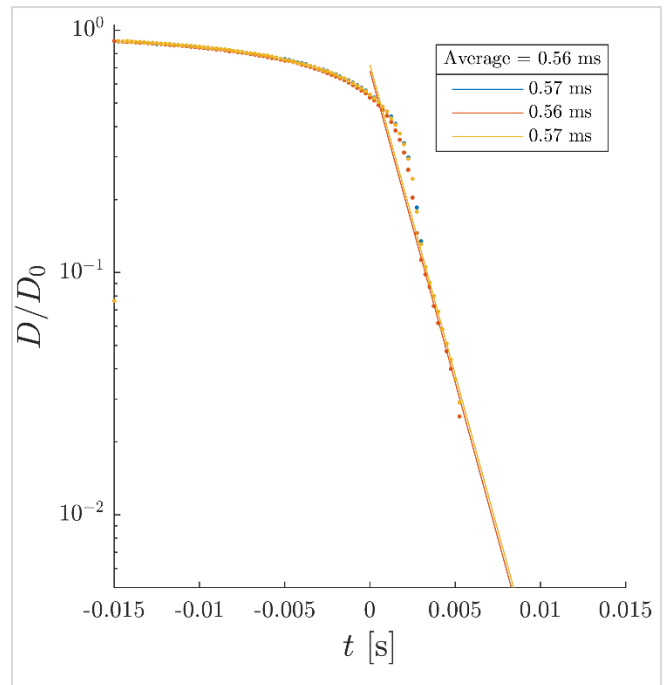Figure D.3.1c: D/D_0 versus t plot for 60% DR, Re: 80000.

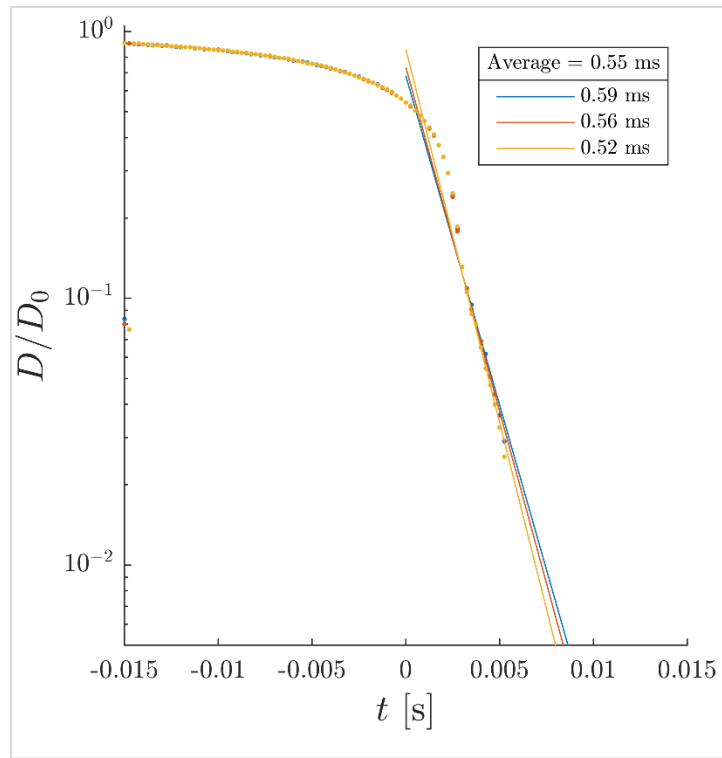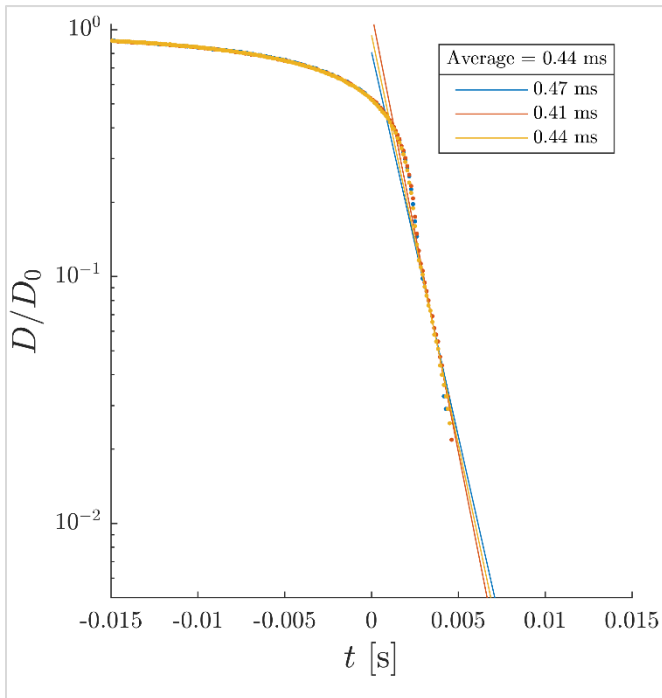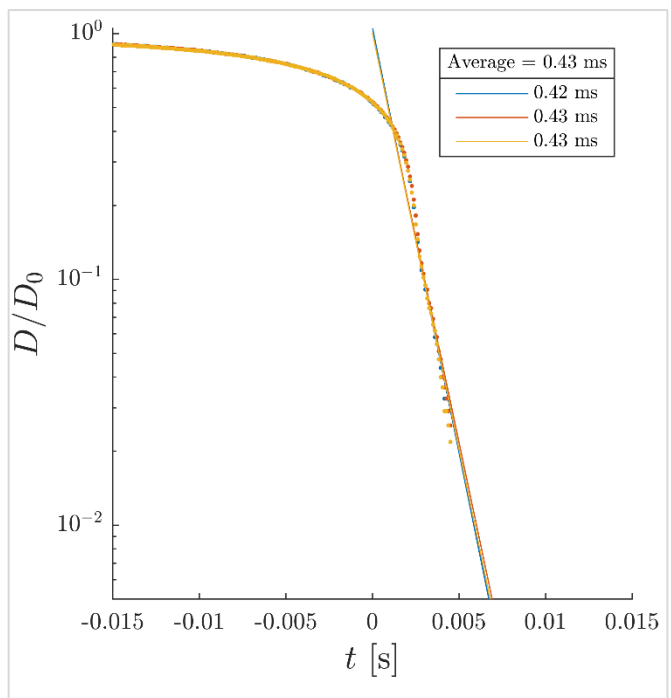Figure D.3.1d: D/D_0 versus t plot for 60% DR, Re: 90000.

Figure A.4.3.1.e: D/D$_0$ vs t plot – 60% DR – Re: 100k (June 28, 2023).

