THE UNIVERSITY OF ALBERTA

THE EFFECTS OF PLASMA JET HYDRODYNAMICS ON COMBUSTION

by

CRAIG WEST

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"The Effects Of Plasma Jet Hydrodynamics On Combustion"

SUBMITTED BY, Charles Craig West

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ABSTRACT

Studies of spark ignition devices over the past decade have revealed several key advantages of plasma jet ignition over conventional systems. Through expulsion of a highly reactive plasma plume, the device creates a turbulent puff which propagates into the surrounding medium, inducing local mixing. The ability to create electrically induced turbulence has provided substantial enhancement in both flame velocity and burning rate.

In the research described here, the influence of plasma jet ignition upon the very early stages of combustion has been investigated in a series of closed vessel measurements. The rate of pressure increase in the very early stages is monitored with a new optical method of pressure measurement. A comparative study examines the ignition and combustion performance of plasma jets against conventional ignition methods. It is found that in near-limit mixtures, the turbulence created by plasma jets disrupts early stage combustion.

From plasma jet studies, it became apparent that (if operated repetitively within the bounds of an air duct) the successive impulses generated by the jet can produce a constant flow of air. Investigation confirmed that high frequency operation was capable of creating substantial flows. Given appropriate circumstances, this feature could

effectively transform a fuel rich, incombustible mixture into one capable of sustaining combustion through air injection.

The effect of injected air and of repetitive igniter operation were examined in a prototype flare stack. The ignition system was exposed to many of the factors experienced by a field installation. Results indicated that the plasma jet igniter was able to improve ignition reliability over conventional ignition, especially for situations involving fluctuating mixture flows and high wind conditions.

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Most of all, I wish to thank and dedicate this thesis to my wife, Louise Marie. Without her endless supply of love, laughter, comfort, and persistant support, this thesis would have never become a reality. To my wife, best friend, and greatest treasure, love and thanks forever............

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1 INTRODUCTION

Combustion research is a field of chemistry and physics which deals with exothermic reactions between fuels and oxidants. Although simply stated, the nature of combustion itself and the parameters which govern its behaviour are complex. The process of gaseous hydrocarbon combustion is typically initiated by an external source heating a mixture of fuel and oxidant to a critical (ignition) temperature level. The reaction process between fuel and oxidant then becomes self-sustaining (flammable), continuing until the supply of fuel and/or oxidant is exhausted. The resultant combustion products are mainly composed of carbon dioxide and water.

For every fuel/oxidant combination, there exist two limits of flammability; the lean limit (excess oxidant) and the rich limit (excess fuel). Between these limits, combustion is possible for a variety of mixture concentrations (Figure 1.1, Kanury, [15]). Whether or not a particular mixture ignites depends upon the amount of heat energy delivered to the mixture by the ignition source (deposition energy). The boundary curve in Figure 1.1 indicates the minimum deposition energy required to attain ignition for a specific mixture concentration.

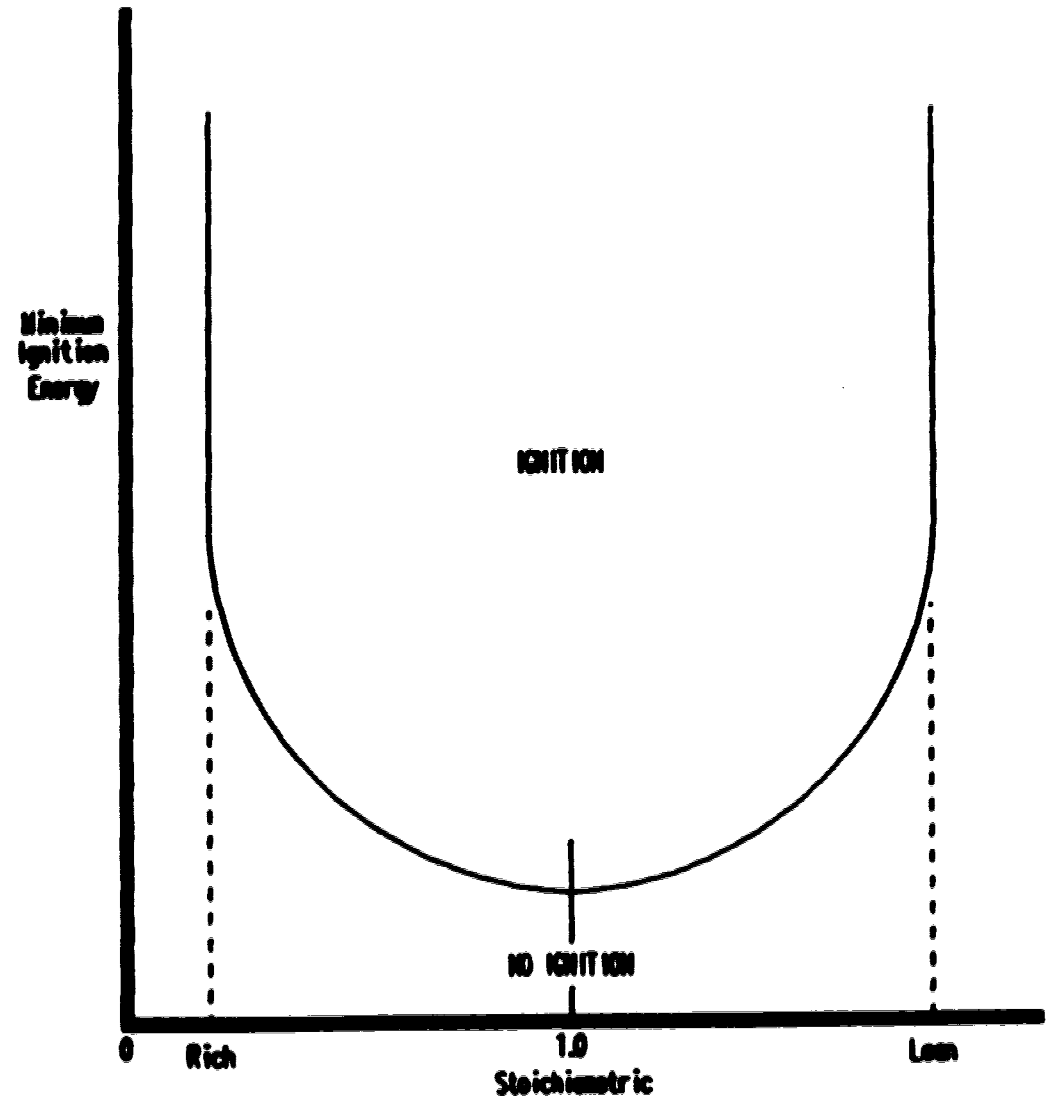

Figure 1.1 Flammability Limits

Automotive combustion research is a specialized field focused on harnessing the energy produced by fuel/air combustion for mechanical work. Lean mixture combustion is of particular interest primarily for improved fuel economy and reduced pollution (Dale et al. [3], Gettel et al. [4]). Lean combustion, however, is characterized by reduced reaction rates which decrease the mechanical conversion efficiency of the process. One possible solution is the development of ignition sources which can increase reaction rates and the speed of flame propagation. One such device is the plasma jet igniter (Figure 1.2).

Combustion by plasma jet ignition has provided marked increases in reaction rates and flame propagation ([1], [5], [7], [9], [12]). Plasma jet igniters exhibit two unique advantages over conventional devices, such as open electrode igniters (Cetegen et al. [1]). As a consequence of the plasma penetrating into the surrounding mixture, combustion is initiated away from the combustion chamber walls, thereby reducing heat loss. Secondly, the combustion process is enhanced by an increase in flame front surface area, created by induced turbulence from the expelled plasma.

Illustrated in Figure 1.2, the process of plasma propagation is initiated by the discharge of a high voltage transient into the igniter cavity, ionizing the gas within. Rapid deposition of source energy into the cavity creates intense temperature and pressure gradients, causing the dissociated gas to expand. The ensuing pressure rise expels a plasma jet out through the orifice, where it penetrates into the surrounding gas atmosphere (Weinberg [17]). The jet of plasma then degrades into a turbulent, gaseous plume capable of propagating beyond the developing flame front. The plume continues to persist long after source discharge termination (Topham et al. [11]). The turbulence is independent of plasma chemistry (Weinberg [12]) and results from flow instabilities along the plume envelope. Turbulence has been shown to be instrumental in improving the transport processes within the flame front of combustible mixtures (Smy et al. [10]).

Optimisation of plasma jet performance requires consideration of several governing parameters. Specifically these are:

(a) plasma medium composition

(b) cavity geometry

(c) deposition energy

(d) discharge period

Plasma composition is primarily dictated by the gas residing in the cavity, which may be foreign (feed gases from other sources), or that surrounding the igniter. The resulting chemistry of the expelled plasma plays a significant role in enhancing the burning velocity of the combustion mixture (Weinberg [17]).

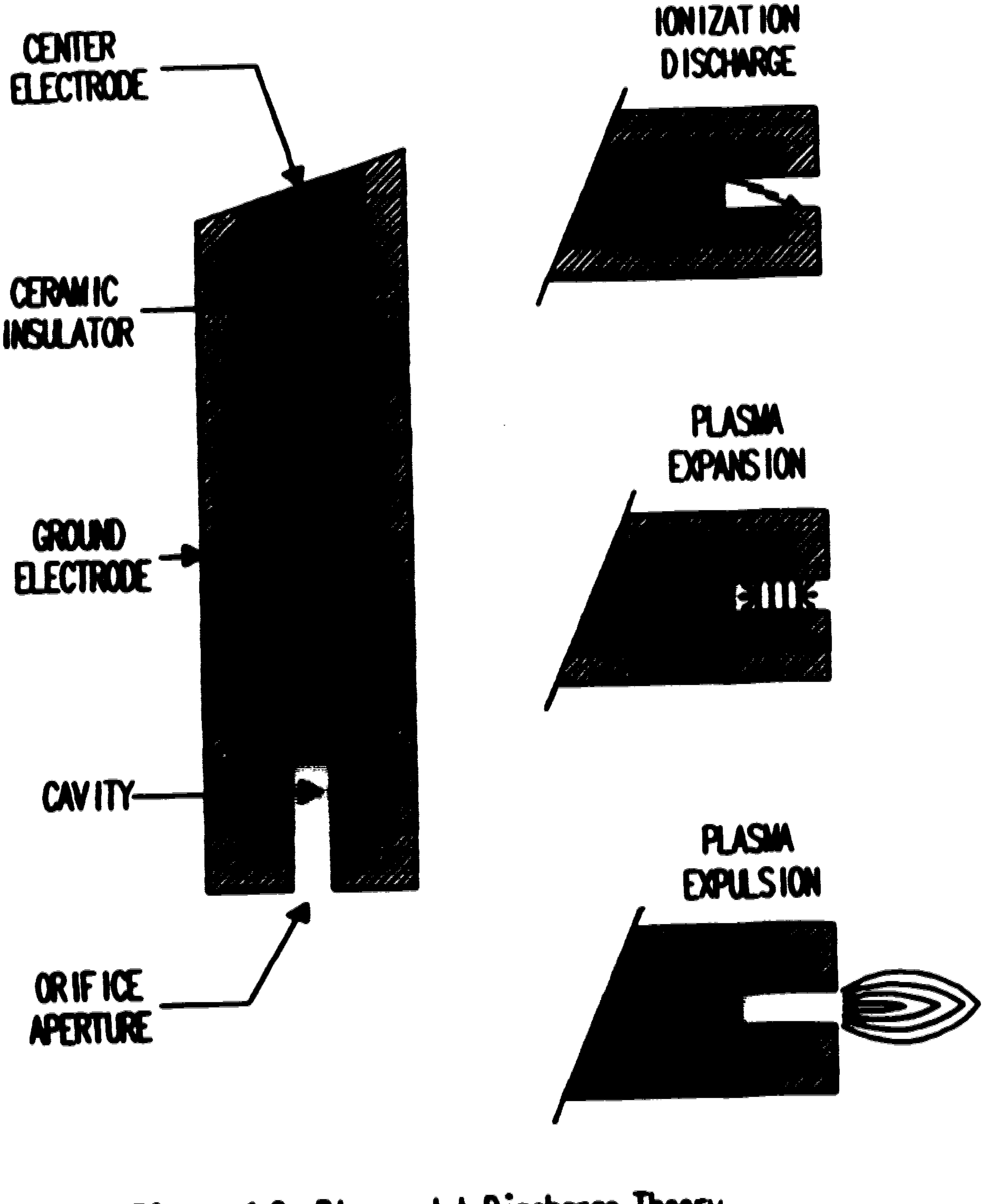

Figure 1.2 Plasma Jet Discharge Theory

Cavity geometry (orifice diameter and length) dictates ejected plasma velocity, cavity mass flow, and the quenching of expelled reactives (Grant et al. [5]). Velocity and mass flow directly influence the depth of plasma penetration into the surrounding gas, as well as the amount of induced turbulence.