D.3.2 Plots for 50% DR (data acquisition rate: 4000 fps)

Figure D.3.2a: *D/D$_0$* versus *t* plot for 50% DR, Re: 60000.

Figure D.3.2b: *D/D$_0$* versus *t* plot for 50% DR, Re: 70000.

Figure D.3.2c: *D/D₀* versus *t* plot for 50% DR, Re: 80000.

Figure D.3.2d: *D/D₀* versus *t* plot for 50% DR, Re: 90000.

Figure D.3.2e: *D/D₀* versus *t* plot for 50% DR, Re: 100000.

D.3.3 Plots for 40% DR (data acquisition rate: 4000 fps)

Figure D.3.3a: D/D_0 versus t plot for 40% DR, Re: 60000.

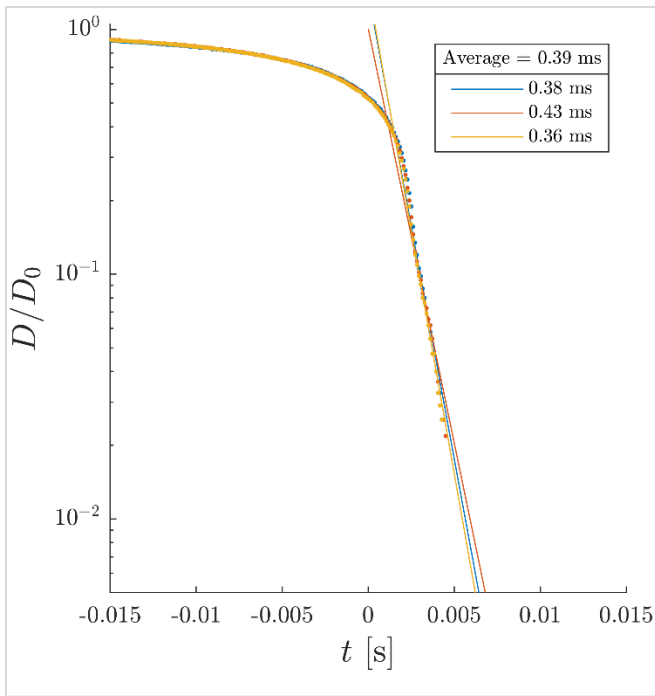Figure D.3.3b: D/D_0 versus t plot for 40% DR, Re: 70000.

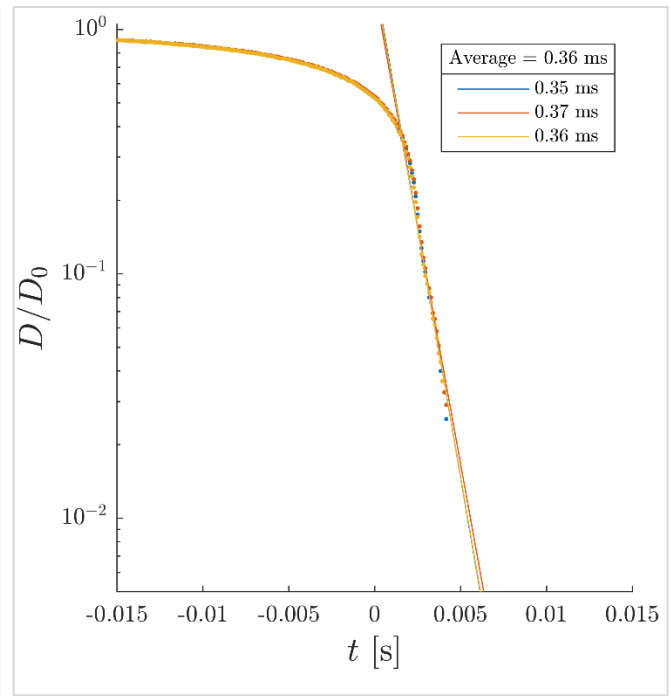Figure D.3.3c: D/D_0 versus t plot for 40% DR, Re: 80000.

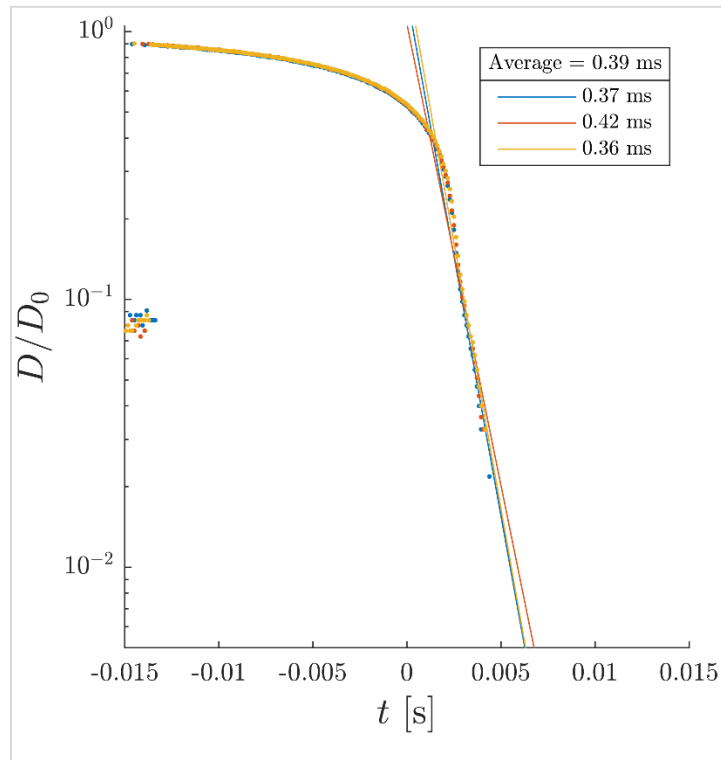Figure D.3.3d: D/D_0 versus t plot for 40% DR, Re: 90000.

Figure D.3.3e: *D/D₀* versus *t* plot for 40% DR, Re: 100000.

D.3.4 Plots for 30% DR (data acquisition rate: 9000 fps)

Figure D.3.4a: *D/D₀* versus *t* plot for 30% DR, Re: 60000.

Figure D.3.4b: *D/D₀* versus *t* plot for 30% DR, Re: 70000.

Figure D.3.4c: *D/D₀* versus *t* plot for 30% DR, Re: 80000.

Figure D.3.4d: *D/D₀* versus *t* plot for 30% DR, Re: 90000.

Figure D.3.4e: *D/D₀* versus *t* plot for 30% DR, Re: 100000.