Plasma jet characteristics may be altered, by electrically controlling the velocity and mass flow of the plasma. Deposition energy and discharge period can be continuously altered to modify the plasma jet for applications where operating conditions are constantly fluctuating, such as in an automobile engine. Increased deposition energy produces higher initial temperatures, thereby increasing the initial rate of reaction (Mittinti et al. [7]). Shortened discharge periods improve the transfer efficiency of source energy to the cavity gas, thereby increasing deposition energy and overall system efficiency (Maley [6]).

The effects of ignition parameters on eraly stage ignition are investigated in Chapter Two including combustion performance near the lean flammability limit. Igniter induced turbulence and deposition energy are of particular interest. These studies are conducted in a bomb or combustion vessel environment, providing control over mixture and ignition variables. This enclosed environment also allows measurement of the behaviour of various combustion processes.

The investigation of igniter induced turbulence was prompted by reports which indicate that the turbulent nature of plasma jet operation can be counter-productive near the lean limit ([2], [8], [12], [13]). These reports suggest that although turbulence is beneficial to flame propagation, it is destructive to flame development in early stage combustion (induces flame extinction). Given that lean mixtures have decreased flame development and propagation rates, the effects of turbulence may become more pronounced as the lean limit is approached. This may dictate limits to the useful range for enhanced combustion by plasma jets.

The effects of igniter induced turbulence are investigated for three igniters, differing in electrode geometry. The ignition characteristics of two plasma jet geometries and a surface gap igniter are explored for several normalized lean mixtures (the ratio of experimental air/fuel mixture to stoichiometric (1.0)). Each igniter is examined for ignition and combustion performance, including the limits of useful operation.

Unlike plasma jet operation, the surface gap device produces virtually no gas turbulence. This absence of ignition turbulence provides an opportunity to study the contribution of deposition energy alone, and also allows comparison with turbulent ignition. From this study, a relationship between the electrical energy dissipated in the local gas and the degree of partial combustion is developed. The study also provides clues as to why partial combustion fails to transform into self-sustaining, full scale combustion.

The phenomenon of partial combustion also focuses attention on the lean flammability limit itself and how it is defined. Determination of the lean flammability limit for air/fuel mixtures neglects ignition influences (Lefebvre [16]). The effects of ignition turbulence on both the position and description of the lean flammability limit are investigated.

To aid in the study of lean combustion processes, a new technique for pressure measurement was developed which provided improved sensitivity and response over conventional piezoelectric pressure transducers. The technique employs the principles of laser interferometry, which is capable of detecting very small perturbations in gas pressure through the interference of laser light. Resultant interference patterns are detected by a photomultiplier tube, significantly improving pressure measurements during early stage flame development and combustion. This optical method is combined with a piezoelectric transducer to achieve a complete pressure history of a combustion event. The combination of the two techniques was necessary to prevent the loss of late stage combustion information, undetected by the optical method due to laser beam distortion (the result of water vapour fogging the interferometer windows).

Chapter Three focuses on the hydrodynamics of plasma jets. In the past, plasma jet research has been directed towards the ignition aspects of the device. As a result of its operational nature and flow dynamics, it is proposed here that if given appropriate surroundings such as a restrictive tube, the plasma jet igniter might also be useful as a gas transport mechanism as well as an ignition source.

This property is particularly useful if one is attempting to ignite an incombustible mixture outside the rich flammability limit. This over-rich mixture can be transformed into a combustible state by pumping external air into the mixture zone using repetitive plasma jet operation. Experimental information of this process also provides insight into the complex flows created by such igniters in the absence of restrictive boundaries. The analysis of the steady-state flow properties generated by a repetitively energised igniter is simplified to the measurement of the flow velocities achieved while operating within a restrictive tube.

Pumping behaviour is investigated by repetitive firing of the plasma igniter into a cylindrical tube which feeds into a large air reservoir. Induced air flows within the tube displace reservoir air, resulting in an equivalent volume of air expelled from a reservoir exhaust tube. The resultant exhaust flow is measured by an anemometer probe.

Chapter Four describes an investigation of the performance of plasma jet ignition in an application environment other than automotive. Unwanted petroleum waste gases are often combusted by a method known as flaring. Although popular, this method of waste gas disposal is typically difficult to maintain and unreliable. These problems, are the result of inconsistent gas composition, flow dynamics, and poor climatic conditions (Environment Canada, [14]). Gas composition problems may consist of incombustible contaminants or the common condition of an over-rich fuel mixture. Flow and wind instabilities can affect any stage of the combustion process.

The standard and most reliable method for flare ignition is by pilot gas torch. Current electrical designs, although more economical to operate, have failed to demonstrate comparable ignition performance. Significant improvements in flare ignition reliability may be possible using plasma jet devices. The ability of the plasma jet to influence local flow patterns may reduce the effects of flare gas dynamics, a determining factor in ignition success. The improved energy conversion efficiency of plasma jets may also prove advantageous.

This flaring experiment is simulated outdoors using laboratory gases and an elevated flare stack model similar to full scale designs currently in use. A comparative study of plasma jet and surface gap ignition (representative of current electrical methods) is conducted for both single shot and repetitive operation. Each device is subjected to a variety of flow and climatic conditions.

The results and concluding statements from the preceding chapters are brought together in Chapter Five. Presented is an overall perspective of plasma jet combustion with particular emphasis on the influence of the research findings described here upon ignition and combustion in conditions of marginal flammability using plasma jet ignition.

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2 CLOSED VESSEL COMBUSTION

The study of combustion processes in a laboratory setting often requires that the combustion event being measured and/or observed, to be isolated in a combustion vessel or bomb. Such confinement facilitates and simplifies the control of the measurement process. Control of the combustion environment is essential to the understanding of parameters governing combustion behaviour, and to understanding the influences of external factors such as ambient pressure or temperature. The studies presented in this chapter focus on two characteristics of ignition sources which directly influence combustion; namely, induced turbulence and deposition energy. In particular, the contribution of each parameter toward the ignition and combustion of lean mixtures is addressed.

The effect of igniter induced turbulence is investigated using three ignition devices, as introduced previously. Plasma jet igniters produce various amounts of local gas turbulence, depending primarily upon their physical geometry. The ignition characteristics of two plasma jet geometries and a surface gap igniter are examined at several normalized lean mixtures. A comparative study of combustion performance and limits is presented.

Producing virtually negligible gas turbulence, surface gap ignition is investigated to understand the contribution of deposition energy to ignition in the absence of turbulence. The aim is to establish both an experimental and theoretical relationship between energy deposited in the local gas at the point of ignition, and the resulting partial combustion (also referred to as burn volume, the volume of gas burned during partial combustion). An explanation for partial combustion is sought including why it fails to become self-sustaining, leading to complete combustion.

The concept of partial combustion also embraces the concept of the lean flammability limit itself. This limit is often illustrated as a solid, defined boundary, separating full and incomplete combustion (Figure 1.1, Kanury [13]). The limit is determined by observing whether or not a given mixture successfully undergoes complete combustion when confined to a vertical glass tube (sealed top). The mixture is judged to be flammable if, when ignited by an open, stable flame at the base of the tube, the resultant flame burns the entire length of the tube (Lefebvre, [14]).

Limit evaluation by this method relies upon both a stable ignition source and a quiescent mixture. Presented with igniter induced turbulence, it is doubtful that similar observations would result. Such an event may produce a lean limit dependent solely on the ignition parameters (neglecting all other effects). Moreover, the turbulent ignition behaviour of devices, such as plasma jets,may not only be able to affect the illustrated "position" of the lean limit, but also the existence of partial combustion beyond the boundary.

The study of the lean flammability limit and pressures associated with early stage combustion, are difficult to monitor using conventional, mechanical transducers. Improved measurement sensitivity is achieved by employing laser interferometry. This optical method, providing indirect pressure measurement, detects pressure changes by the change in optical path length in one arm of an optical interferometer. The shift of interference patterns, produced by the resultant beam combination, relate directly to the pressure variations of combustion.

The useful range of this optical technique extends only up to the latter stages of combustion. Water vapour, a product of combustion, obscurs the interferometer beams, preventing pressure measurement. A conventional piezoelectric pressure transducer is used simultaneously with the interferometer to record latter stage combustion pressures. Information from the two techniques is later assembled to provide a complete pressure profile of the combustion event.

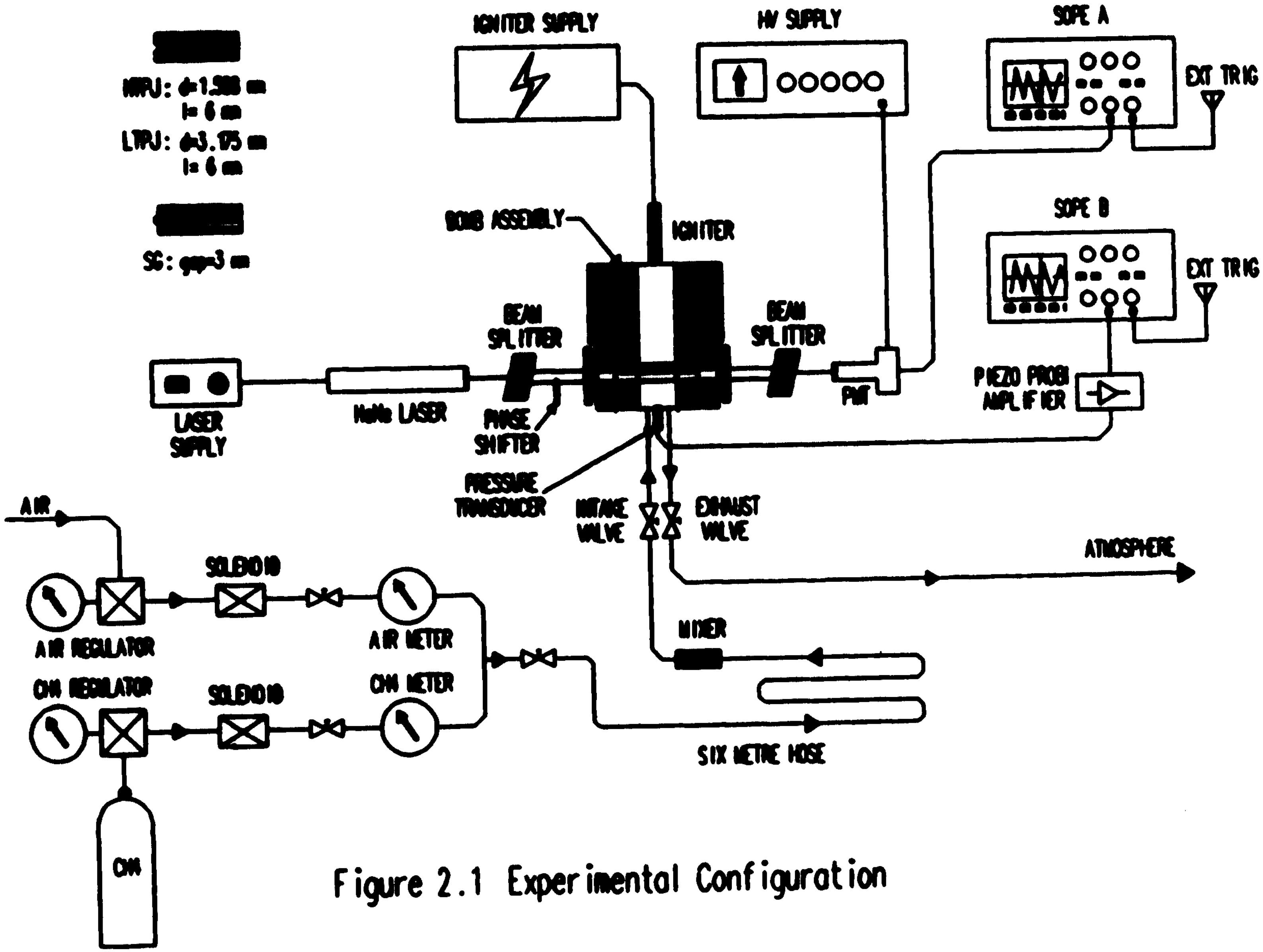

Figure 2.1 Experimental Configuration

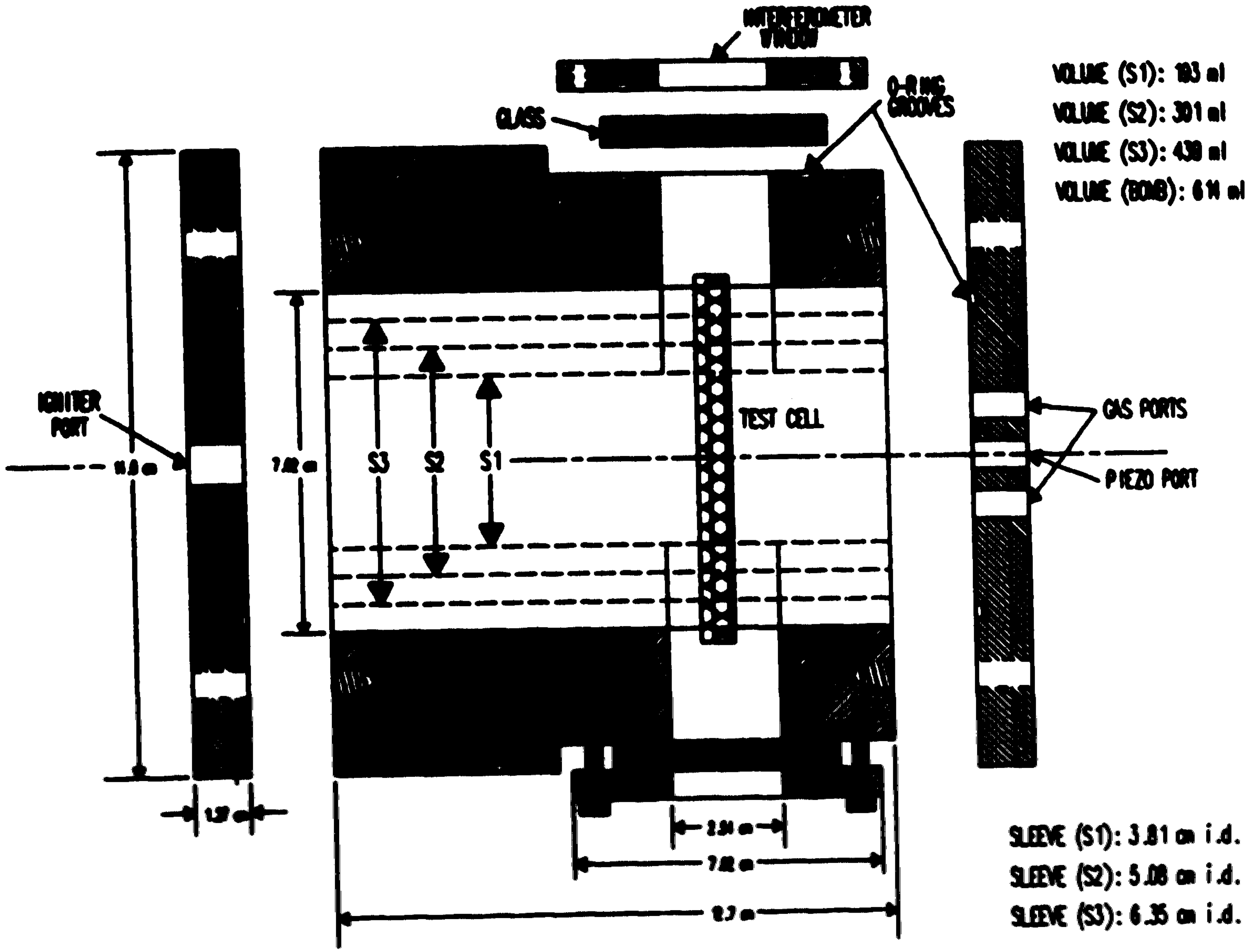

Figure 2.2 Combustion Bomb Assembly

2.1 EXPERIMENTAL CONFIGURATION

The study of combustion processes confined to a closed vessel environment requires the integration of several dedicated systems. The complete arrangement is illustrated in Figure 2.1. Divided into three sections, the experimental layout consists of a mixture control network, measurement apparatus, and ignition control electronics.

2.1.1 Mixture Control

This section is comprised of the combustion "bomb", and the mixture control unit. As illustrated in Figure 2.2, the bomb assembly consists of a cylindrical chamber with an optical corridor perpendicular to its axis. Machined from solid steel, the bomb's outer housing was constructed to allow three different sleeve inserts to be placed inside, thereby effectively providing a choice of bomb volumes. The results presented in this chapter are based on the volume of sleeve S1 (193 ml). The inlet and exhaust gas ports were located on axis at one end of the bomb while the igniter under study was located at the other end. O-rings provided the seal for each removable section.

The mixture control unit consisted of a pair of metered gas lines (CH_4 and air) which terminated into one main control valve. Each section comprised an inlet gas regulator, solenoid valve, and a ball flow meter (Fischer-Porter 10A6131N). Prior to release into the bomb volume, the mixture passed through six metres of 6mm diameter hose as well as a mixer which consisted of steel wool inside a small pipe fitting. This was done in order to ensure a well mixed and consistent mixture at the bomb inlet. Repeated ignition trials with surface gap ignition produced virtually identical piezoelectric probe responses. This evidence indicates that a consistent, well mixed mixture was filling the bomb cavity. The surface gap igniter was used since the characteristics of plasma jet combustion often differ from one event to another because of the irreproducible nature of turbulence.

Mixture consistency was also monitored and verified by the interferometer technique. This was accomplished by observing oscilloscope fringe activity for each combustion event. A similar fringe displacement for each event indicated a mixture consistent with the previous. Fringe displacement is influenced by variations in gas density (proportional to mixture concentration). The interferometer measurement technique is reviewed in the next section.

The by-products from each combustion event were purged from the bomb cavity by the incoming flows of the new test mixture entering the bomb. The evacuated by-products were then vented to the outside.

2.1.2 Measurement Apparatus

To monitor combustion pressure variations within the bomb, two measurement techniques were required to provide a complete pressure record. Mechanical pressure transducers have traditionally been used to study pressure behaviour. These sensors, however, lack sensitivity in detecting the small pressure fluctuations associated with early stage combustion. To capture the missing information, an optical method of measuring pressure was developed.

The principles of interferometry were utilized to indirectly detect changes in gas density (pressure). Since this optical method does not physically disturb the measured combustion process, it was possible to provide increased sensitivity and response over mechanical systems. The enhancement was sufficient to detect the minute pressure variations of early stage combustion and igniter discharge. This optical technique was validated by comparing record overlaps between simultaneous interferometer pressure records and those obtained conventionally by a piezoelectric pressure transducer (Section 2.3).

The interferometer depicted in Figure 2.1 is of Mach-Zehnder configuration, and consists of a HeNe laser (Melles Griot GreNe, model 05-LGR-171), two beam splitters, a correction phase shifter, and a photomultiplier tube (RCA 8645, Fluke 412B power supply). The bomb housing and its associated sleeves, as discussed previously, each have a small 9mm diameter, 68mm long reference tube parallel to their window corridors. Small windows cemented to each end of these reference tubes provide an isolated air environment inside the tubes unaffected by the combustion processes surrounding them.

The interferometer functions on the principle that two identical light beams, one passing through the reference tube and the other passing through the burning test medium, experience a phase shift difference when the density of the test medium changes. The interference fringes, so generated when passed through a pinhole at the entrance to a photomultiplier tube, produce a measurement signal proportional to the level of fringe intensity variation. A storage oscilloscope records the sinusoidal variation in fringe intensity as produced by combustion pressure variations within the bomb (Figure 2.5). The laser/beam splitter combination produces and combines the two beams, while the phase shifter allows for fringe position correction as seen on the storage oscilloscope (Tektronix 2430A) prior to a combustion event. Fringe correction was sometimes necessary to position the fringe pattern on the oscilloscope grid for maximum fringe sensitivity.

Apart from the advantages of the optical method, two problems were encountered. Instabilities of the interferometer system over time intervals of the order of

3-5 minutes, required recalibration to achieve accurate results. This involved adjusting the fringe pattern, as viewed on an oscilloscope, for optimum sensitivity (midpoint between maximum and minimum fringe displacement). The second problem occurred during the latter stages of a combustion event. A product of combustion, water vapour would condense on the bomb windows, distorting the interference beam passing through the bomb assembly. The amount of water vapour and its formation time on the windows, decreased as mixtures approached the lean flammability limit, increasing the observation time of the interferometer.

The second measurement technique employed a typical piezoelectric pressure transducer (PCB 102A02) and charge amplifier (PCB 482A). When the interferometer became inoperative because of window fogging, the piezoelectric sensor was necessary to capture latter stage information which would otherwise be lost. Combining the pressure information from each technique produced a complete combustion pressure record.

A piezoelectric pressure transducer responds mechanically to the time varying pressure of a combustion event via distortion of a piezoelectric crystal. This action produces a detectable charge potential across the crystal, which is then amplified and fed to a second storage scope (Figure 2.5). Separate but similar oscilloscopes and triggers were utilized for each diagnostic technique. This allowed for the comparison and combination of piezoelectric and interferometer information.

2.1.3 Ignition Sources

The investigations of this chapter were conducted using three different igniter designs, each unique in both geometry and the level of generated turbulence. Figure 2.3 illustrates these igniters along with their discharge supply schematics.

Two plasma jet geometries were selected to represent "high" and "low" levels of induced turbulence. As the name suggests, the high turbulence plasma jet (HTPJ) produces a high intensity turbulence field compared to an open electrode ignition device. A HTPJ igniter is characteristzed by the combination of a large cavity length and a small orifice diameter. The label of low turbulence plasma jet (LTPJ) denotes the reverse combination, producing turbulent field levels in between those generated by open electrode and HTPJ igniters.

The surface gap igniter (SG), chosen to represent ignition in the absence of turbulence, is an example of open electrode ignition. Coaxial electrodes located at the igniter's surface produce an arc discharge which is representative of most conventional igniters. This geometry, however, has improved electrical efficiency and reduced electrode heat losses over other open electrode designs.

These characteristics produce a negligible level of local turbulence, as compared to plasma jets (Burland [3]). This aspect thereby facilitated the study of ignition parameters outside a turbulent gas environment.

The discharge supply (Figure 2.3) was designed primarily for plasma jet operation, but was utilized for all three igniters. Its function is based on a two stage principle, whereby a high potential discharge is first initiated at the igniter. This initial discharge transient is produced by discharging energy stored in capacitor C4 through the SCR (silicon controlled rectifier). The discharge path of C4 also includes the primary of transformer T4, which induces a high voltage secondary pulse (25-30 kV) across the igniter electrodes. This discharge also ionizes three-point gap G1, thereby allowing a second stage energy pulse from capacitor C3 (approx. 1200 V, 0.75 J) to bridge this isolation gap and discharge into the pre-ionized igniter. For safety, gap G1 isolates the supply of capacitor C3 from the igniter and prevents premature igniter discharges, in the event of contaminants shorting the igniter electrodes.