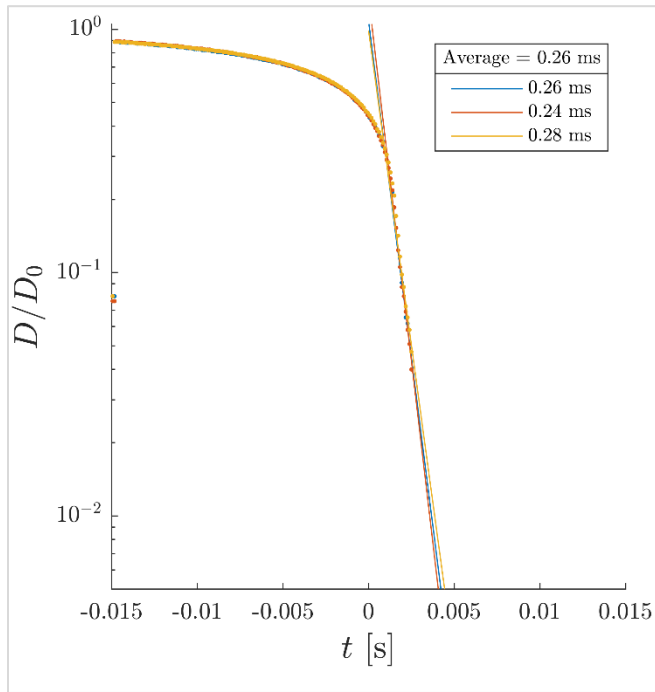# D.3.5 Plots for 20% DR (data acquisition rate: 9000 fps)

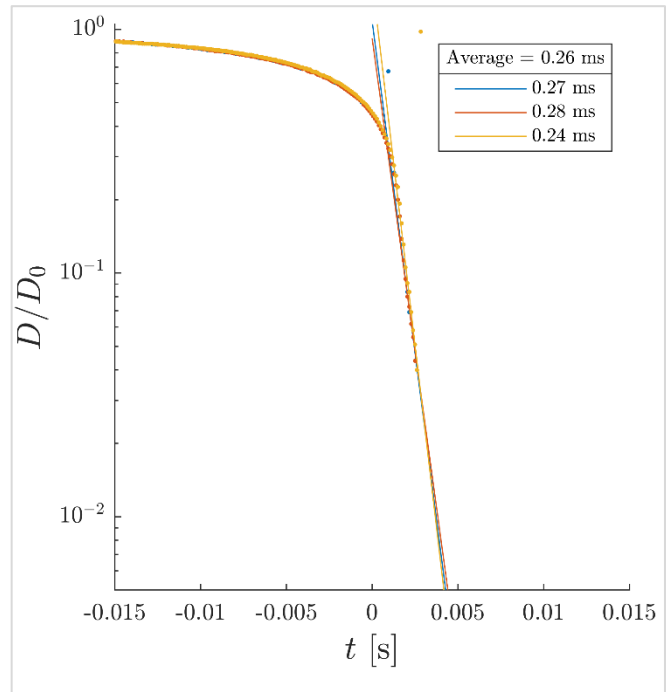Figure D.3.5a: D/D_0 versus t plot for 20% DR, Re: 60000.

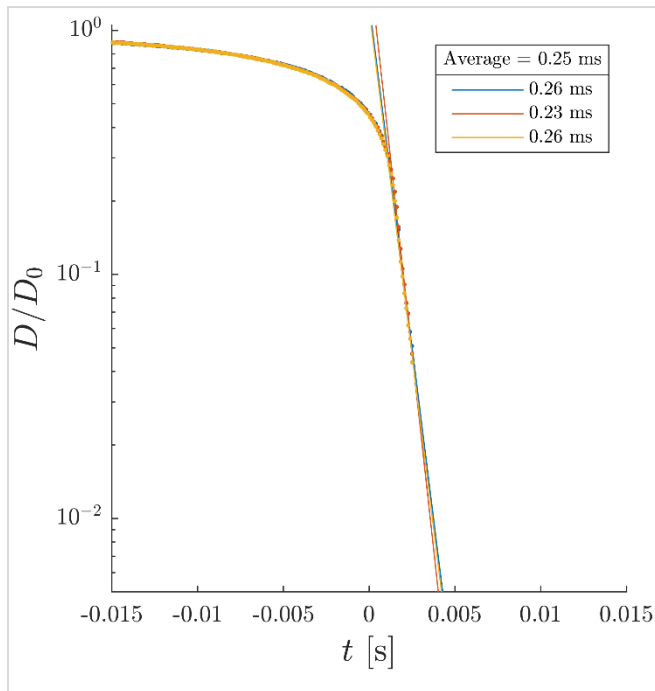Figure D.3.5b: D/D_0 versus t plot for 20% DR, Re: 70000.

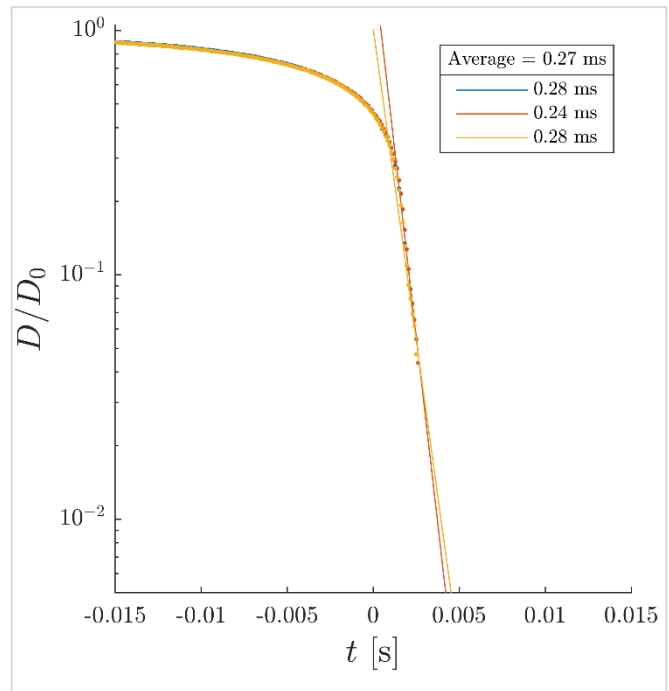Figure D.3.5c: D/D_0 versus t plot for 20% DR, Re: 80000.

Figure D.3.5d: D/D_0 versus t plot for 20% DR, Re: 90000.