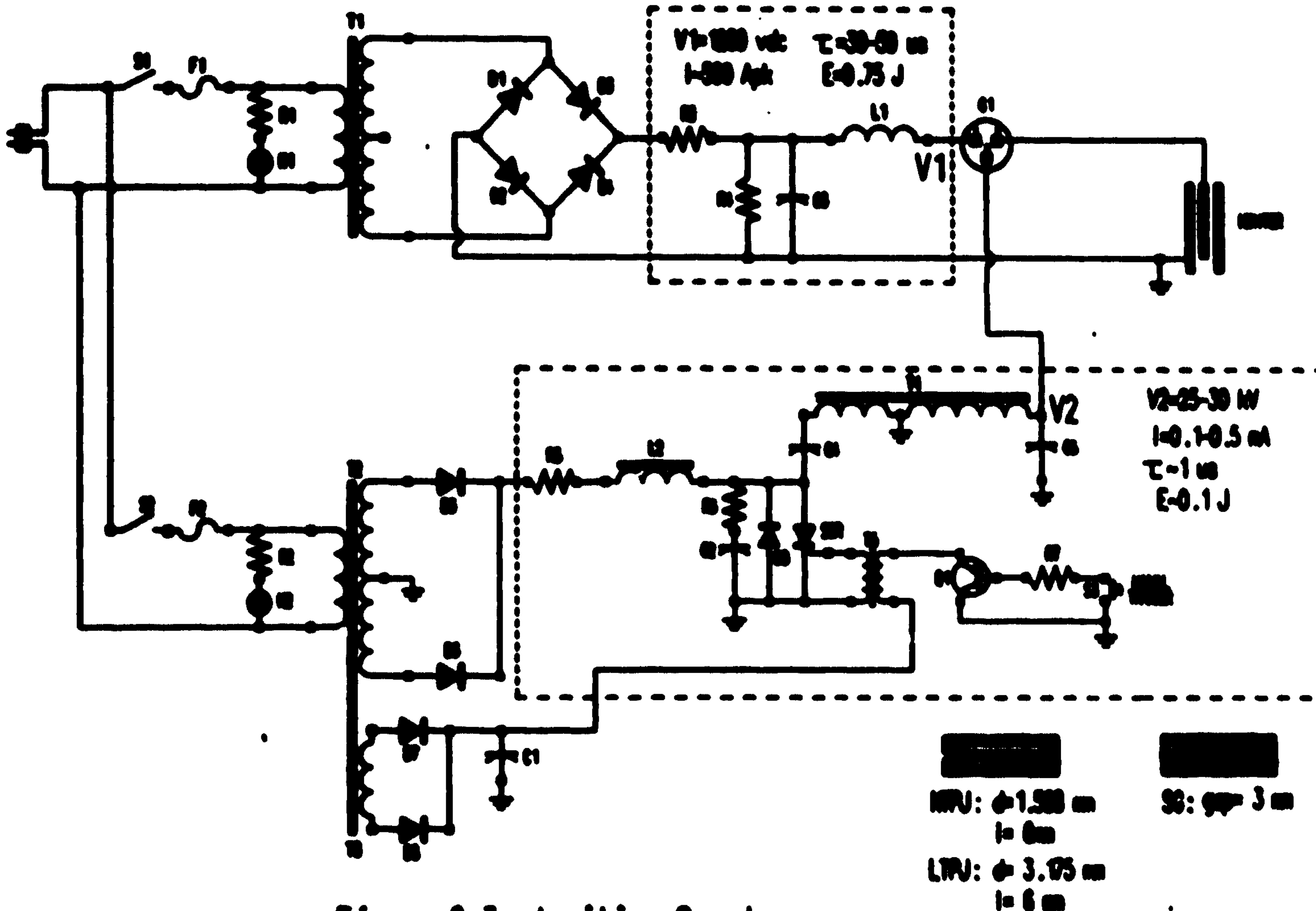

Figure 2.3 Ignition Supply

2.2 INVESTIGATIVE APPROACH

Before the collection of combustion data, equipment calibration and error analysis was necessary to achieve accurate results. Error analysis required identification and estimation of systematic errors as well as a "recipe" procedure for consistent data results between combustion events.

2.2.1 Calibrations

Several calibrations were required in order to create valid results from methane flow metering, interferometer waveforms, and igniter deposition energy.

Flow measurements of methane and air prior to mixing were obtained from ball-level flow meters. Many instruments of this type are calibrated and marked for air metering only. To accurately measure methane gas flows required recalibration. This information was obtained by recording the time required for methane, at a specific flow meter setting (cm^3/s), to fill a known volume. From several trials a calibration curve was created.

Interferometer fringe calibration was obtained by injecting 1.0ml of air from a syringe into the bomb volume (209 ml including sleeve S1, associated valves & fittings) and recording the fringe displacement. Knowing the displacement of one full fringe (from an oscilloscope profile), it was possible to estimate the fractional change of a fringe as a result of the injected air. On average, a 1.0 ml injection of air corresponded to a 0.195 fringe shift. This fractional change can also be calculated theoretically (Haley [12]):

$$S = v/V * (n-1) * L/\lambda = 0.175 \qquad \text{[Eqn. A]}$$

where: S= number of fringe shifts
v= injected volume (1.0 ml)
V= bomb volume (209 ml)
n= refractive index of air (1.000293)
L= reference tube path length (68.0 mm)
λ= wavelength of reference beam (543.5 nm)

The error between calculated and experimental data approximately 11.4%. This is judged to be acceptable, given the accuracy of the experiment and the omission of temperature effects in the theoretical calculation. Since a 1.0 ml volume increase corresponds to a pressure rise of 1/209 atm (and an experimental fringe shift of 19.5%), one full fringe (100%) would correspond to 0.0245 atm. This pressure rise associated for one full fringe was then converted kPa based on the local barometric pressure. The final (recorded) pressure figure was the product of the barometric pressure rise for one full fringe and a linear correction factor of pi/2 to account for the sinusoidal variation of the interferometer fringe pattern.

The last calibration procedure required a measurement of relative efficiencies of each igniter in converting stored supply energy to plasma energy in the bomb gas. Each igniter was discharged into a small test cell while its induced pressure level was recorded with a piezoelectric transducer. The relative efficiency of each ignition device is a comparison between the pressure produced by the device and the expected pressure resulting from 100% of the stored source energy discharged into the test volume. This source induced pressure rise is calculated by (Haley [12]):

$$P = (nRE_s)/(\rho V^2 c_v) \qquad \text{[Eqn. B]}$$

where:
- P = pressure
- V = test cell volume (19.0 cm^3)
- ρ = air density (1.18 * 10-3 g/cm^3)
- R = 8.3143 J/mol K
- n = 0.779 * 10-3 mol
- C_v = specific heat @ constant volume (0.717 J/g K)
- E_s = stored supply energy (1.08 J)

If the full capacity of the power supply (E_s) could be discharged into the test cell, a pressure rise of 22.9 kPa would be realised. Given measured pressures of 5.53, 3.94, and 2.15 kPa for the MFPJ, LFPJ, and SG respectively, relative efficiencies of 24.1%, 17.2%, and 9.4% result. The improved energy conversion efficiency of the plasma jet geometry over open electrode designs is primarily due to the influence of cavity parameters (orifice diameter and cavity length) on plasma behaviour (Weinberg [15]).

For verification, the surface gap test was repeated in in the combustion bomb using the interferometer technique. A recorded pressure of 2.26 kPa (corresponding to an efficiency of 9.9%) supports the accuracy of the piesoelectric measurements.

2.2.2 Error Considerations

In addition to the aforementioned error sources of interferometer window fog, periodic fringe adjustment, and experimental assumptions, several other error factors required attention. Inherent to their operation, plasma jets produce strong initial shock fronts which are capable of distorting and severely limiting the resolution of interferometer measurements. Fortunately, this phenomena presents itself only as a burden for early stage combustion measurements and is somewhat controllable via manipulation of plasma jet ignition parameters.

The repeatability of individual combustion experiments is perhaps the most difficult error source to control. Discharge characteristics of each igniter vary from one event to another, especially in plasma jets where plume development is largely governed by the chaotic behaviour of local turbulence fields. Such problems are compounded by the difficulty in reproducing consistent bomb mixtures. Within the resolution limits provided by the flow meter graduations, mixture concentrations were closely monitored. Sometimes, this still produced different combustion events. Averaging over several combustion events helped reduced such errors, but required a substantial amount of time to perform. This allowed other variations such as changes in ambient temperature to interfere.

To aid mixture monitoring, the interferometer was used to observe internal mixture levels within the bomb volume after the purge valves had been closed. Provided the time span between successive purges is kept small, this method provided reasonable accuracy in ensuring that the fuel-air ratio was close to its predecessor. The method also provided visual indication of when internal bomb mixtures had reached non-turbulent, stagnant conditions. This was possible by observing the stability of the oscilloscope fringe pattern.

2.2.3 Experimental Procedure

After monitoring the incoming test mixture to the bomb, a "recipe" pre-ignition procedure was established. Having adjusted the interference fringes for optimum sensitivity on the storage scope (along the linear portion of the fringe pattern), the inlet/exhaust purge valves to the bomb were opened. Once a consistent mixture had been measured by the flow meters, the mixture was allowed to flow through the bomb cavity for approximately two minutes, at which time the inlet valve was closed. Once the interferometer had indicated little internal gas activity the exhaust valve was closed. It was assumed that such a procedure achieved atmospheric pressure within the bomb, since the exhaust tube vented directly to the outside atmosphere. The interferometer beam was again adjusted for optimum sensitivity and set along with the piezo probe scope to record the combustion event. Both storage scopes were externally triggered by radio-frequency emissions from the igniter supply.

2.3 EXPERIMENTAL RESULTS

Illustrated in Figures 2.4(a), 2.4(b), and 2.4(c) are the instantaneous pressure characteristics of each igniter (HTPJ, LTPJ, & SG) for three normalized mixture values. The associated plots were created from typical interferometer and piezoelectric probe traces, as depicted in Figure 2.5. Data points along the interferometer fringe sinusoid waveform were converted to values of pressure (Eqn. A) and subsequently plotted along with a simultaneous piezoelectric pressure profile. As previously discussed, analyzing and linking the interferometer information to that simultaneously recorded by the piezoelectric probe significantly enhances the resolution of early stage combustion. This is readily apparent if one compares the early information, supplied in Figures 2.4(a,b,c), to that of the piezoelectric probe traces of Figure 2.5. The improved sensitivity of the optical technique is most noticeable for responses below 20ms.

Although the vertical resolution of the piezoelectric trace could be increased, the information signal is quickly distorted by increased electrical noise. The dotted vertical line at 50 ms indicates the termination of interferometer information (open symbols). Piezoelectric responses are denoted by solid symbols and are presented below the 50ms time frame for comparison against interferometer results. The error in pressure measurement is estimated at ±5 kPa, based on the average variance between piezoelectric and interferometer measurements.

Figure 2.4(a) clearly shows the improved performance of plasma jets over surface gap ignition given a moderate lean mixture of 1.70 (normalized with respect to stoichiometric, ±0.03 error). A marked improvement is apparent immediately at the very start of ignition. However, as one progresses towards the lean flammability limit (towards a normalized mixture of 1.86), the performance characteristics of each igniter begin to differ from each other much later in combustion history. The close data scatter of Figure 2.4(c) illustrates this point as individual curves do not begin to deviate until the 80ms time mark. The reduced separation between individual response curves indicates a decline in plasma jet ignition enhancement, particularly in the early stages of combustion as mixtures become leaner.

One possible explanation for this effect is, as the mixtures become leaner, turbulence effects created by the plasma jets begin to destructively influence ignition.