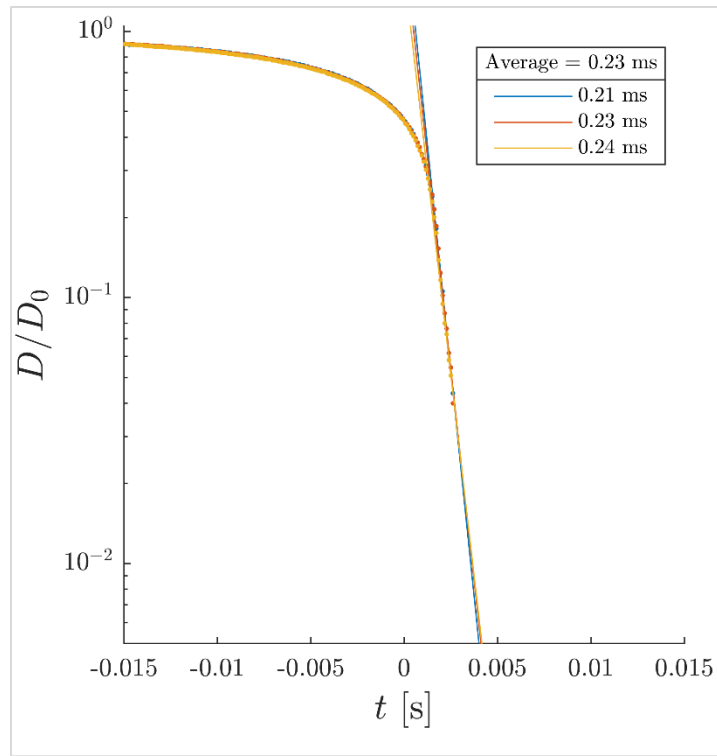Figure D.3.5e: *D/D₀* versus *t* plot for 20% DR, Re: 100000.

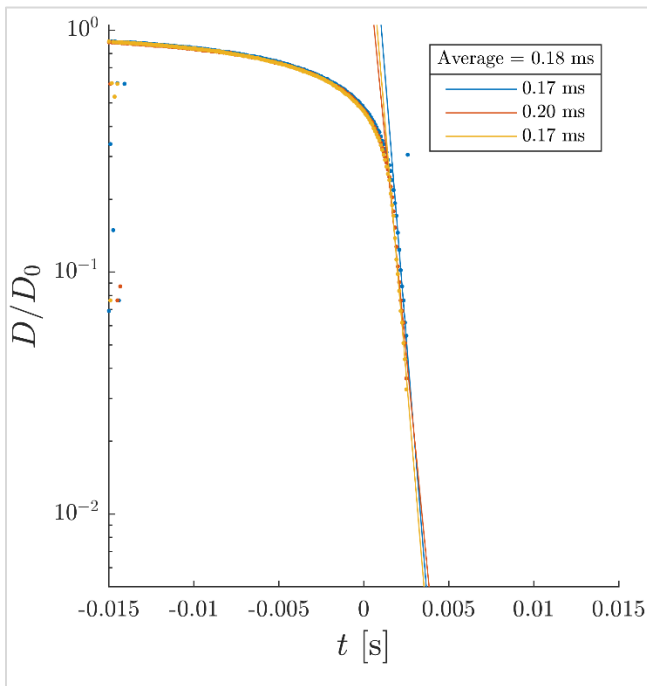## D.3.6 Plots for 10% DR (data acquisition rate: 12000 fps)

Figure D.3.6a: *D/D₀* versus *t* plot for 10% DR, Re: 60000.

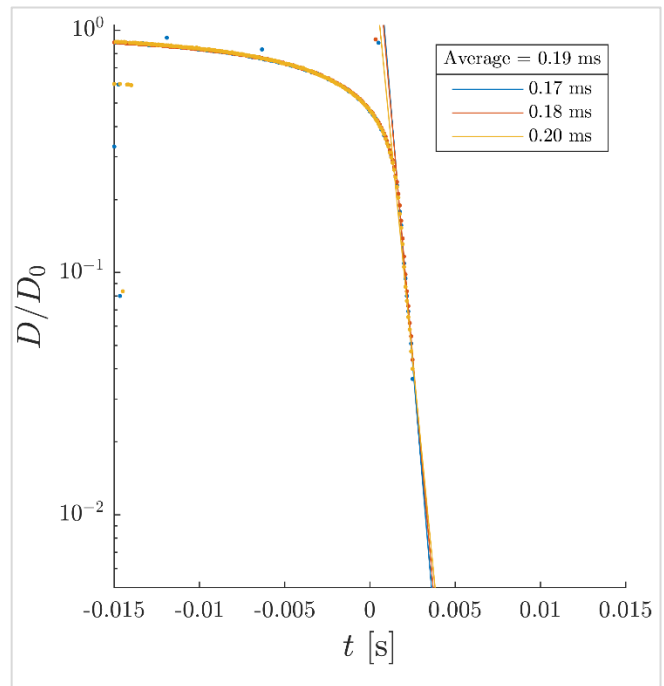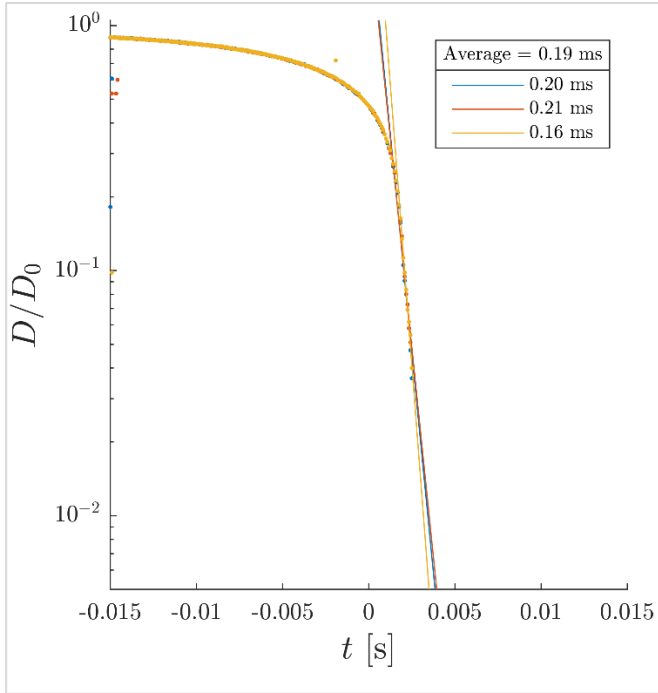Figure D.3.6b: *D/D₀* versus *t* plot for 10% DR, Re: 70000.