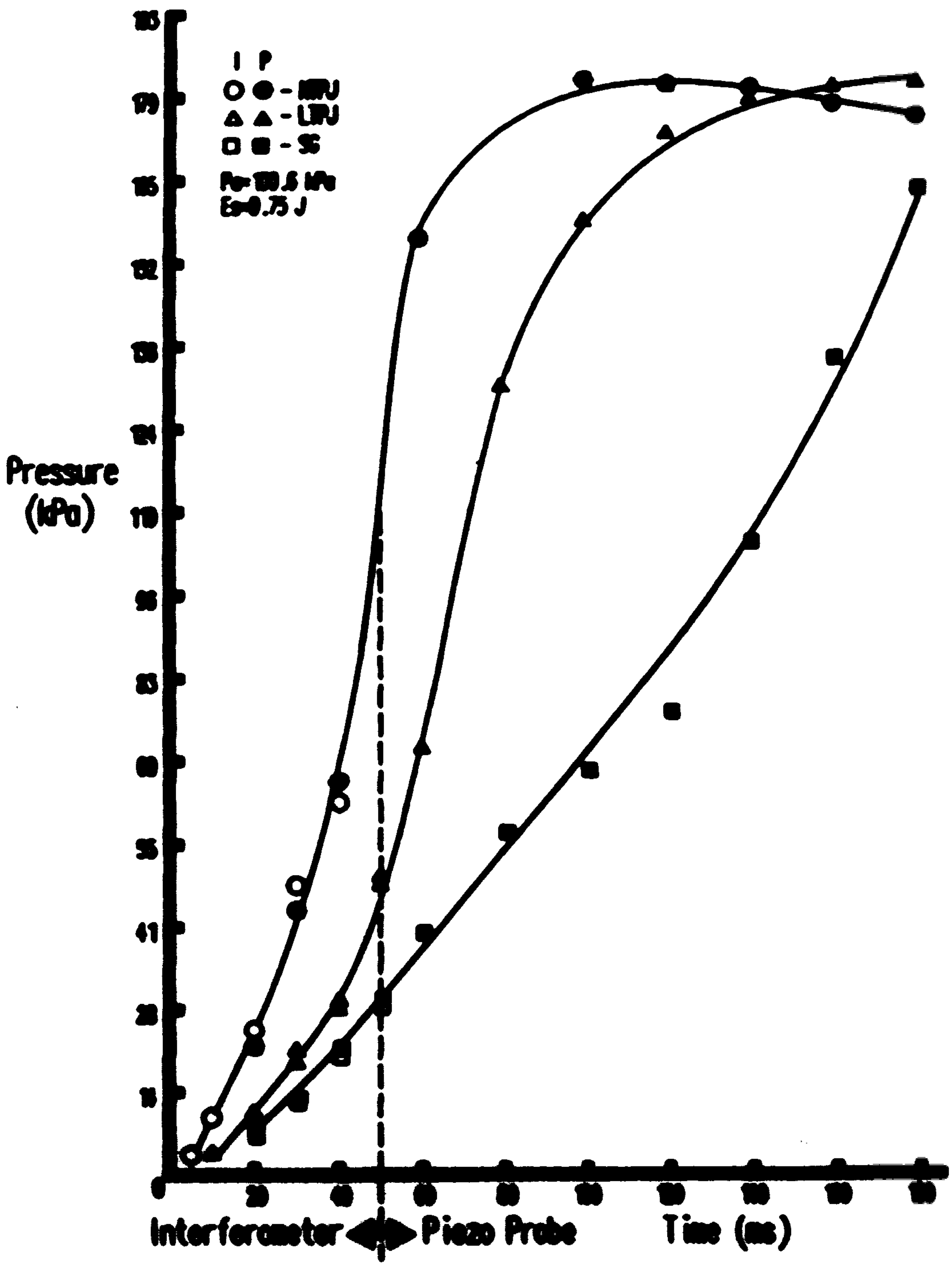

Figure 2.4(a) Pressure vs Time, λ=1.70

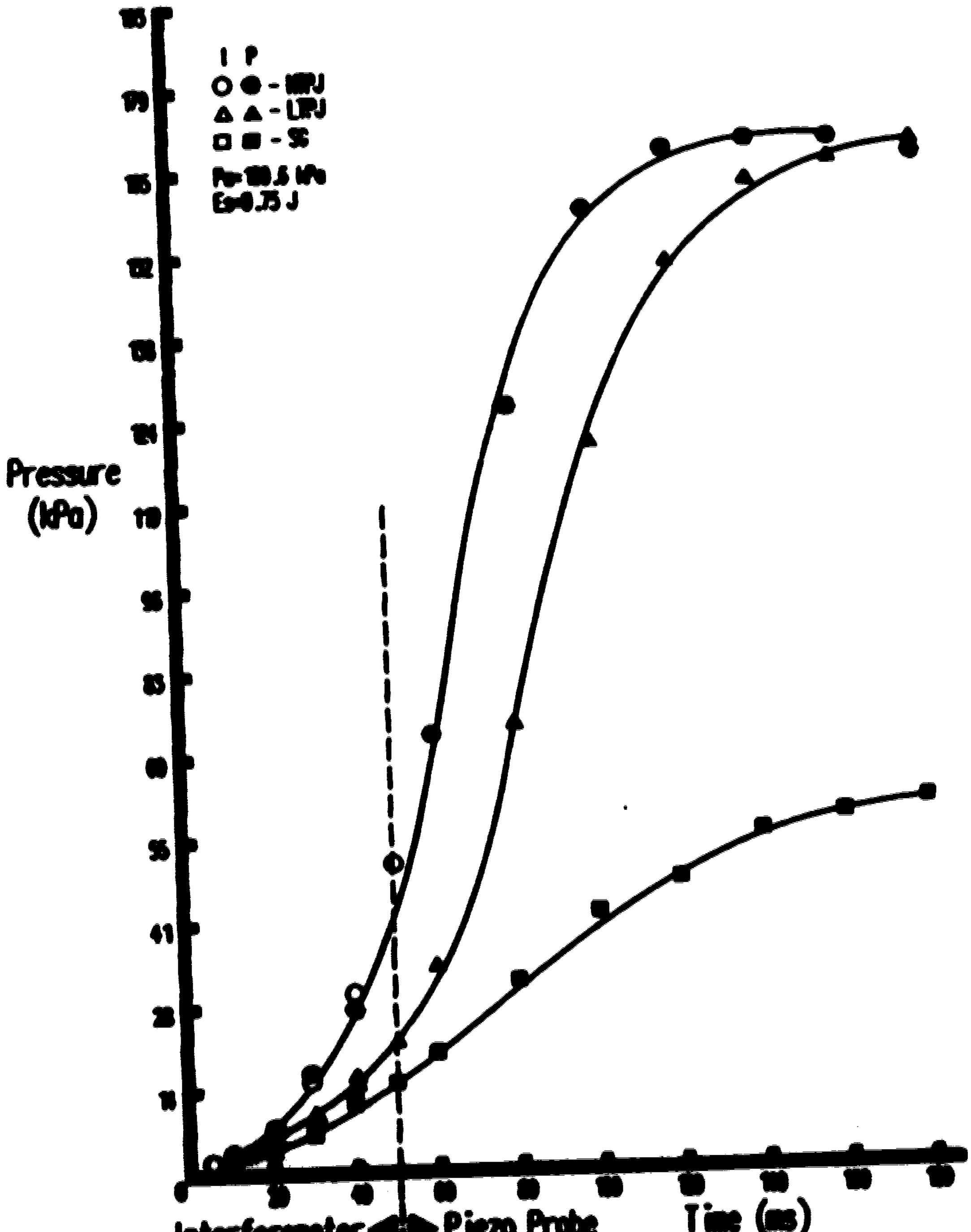

Figure 2.4(b) Pressure vs Time, $\lambda = 1.78$

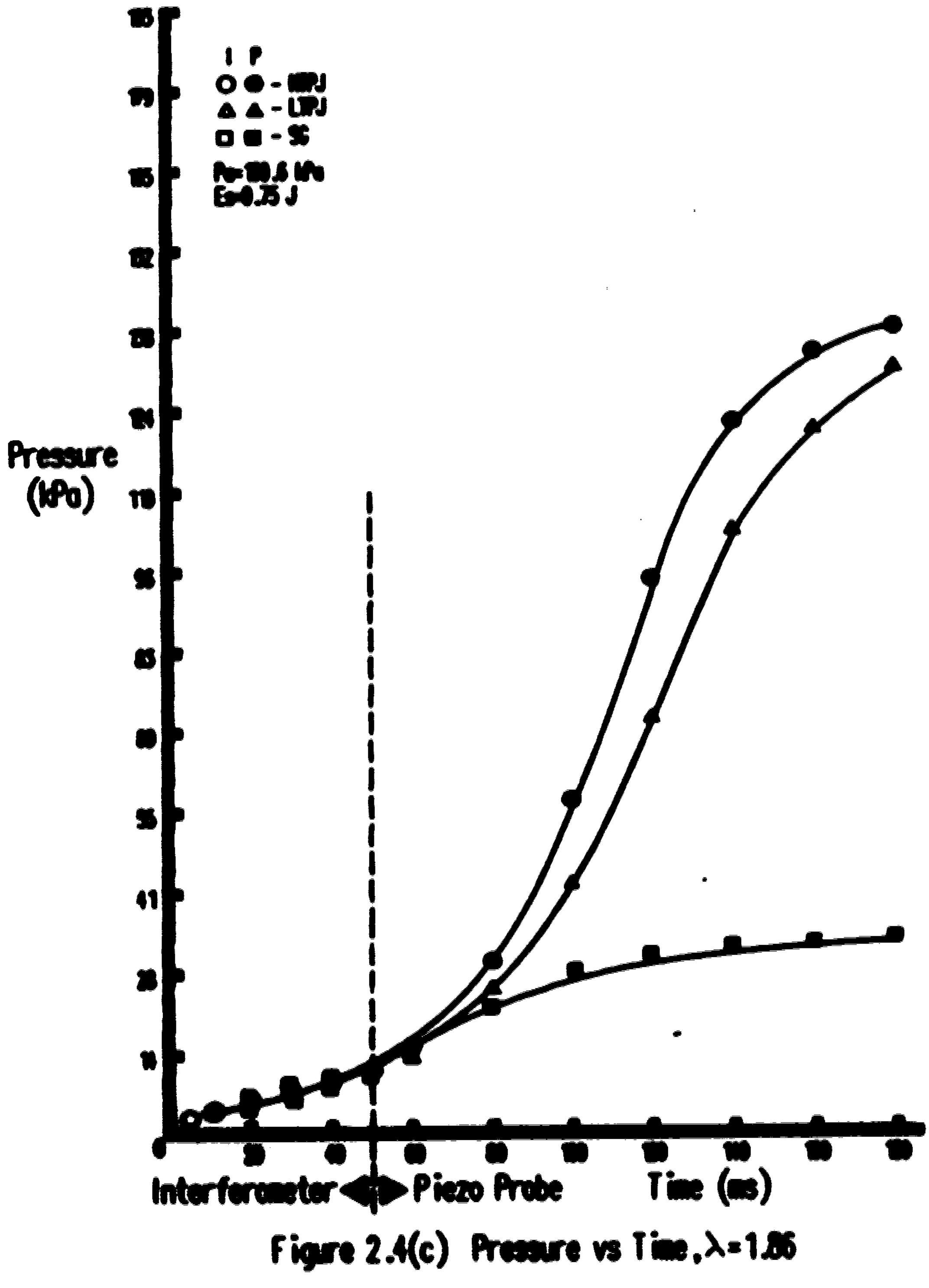

Figure 2.4(c) Pressure vs Time, λ=1.86

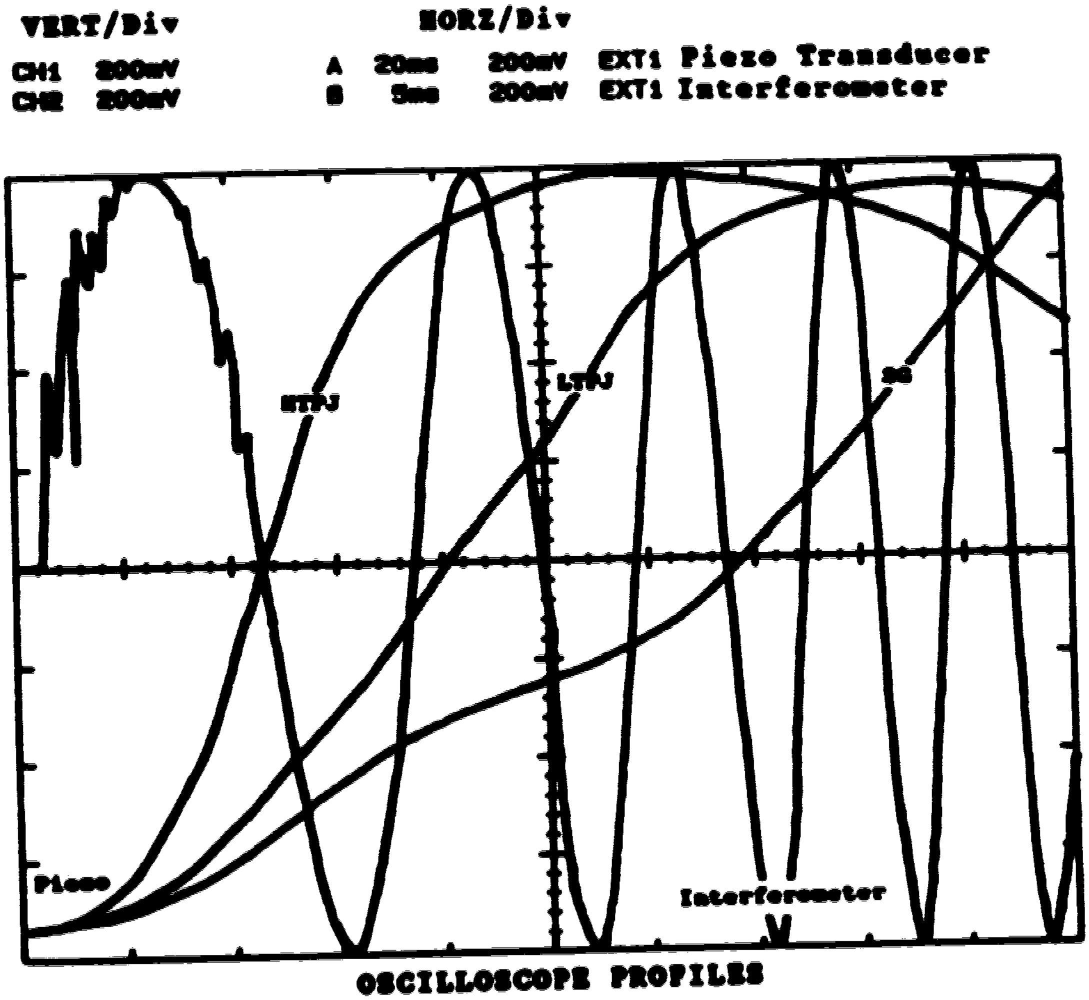

Figure 2.6 Interferometer/Piezo Transducer Responses

Although providing support and improvement to flame propagation, turbulence at these limits may introduce flame extinction by either violent disruption of the developing flame front or by moving the flame front towards the walls of the combustion chamber ([2], [7], [8], [9], [10], [11], [15]). Murase et al. [8] reported that increasing the deposition energy and orifice diameter of plasma jets while decreasing their cavity volume, extends the lean mixture performance through decreased turbulence. Furthermore, it was explained that intense turbulent zones created by very small orifices (compounded by high shear stress layers and heat losses at the orifice exit) failed in some cases to produce successful ignition at stoichiometric mixtures. This destructive nature of turbulence, despite its enhancements to flame propagation, suggests a dilemma situation between ignition success and combustion performance.