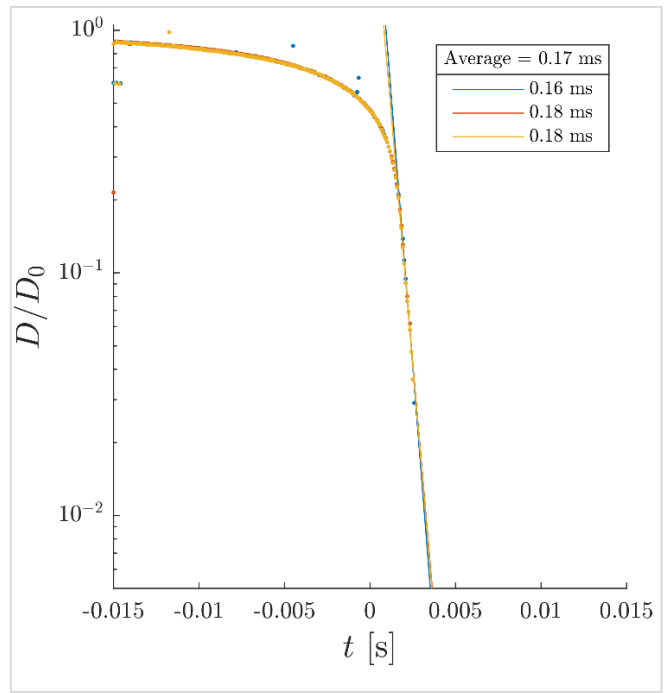Figure D.3.6c: *D/D₀* versus *t* plot for 10% DR, Re: 80000.

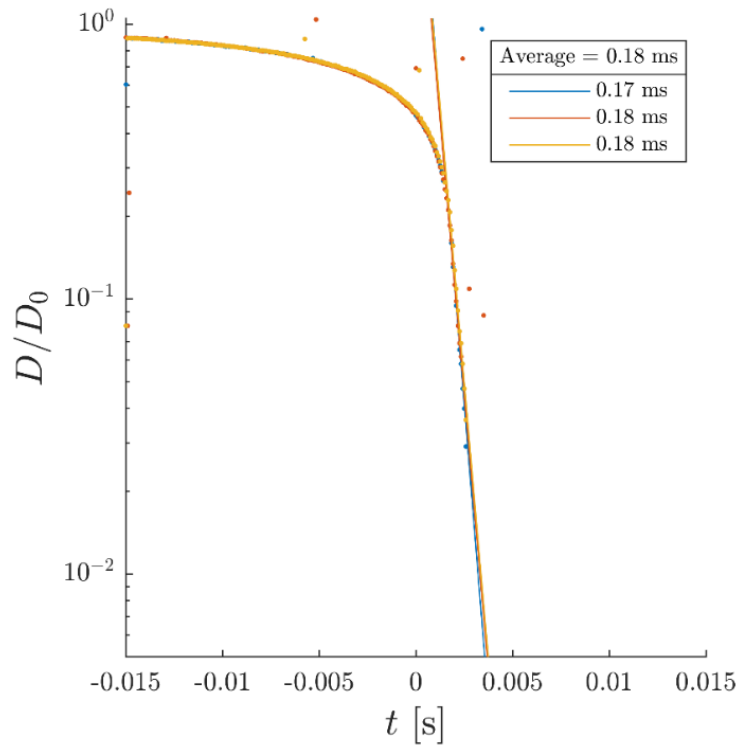Figure D.3.6d: *D/D₀* versus *t* plot for 10% DR, Re: 90000.

Figure D.3.6e: *D/D₀* versus *t* plot for 10% DR, Re: 100000.

Appendix E

Safe operating procedure for diesel flow loop

Process: diesel flow loop – start up – operation – shut down

Department/faculty: mechanical engineering

Location (room # and building): 3-31, MECE

Supervisor: Sina Ghaemi   Phone #: 780-248-2056   Email: ghaemi@ualberta.ca

Emergency contact: +1 (403) 923-4647 (Satyajit Singh)

After-hours contact: +1 (403) 923-4647 (Satyajit Singh)

Scope:

This document details the safe operating procedure for the start-up, operation and shut down of the diesel flow loop in MECE 3-31.
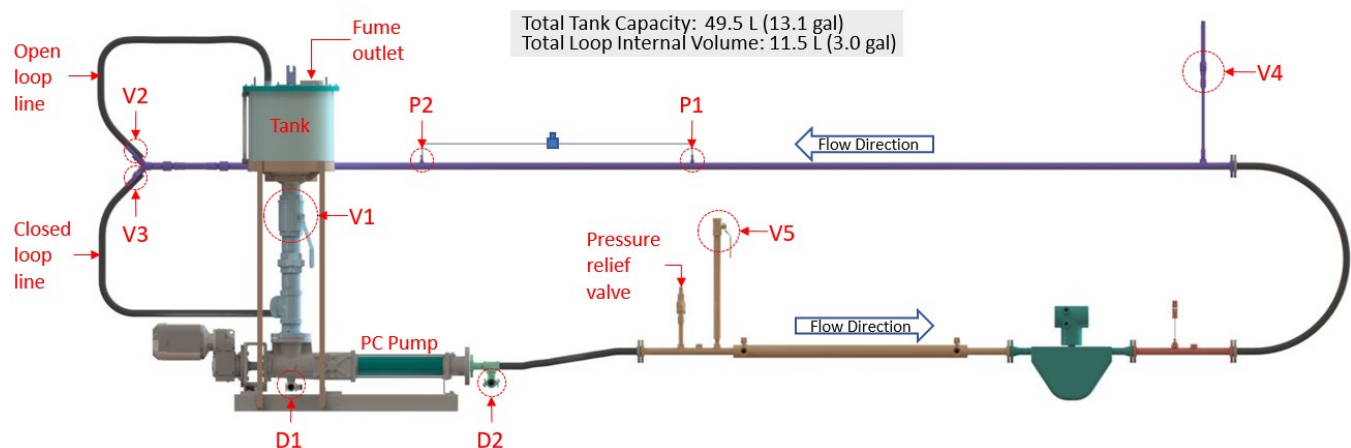
Hazard identification:

1. Diesel may spill while filling up the tank.
2. Diesel may leak from any pipe joint
3. While running the pump if the correct valve configuration is not followed, the system can be over pressurized activating the pressure relief valve, this may damage the pump and/or compromise any joints.
4. A spark can be a fire hazard if any electrical equipment is not grounded.