Consider the curves presented in Figure 2.6, based on pressure gradient analysis introduced by Cote et al. [4]. These curves illustrate ignition behaviour supportive of the previous discussion concerning turbulence. Despite having inferior energy conversion efficiency, the surface gap igniter was able to achieve ignition and partial combustion beyond the capabilities of plasma jet ignition. This improved ignition success, in the absence of igniter induced turbulence, provides evidence of the destructive properties of turbulence during the early stages of combustion, in particular, flame development.

One might expect that the LTPJ curve would extend slightly beyond that of the HTPJ igniter, given its reduced level of turbulence. The absence of this effect is likely the result of too large a mixture increment (1.85 - 1.95).

Within specific limits, plasma jet ignition most certainly surpasses conventional ignition systems due to its hydrodynamics as outlined in Chapter One. However, an understanding of why plasma jet performance fails to show enhancement near or beyond conventional igniter ignition limits requires a more detailed understanding of the contributing factors to ignition enhancement. One factor to consider, is the partial contribution of igniter deposition energy in heating the surrounding gas (in the absence of turbulence).

Adopting the surface gap igniter for study allows for experimentation in the absence of high turbulence fields. This isolates deposition energy as the dominant force in both the heating of local gases and early stage flame development.

The curves presented in Figure 2.7 are the result of combustion limit experiments performed at two different ambient temperatures. "Ambient" refers to the internal temperature of the combustion bomb, which was heated to 100°C by a heat belt wrapped around the bomb's exterior.

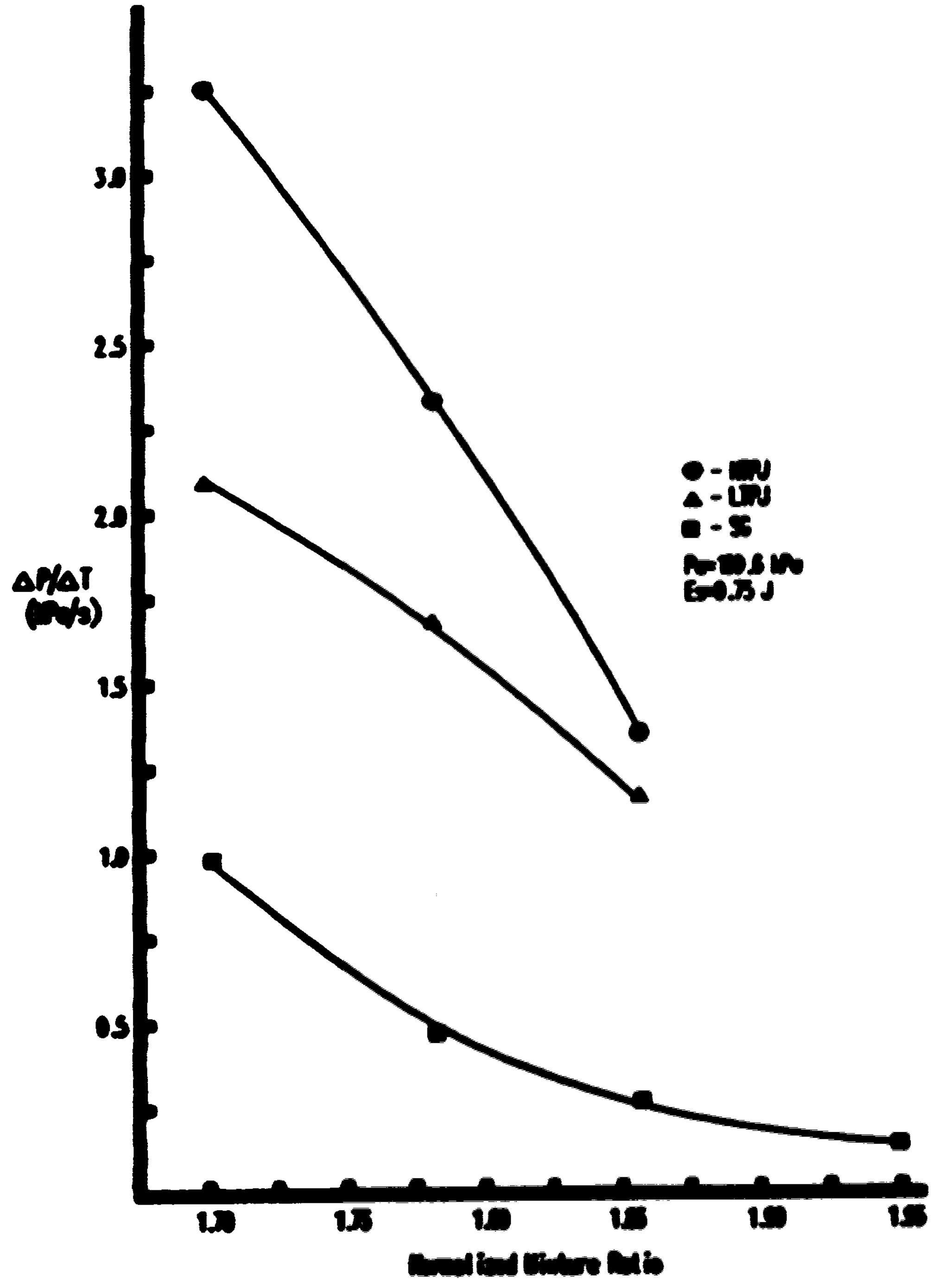

Figure 2.6 Combustion Limits (HTPJ, LTPJ, SG)

Internal temperature was monitored through the igniter port with a temperature probe. Charging the bomb with a particular mixture required a modified procedure from that discussed previously in Section 2.2.3. After the two minute flush period, the purge valves were closed and the mixture was allowed to rest for five minutes. This time frame was experimentally determined as being sufficient for the bomb walls and surrounding mixture to return to the desired 100°C. Once ambient temperature was attained, the exhaust valve was reopened to establish atmospheric pressure, then closed. The igniter was subsequently discharged. Unfortunately, because of beam instabilities created by thermal expansion of the interferometer windows and thermal inconsistencies over the beam path, the interferometer could not be used. Consequently, the curves of Figure 2.7 are derived solely from piezoelectric transducer responses.

Given the curves presented in Figure 2.7, it is now possible to examine two possibilities for the phenomenon of partial combustion at the lean limit. One possibility is that the formation of the ignition plasma increases the rate of reaction. This would suggest that the induced reaction would only sustain itself for as long as the plasma persisted. Observations show that although this may be a factor, combustion continues after plasma extinction, thereby indicating other contributing factors.

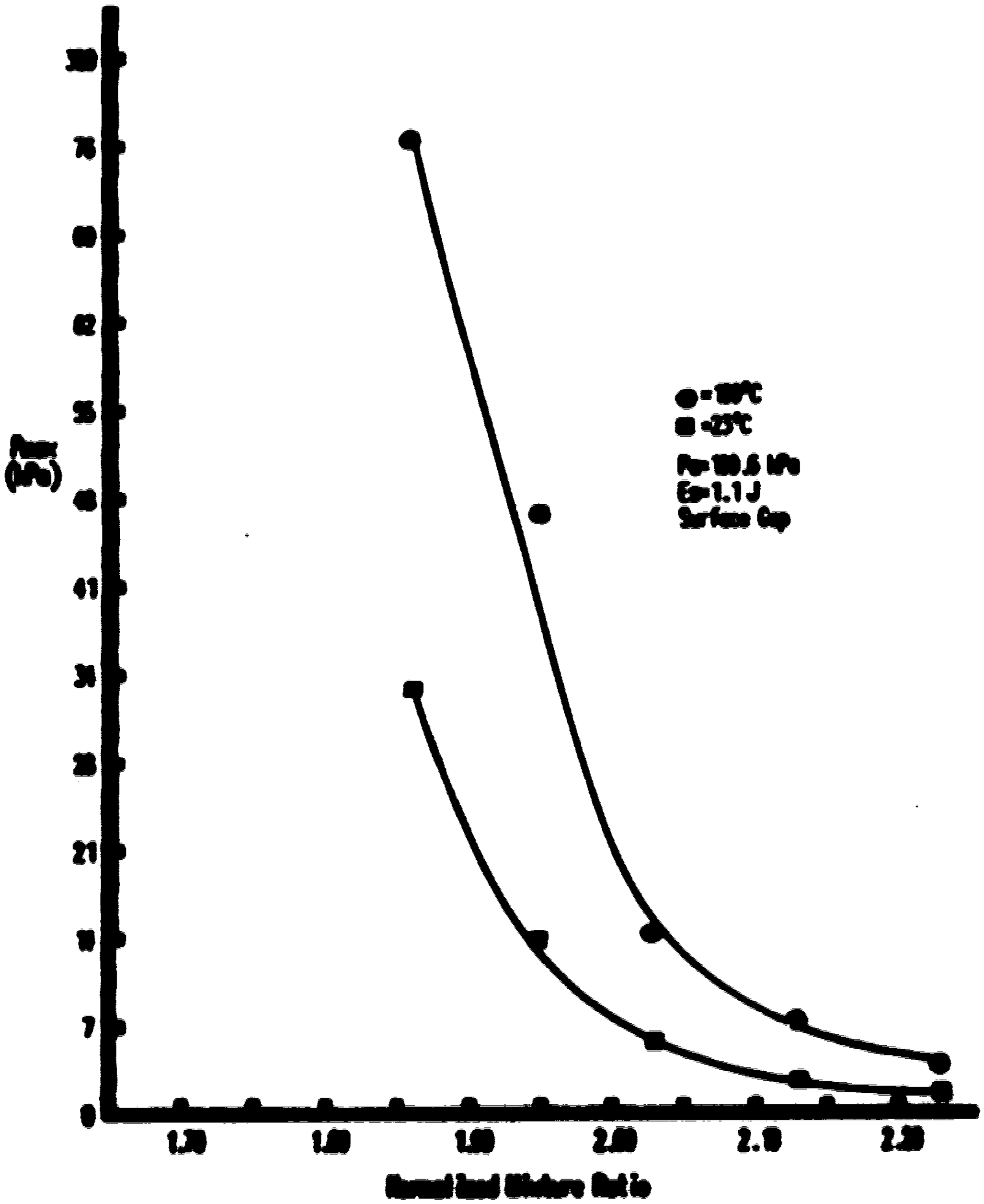

Figure 2.7 Temperature Profiles. Pmax vs λ

A second possibility that is the plasma discharge increases the initial temperature of the local gas sufficiently to alter the lean flammability limit (i.e. able to temporarily create a combustible mixture). To examine this hypothesis, an understanding of the dependence of partial burning upon initial gas temperature is required. Surface gap ignition at mixtures of 1.70 have routinely shown an average maximum pressure rise of about 207 kPa. Extrapolating from this full burn situation, it can be expected that full burning (209 ml bomb volume) at a mixture of 1.95 will yield a pressure rise approaching 179 kPa (approximated linear dependence). Referring to Figure 2.7, a 14 kPa pressure rise was recorded at 23°C for a 1.95 mixture. Comparing this result to the estimated maximum pressure possible, this partial burn situation corresponds to nearly 16 cm^3 (14 kPa/179 kPa * 209 cm^3) of the bomb volume combusting.