5. Diesel fumes can cause irritation if not properly ventilated.

6. Running the pump empty can cause internal damage and unsafe working conditions.

Control/protective measures:

1.1. Use the 5-gallon portable diesel can with spill protection to fill the tank.

1.2. In case of spill, use the diesel compatible spill kit available and accessible in the lab.

2.1. The entire loop teak test was performed with compressed air prior to filling the loop for the first time.

2.2. Metal spill trays (2) are present and are in correct position to ensure spill containment.

3.1. The below show valve configuration must be followed for each type of operation.

Operation	Filling tank		Filling loop		Open loop run		Closed loop run		Draining loop		Pressurized drain	
	Valve	Open / Closed	Valve	Open / Closed	Valve	Open / Closed	Valve	Open / Closed	Valve	Open / Closed	Valve	Open / Closed
	V1	CLOSED	V1	OPEN	V1	OPEN	V1	CLOSED	V1	OPEN	V1	CLOSED
	V2	CLOSED	V2	OPEN	V2	OPEN	V2	CLOSED	V2	OPEN	V2	CLOSED
	V3	CLOSED	V3	OPEN	V3	CLOSED	V3	OPEN	V3	OPEN	V3	OPEN
Valve Configuration	V4	CLOSED	V4	OPEN	V4	CLOSED	V4	CLOSED	V4	OPEN	V4	OPEN
	V5	CLOSED	V5	CLOSED	V5	CLOSED	V5	CLOSED	V5	CLOSED	V5	CLOSED
	D1	CLOSED	D1	CLOSED	D1	CLOSED	D1	CLOSED	D1	OPEN	D1	OPEN
	D2	CLOSED	D2	CLOSED	D2	CLOSED	D2	CLOSED	D2	OPEN	D2	OPEN
	P1	CLOSED	P1	CLOSED	P1	CLOSED	P1	CLOSED	P1	CLOSED	P1	CLOSED
	P2	CLOSED	P2	CLOSED	P2	CLOSED	P2	CLOSED	P2	CLOSED	P2	CLOSED
VFD Status	OFF		OFF		ON		ON		OFF		OFF	

3.2. Ensure the pressure relief valve exit pipe is securely placed into the splash proof, diesel compatible container provided.

4. All electrical equipment and metal framing are properly grounded.

5. Proper ventilation with a correct flow rate is ensured at any place where diesel is exposed to the environment.

6. Pump must never run empty. Refer to point 4.1 for VFD status to follow for different operations.

Tools, materials, equipment, and PPE:

1. Safety glasses.
2. Lab coat (only while filling and draining the loop).
3. Nitrile gloves (only while filling and draining the loop).

Emergency procedures:

1. In case of small fire (size of a trash bin), Use the fire extinguisher, refer to appendix E.1 for procedure.

2. In case of bigger fire, STOP operations, pull the alarm and evacuate, refer to appendix E.1 for procedure.

3. In case of a small spill or leak, STOP pump immediately and use the diesel spill kit to contain it.

4. In case of larger spills, refer to appendix E.2 for hazardous spill response procedure.

5. In case of over pressurization and activation of pressure relief valve.

    5.1 Stop the pump immediately.

    5.2 Ensure no spill around the pressure relief valve, if there is spill follow step 3 or 4.

    5.3 Verify the loop to check for leaks from any other location.

    5.4 Verify that correct valve configuration is followed.

    5.5 If leak is observed, drain loop safely and completely, then perform root cause analysis.

Step by step procedure

Filling the loop:
1. Ensure all personals are wearing the required PPE.
2. Ensure all valves are closed prior to filling the tank.
3. Use proper height ladder / step stool to manually fill the tank through the fume outlet port.
4. Ensure correct volume by monitoring the sight gauge on the tank.
5. Replace the exhaust duct over the fume outlet once the tank is filled.
6. Ensure the valve configuration for filling the loop as mentioned above in the following order: V4→V2→V3→V1.
7. After gravity assisted fill is completed, set open loop valve configuration by closing V3 then closing V4 (V1 and V2 must be open).
8. Turn ON the VFD and start the pump at 8 Hz to let the open loop line get filled with diesel.
9. Now ensuring V1 and V2 are open, open V3 intermittently and close to flush the close loop line.
10. Now the flow can be adjusted by VFD to de-air the system.

Draining the loop:
1. Ensure VFD is OFF.
2. Attach the two drain-hoses to their respective drain port and place the steel pan under it.
3. Ensuring the hose ends are securely placed in the drain barrel. Then set the valve configuration to drain.
4. Now let the loop drain by gravity. Leave it for 10 minutes.
5. Once gravity drain is complete, set the valve configuration to closed loop.
6. Attach the compressed air hose to the inlet above V4.
7. Ensure the pressure regulator is set at 20 PSI.
8. Now, open V4 for 30 seconds to pressurize the loop at 20 PSI, then close V4
9. With the loop under pressure, open D1 releasing the pressure along with the remaining fluid into the barrel. Once de-pressurized, close D1.
10. Repeat step 8, followed by opening D2, releasing the pressure along with the remaining fluid into the barrel. Once de-pressurized, close D2.
11. Repeat steps 8, 9, and 10 two more times with a 10-minute gap between each attempt to let the fluid settle down.
12. Once drain completes, set to close loop valve configuration and remove the two drain hoses carefully dripping any leftover diesel in the steel pan.
13. Empty the pan in the barrel and secure the hose and pan at their designated location.
14. Move the diesel barrel to the fuel room safely.

Prepared By: Satyajit Singh   Date: 17th September 2023

Approved by (supervisor): Dr. Sina Ghaemi   Date:

WHAT TO DO
IN CASE OF FIRE

IF YOU DISCOVER A FIRE

- Extinguish the fire if it is safe to do so.
- If you cannot extinguish it:
  ○ Close all doors to prevent the spread of fire and smoke.
  ○ Pull the manual fire alarm near the marked fire exit.
  ○ Evacuate to the building muster point.
- Call 911 and then 780-492-5050.

IF YOU HEAR AN ALARM

- Evacuate the building immediately via the closest exits.
- DO NOT USE ELEVATORS.
- Report to the muster point.

IF YOUR EXIT IS BLOCKED

- Try another exit.
- If both exits are unsafe, stay in an area away from smoke or flame and call 911 and then 780-492-5050.

IF YOU ARE IN A WHEELCHAIR OR OTHERWISE MOBILITY IMPAIRED

- Move to an exit stairwell, or
- Move to the elevator lobby or to a safe location.
- If possible, close the door.
- Send a runner to meet the Fire Department or Protective Services, or
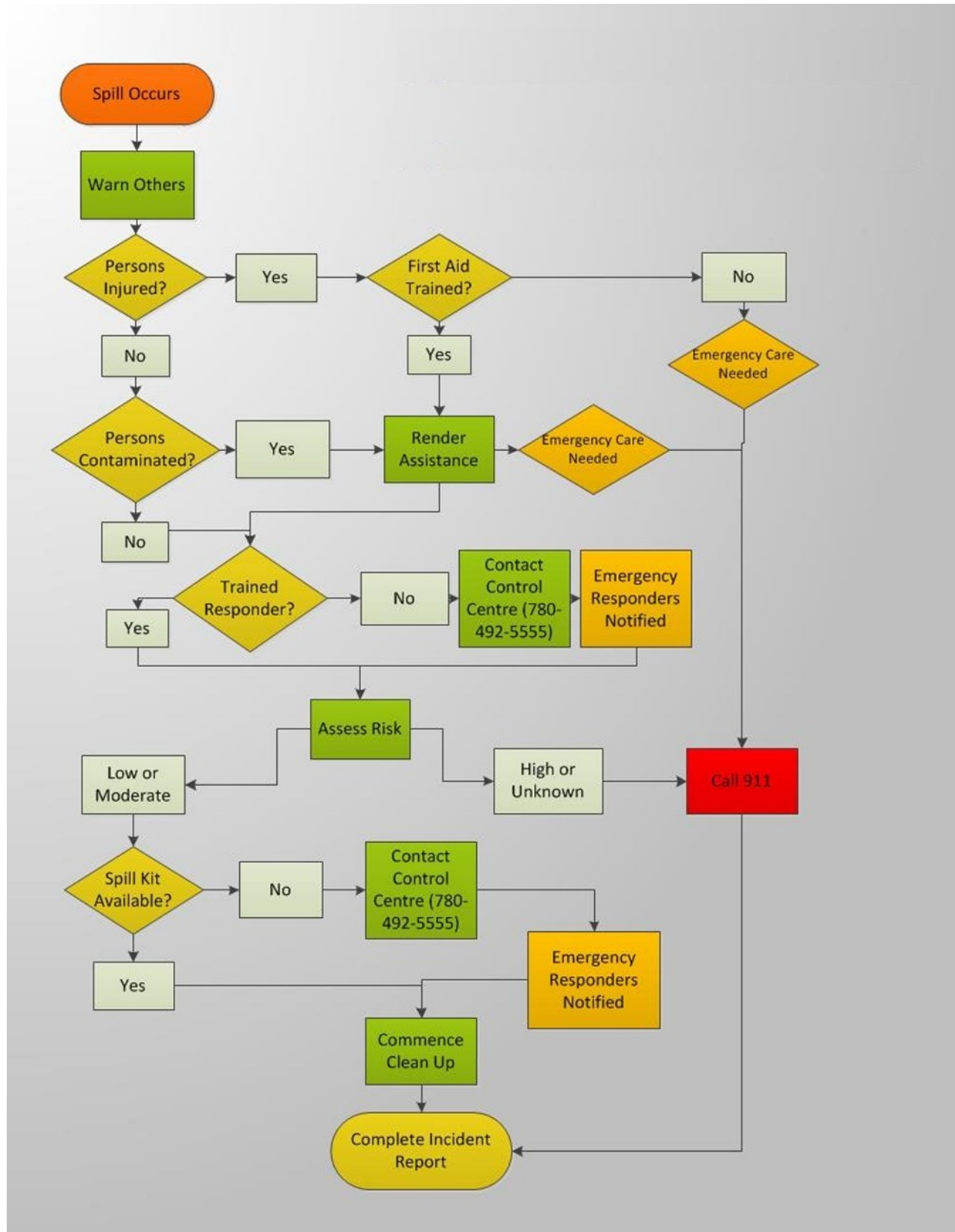- Call 911 and then 780-492-5050 and tell them where you are.

KNOW YOUR EMERGENCY PLAN AND PRACTICE IT

- Where are your exits?
- Where are the exit stairs?
- Where are manual fire alarm pull stations?
- Where are the fire extinguishers?

All fires can be deadly! After you get out, stay out!
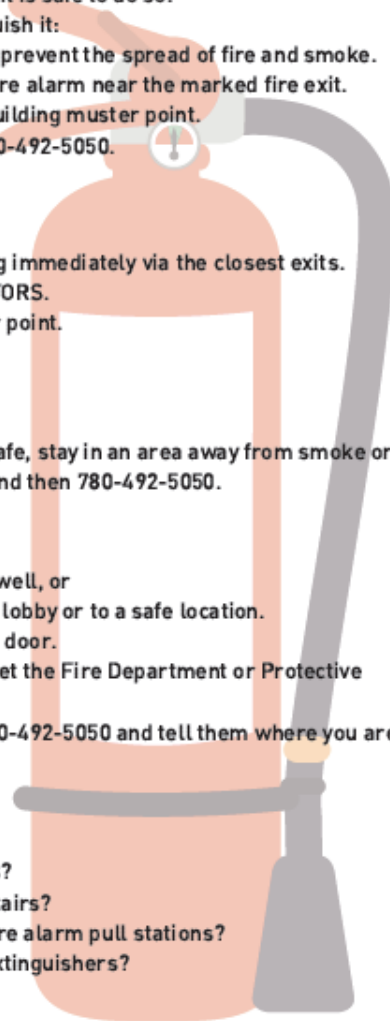
Appendix − E.2

Appendix F

NETZSCH PC pump drawing and curve.