It is now possible to calculate the temperature rise of this partial burn volume. Observing the pressure responses of Figure 2.7 at the normalised mixture ratio of 1.95, it is clearly seen that the 100°C curve has a 33 kPa advantage over its 23°C counterpart, representing a change in temperature of 77°C. Since a 77°C increase produces a 33 kPa pressure differential, to produce the previous pressure rise of 14 kPa would require a 32°C rise. Given a specific heat for a CH_4/Air mixture @ 1.95 (C_v= 0.925*10-3 J/cm^3°C), it can be expected that to heat 16 cm^3 of the mixture to 32^oC would require 0.47 J of energy (16 cm^3 * 32^oC * 0.925*10-3 $J/cm^{3o}C$). This is the required energy to be delivered by the igniter to the surrounding gas in order to combust 16cm^3 of gas.

To validate these calculations, a second experiment was performed to study the relationship between the resultant energy produced by a combustion event and the input energy delivered by the surface gap igniter. Figure 2.8 illustrates the relationship of E_{out}/E_{in} for a lean normalized mixture of 1.95. As the stored supply energy is increased, the ratio of E_{out}/E_{in} decreases, indicating that increasing the energy level does not create an equivalent increase in combustion energy. This effect has been well established for plasma jets and other igniters by several sources (Boston et al. [2], De Soete [5], Murase et al. [8]). However, it appears from Figure 2.8, the ratio of E_{out}/E_{in} begins to behave as a constant at an energy level close to the energy required to satisfy the previous partial burn situation. Assuming this behaviour initially occurs at a stored energy of 4.3 ±0.1 J (Figure 2.8), this results in a deposition energy of 0.41 J by the SG igniter (9.4% efficiency), which is quite close to the previous figure of 0.47 J.

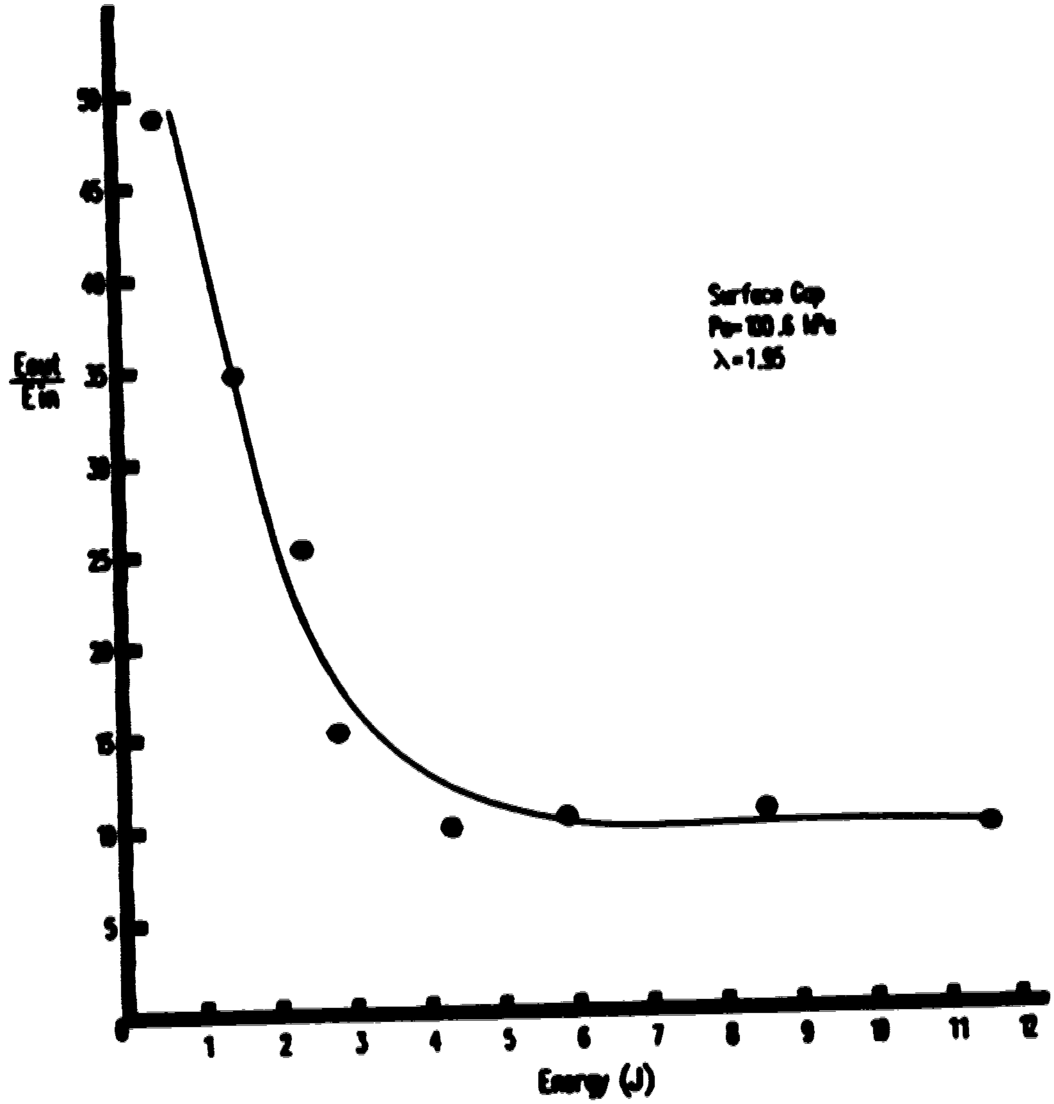

Figure 2.8 Output Energy / Input Energy vs Discharge Energy

One possible explanation for this occurrence is that having been saturated to its full energy potential, any additional energy delivered to the gas, produces a corresponding increase in temperature, thereby increasing the burn volume (Grant et al. [6]). This increased burn volume produces a proportional increase in output energy. If the volume burn increase is proportional to the amount of surplus energy, the ratio of E_{out}/E_{in} will remain constant.

2.4 SUMMARY

The investigation of lean flammability limit combustion yields several important results. For normalized mixtures approaching 1.70, plasma jet ignition produces a substantial improvement in combustion performance over conventional (surface gap) ignition. Resultant combustion pressure is increased along with a reduction in burn time. Although superior energy conversion efficiency is partly responsible, igniter induced turbulence is the dominant factor. These enhancements, however, decrease as mixtures become leaner. Eventually, plasma jet ignition fails while surface gap ignition continues to display ignition and partial combustion. Despite its contributions to flame propagation, results have shown that igniter induced turbulence is detrimental to early stage flame development. This suggests an optimal range for ignition by turbulent igniters (ie. plasma jets) if the device is intended to provide both high ignition reliability and combustion performance. The mechanisms by which turbulence produces flame extinction (disruptive flow patterns, increased heat losses, flame dispersal, etc.) have not yet been established.

The improved ignition success of the surface gap igniter over plasma jet ignition beyond mixtures of 1.86 indicates the importance of considering ignition parameters in lean flammability limit determination. Both the "position" of the lean flammability limit and the range of partial combustion are affected by igniter characteristics. This suggests that for some ignition sources (such as those which generate small amounts of turbulence), the lean flammability limit is more accurately represented as a "transition" region, gradually separating complete combustion from none. For other sources, the typical "solid line" boundary provides be the best representation, indicating a rapid decline in ignition performance.

The use of interferometry for recording combustion pressure proved to be beneficial, especially for measurements up to 20ms post ignition. The ability of this optical technique to detect pressure perturbations this early in combustion history provided information previously unavailable by conventional techniques. Although a piezoelectric transducer was required to supplement latter stage combustion information, the improved sensitivity and response of the optical method more than compensated.

The separate study of surface gap ignition was able to address the question of how partial combustion occurs. It was shown that the volume of gas heated was directly dependent upon its final temperature, heat capacity, and the amount of energy delivered by the igniter. It is suggested that the energy delivered by the igniter, in heating this volume of gas, was able to alter the lean flammability limit favorably to support partial combustion. This temporary adjustment would foster ignition and combustion until external mixture conditions intervened. Lacking sufficient heat energy to be come self-sustaining, the combustion process would fail.

The investigations of this chapter have confirmed the findings of previous research concerning the destructive nature of ignition turbulence. New evidence has brought forth explanations for the phenomenon of partial combustion and questions pertaining to the description of the lean flammability limit. The introduction of optical pressure measurement provided new information on the processes and forces present in the infancy of combustion.

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3. GAS PUMP DYNAMICS

When considering the characteristics of plasma jet operation and particularly its ability to transport discharge products to the surrounding atmosphere, it becomes apparent that this property may also be useful to transport gas surrounding the igniter from one zone to another. The benefit of such an ability is illustrated in the situation of an incombustible mixture outside the rich flammability limit. This over-rich mixture could be transformed into a combustible mixture by pumping external air into the mixture zone using repetitive plasma jet operation.

The plasma jet creates, in a region adjacent to its luminous plume, turbulent "eddies" of gas which entrain surrounding gases to form an expanding, propagating, plume of gas (Cetegen et al. [2]). This turbulent plume has been shown to be very effective in propagating particles from the igniter's vicinity and eventually, in the fine scale mixing of the local gas (Simeoni et al. [5]). The transport processes of plasma jets and the development of the turbulent plume have been subjects of considerable interest (Cavolowsky et al. [1], Clements et al. [3], [4]). It is here suggested that by introducing a tube around the igniter, restricting and directing the travel of the plume, it may be possible to effectively harness plume kinetic energy. By operating the igniter repetitively, successive pulses of plume energy would create a pumping effect, transporting gases local to the igniter to some other zone. Eventually, as the frequency of repetition is increased, the convective flows developed inside the tube will progress from pulsing to near "steady-state". Experimental information of this process also provides insight into the complex flows created by plasma jet igniters in the absence of restrictive boundaries (Figure 3.1(b)).

3.1 THEORY

A controlling parameter in the propagation of the plume is the momentum initially imparted to the local gas. This momentum has been measured as a function of various igniter parameters (Smy et al. [6]). It was found that the igniter geometry (cavity length and orifice diameter) has pronounced effects, especially on the depth of jet penetration and turbulence generation. Deposition energy also has marked effects on momentum, although only a small percentage of this energy is converted into kinetic energy of the expelled plasma (Clements et al. [3]). Deposition energy contributes primarily to the volume of the plasma jet.

The imparted momentum determines the subsequent propagation of the plume but, by itself, is not responsible for conditions within the plume. The intensity and scale of the ensuing turbulence is also not the sole result of momentum imparted, but that of the efflux velocity from the