This section presents the engineering drawing for the NM038 model pump-motor assembly, and the pump curve as provided by the pump supplier NETZSCH Canada, Inc.
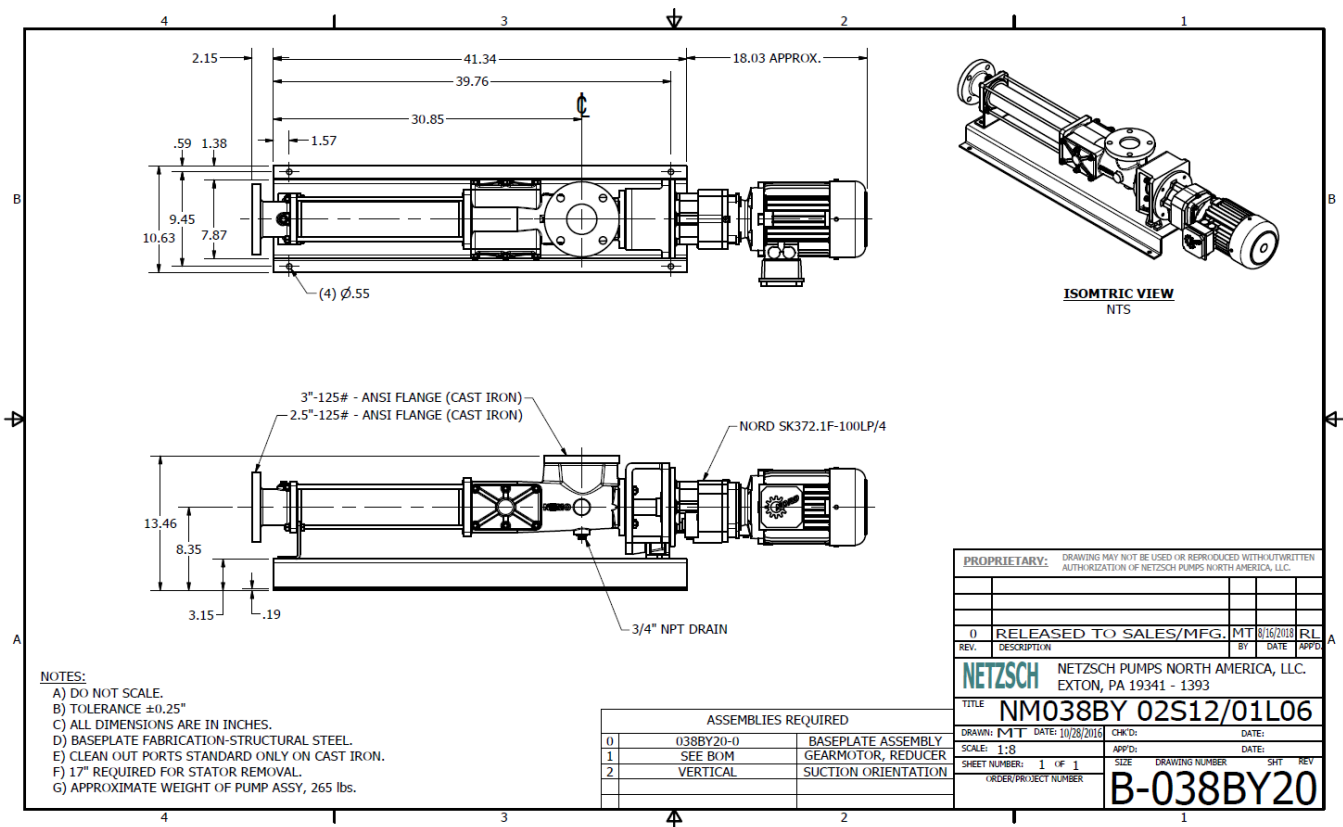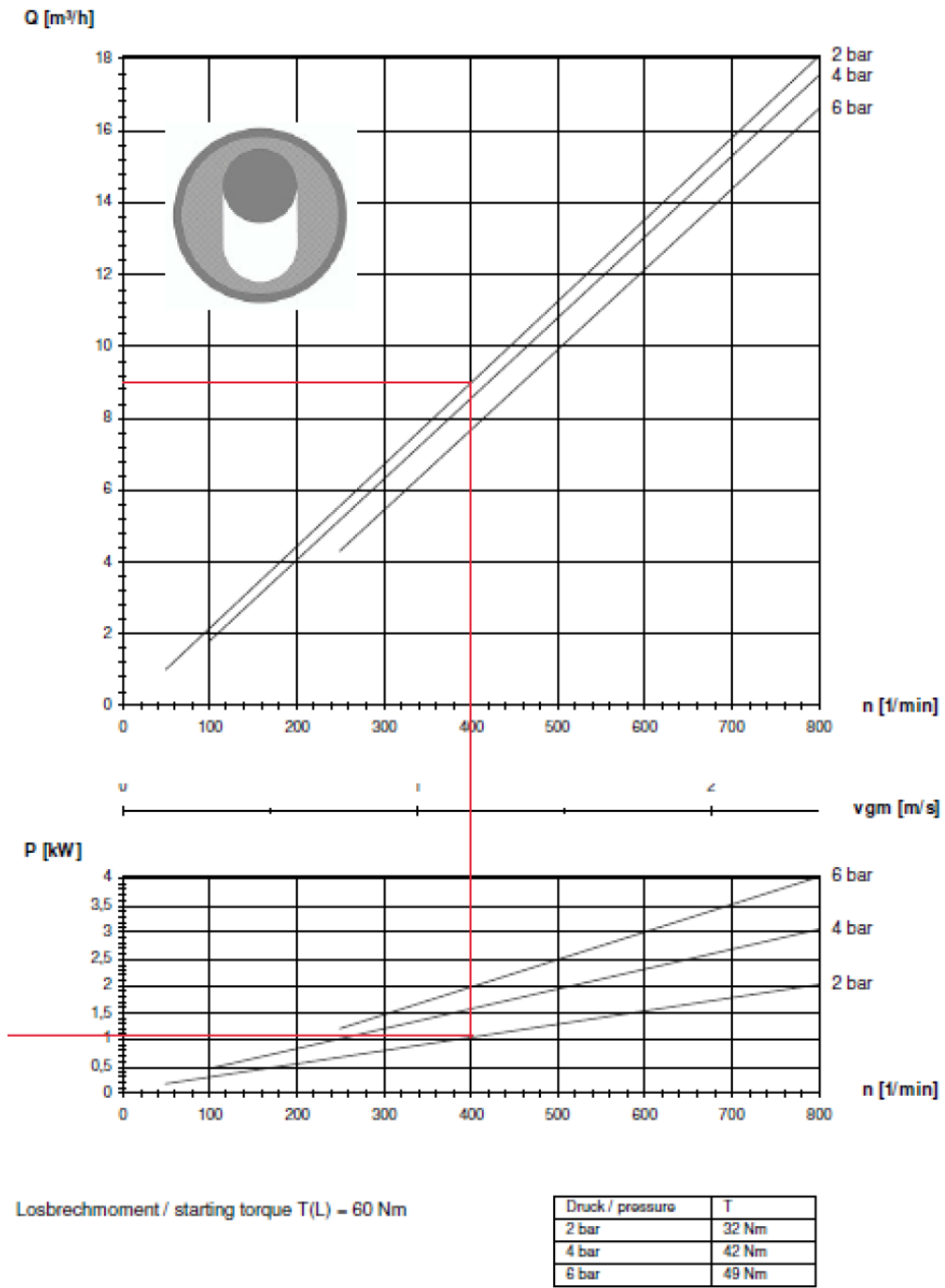

Figure F1: Engineering drawing for NM038 model pump-motor assembly provided by NETZSCH Canada, Inc.

Q [m³/h]

18
16
14
12
10
8
6
4
2
0

2 bar
4 bar
6 bar

0   100   200   300   400   500   600   700   800   n [1/min]

vgm [m/s]

P [kW]

4
3,5
3
2,5
2
1,5
1
0,5
0

6 bar
4 bar
2 bar

0   100   200   300   400   500   600   700   800   n [1/min]

Losbrechmoment / starting torque T(L) = 60 Nm

Druck / pressure	T
2 bar	32 Nm
4 bar	42 Nm
6 bar	49 Nm

Gültigkeit für Wasser (1 cP) bei 20 ℃. Toleranzen nach VDMA 24284 (+10%/-5%).
Valid for water (1 cP) at 20 ℃ (70 ℉). Tolerances are in accordance with VDMA 24284 (+10%/-5%).

www.netzsch-pumpen.de

Figure F1: Pump curve for NM038 model pump-motor assembly provided by NETZSCH Canada, Inc.