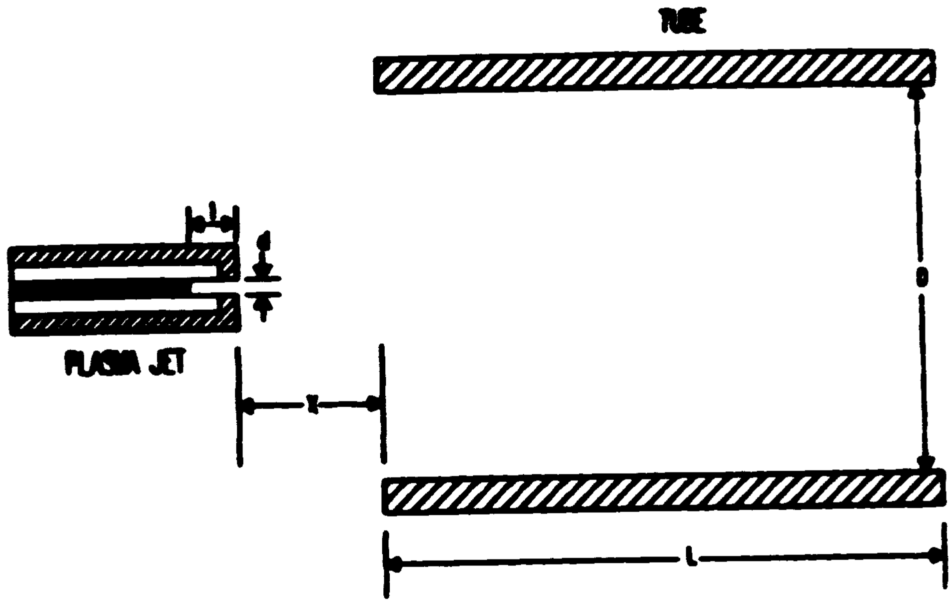

Figure 3.1(a) Plasma Jet Igniter/Tube Combination

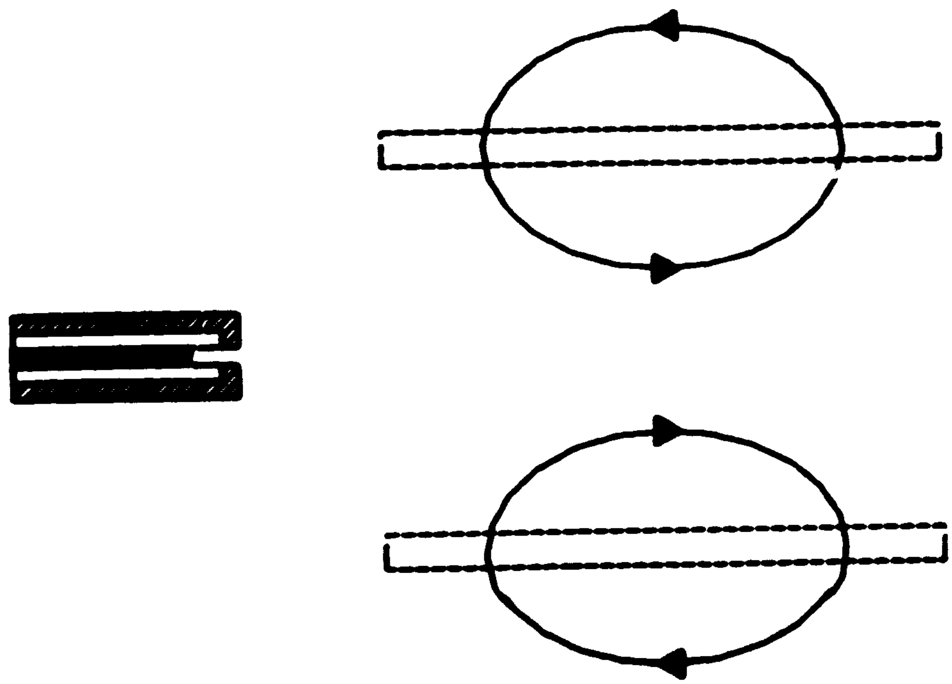

Figure 3.1(b) Plasma Jet Flow Circulation

cavity (Smy et al. [6]).

It has been shown (Smy et al. [6]) that for the plasma igniters used in the forthcoming experiment, the imparted momentum (P) is approximately 40% of the theoretical limit:

$$P = (2Em)^{0.5} \qquad (1)$$

where: E= cavity deposition energy (J)
m= cavity mass ($2 * 10^{-8}$ kg)

The igniter-tube combination of Figure 3.1(a) illustrates the principle that by controlling the momentum imparted to each puff, directed and concentrated flows can be achieved. Orifice diameter (d) dictates the quantity of cavity mass available for expulsion for a given cavity length. For conditions of minimal viscous losses and optimal physical parameters (to be investigated), the flow momentum generated within the tube will be a substantial fraction of the theoretical momentum (1). Hence for an igniter operating at a frequency (f) the momentum imparted per unit time (M) to the gas within the tube will be:

$$\begin{aligned} M &= Pf \\ &= 0.4f(2Em)^{0.5} \\ &= 0.6f(Em)^{0.5} \qquad (2) \end{aligned}$$

Given an experimental method for calculating the repetitive momentum imparted to the local gas surrounding the igniter, it is now possible to derive an expression to describe the volumetric flow rate. Equation (2) may be rewritten as:

$$
\begin{aligned}
M &= \rho Q v \\
  &= \rho Q(Q/A) \\
  &= \rho Q^2/A
\end{aligned}
\qquad (3)
$$

where: ρ = gas density (1.2 kg/m^3)
Q = volumetric flow rate (m^3/s)
v = flow velocity (m/s)
A = flow cross-sectional area ($pi \cdot D^2/4$)
(D = diameter of restricting tube)

Combining equations (2) and (3) and solving for volumetric flow rate (Q):

$$Q = 0.75(Af/\rho(Hm)^{0.5})^{0.5} \qquad (4)$$

Although this final expression neglects the effects of viscosity and other losses, it can be expected to give a reasonable estimation of flows developed by repetitive igniter operation in short tubes. Equation (4) will, of course, decrease substantially for long tubes, as viscous effects will become more pronounced. The error in Q is estimated at ±3%.

Operating the igniter in the absence of a tube, such as depicted in Figure 3.1(b), will result in the circular flow patterns shown. The outward flows described by equation (4) will be balanced by peripheral returning flows. The velocities of such circulating flows will be of similar magnitude to those intercepted by the tube. Thus the latter will give a reasonably accurate indication of the magnitude of the steady induced flows in the igniter's vicinity.

3.2 EXPERIMENTAL METHOD

The pumping characteristics of plasma jet operation was studied by repetitively discharging the igniter (PJI) into a cylindrical inlet tube connected to a large reservoir tank (45 L). Induced air flows within the tube displace reservoir air, resulting in an equivalent volume of air expelled from an exhaust tube. The resultant exhaust flow was measured by a hot-wire anemometer probe (TSI model 1650).

The experimental layout is illustrated in Figure 3.2. Since the plasma supply is the same as that used in Chapter Two, the operation of the supply and the events leading to igniter discharge are identical. Discharge control is provided by a series of equal mark/space ratio square wave pulses originating from a conventional pulse generator (Hewlett Packard 3311A). The examination of pumping performance involved the combinations (1920 data samples) of several parameters:

Frequency (f): 5, 10, 15, 20, 25, 30, 35, 40 (Hz)
Stored Energy (E): 1.2, 1.8, 2.4 (Joules)
Orifice Diameter (d): 1.6, 2.4, 3.2 (mm)
Cavity Length (l): 3.0, 6.0, 9.0 (mm)
Tube Diameter (D): 13, 19, 25 (mm)
Tube Length (L): 76, 152, 228 (mm)
Igniter Position (X): +20,+10, 0,-10,-20,-30,-40,-50 (mm)

The igniter-tube inlet arrangement consisted of the igniter positioned (X) in Figure 3.1(a) relative to the tube entrance plane. Positive values indicate the igniter was positioned inside the tube.

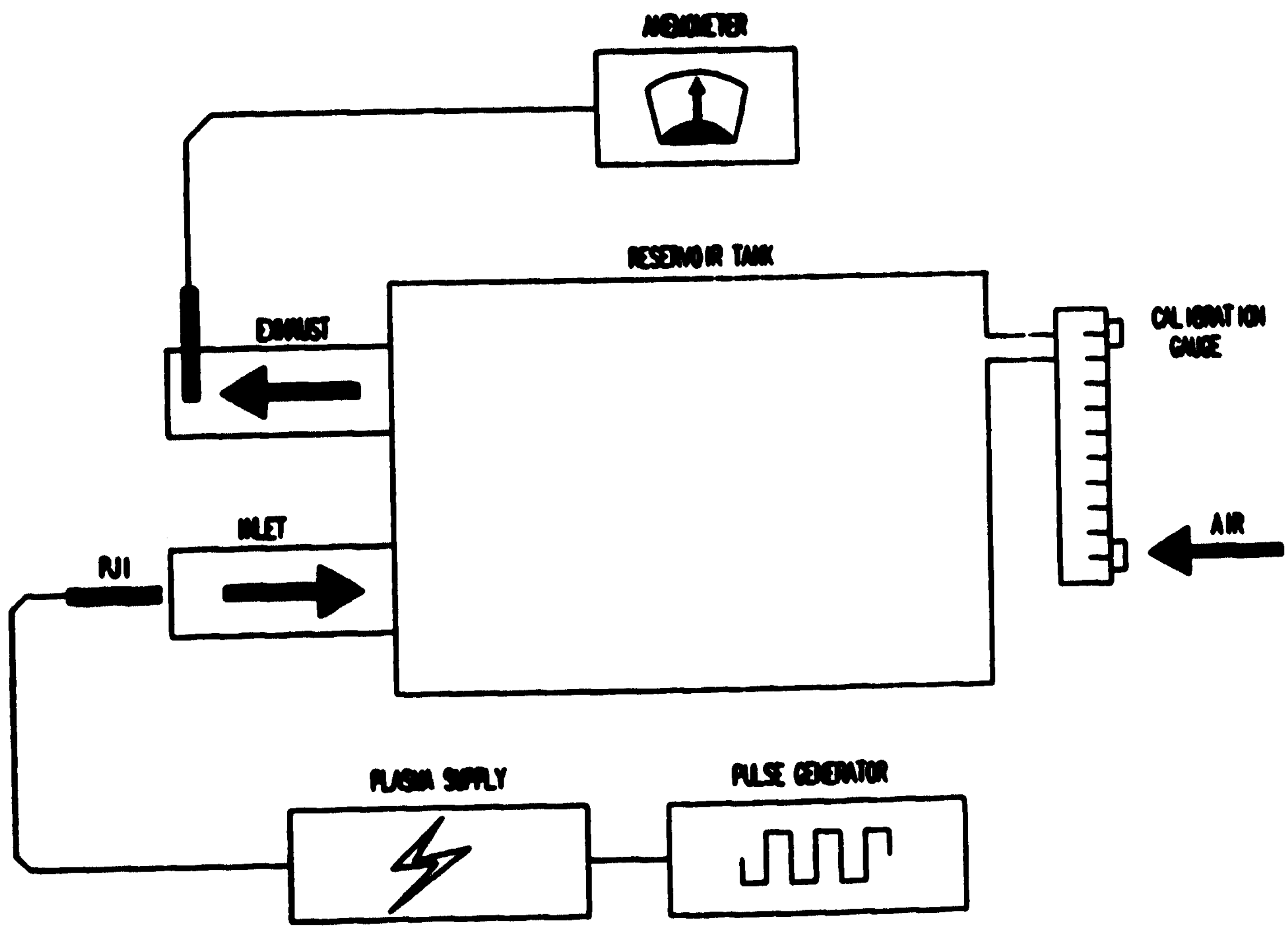

Figure 3.2 Pump Experiment Configurotion

The reservoir tank was required to provide a large volume of air in order to prevent erroneous results from plasma emissions interacting with the flow meter probe. The anemometer chosen, measures gas flow by detecting the change in temperature of a heated probe wire inserted into the flow. The anemometer's reference is the static temperature of the measured gas. Since the discharge of plasma jets produces local gas heating, repetitive operation would eventually heat the gas flow above ambient temperatures (static temperature of the gas). The reservoir tank provided sufficient volume to allow for 30-40 seconds of flow monitoring without adverse effects.

The hot-wire anemometer probe was inserted radially into the exhaust tube to measure the on-axis velocity of the expelled air. This tube was somewhat larger than the experimental inlet tubes, to aid in increasing the sensitivity of flow measurement. Typical hot-wire anemometers have a non-linear response to flow with sensitivity decreasing as flow velocity increases. These devices provide accurate measurements in unknown environments, provided the gas temperature, composition, and density remain unchanged. Accuracy is also dependent on whether the flow entity is compressible and on the level of turbulence (Goldstein [8]). The latter suggests that the velocity recorded by the hot-wire technique represents some combination of turbulent and convective velocities (Clements et al. [4]). The use of a reservoir tank for this experiment improves the accuracy of convective flow measurement by reducing flow turbulence.

Since the anemometer probe measures resultant exhaust flow and not the actual flow at the reservoir inlet tube, a calibration curve was required. This was determined by injecting a measured quantity of air (using a precision ball flow meter (Lab Crest FP-1/4-4-G-6)) into the reservoir tank and measuring the exhaust tube flow with the anemometer. The experimental volumetric flow rate (Q_E) illustrated in Figures 3.3, 3.4, and 3.5 is calculated from the product of measured flow velocity (v) and exhaust tube area (A). Theoretical volumetric flow rate is denoted by Q_T ($= 0.75(\Delta f/p(Em)^{0.5})^{0.5}$). The error associated in measuring Q_E is estimated at ±5% considering air compression with the reservoir, turbulence, and anemometer accuracy.

The experiment was conducted by operating the plasma jet at a desired frequency until a stable flow measurement could be obtained. The reservoir tank was then purged with air to expel heated air inside the tank and to cool the igniter housing, heated by repetitive operation.

3.3 DISCUSSION

To correlate experimental results with the theoretical relationships established previously (eqn. (4)), a similar set of igniter parameters are required as documented by

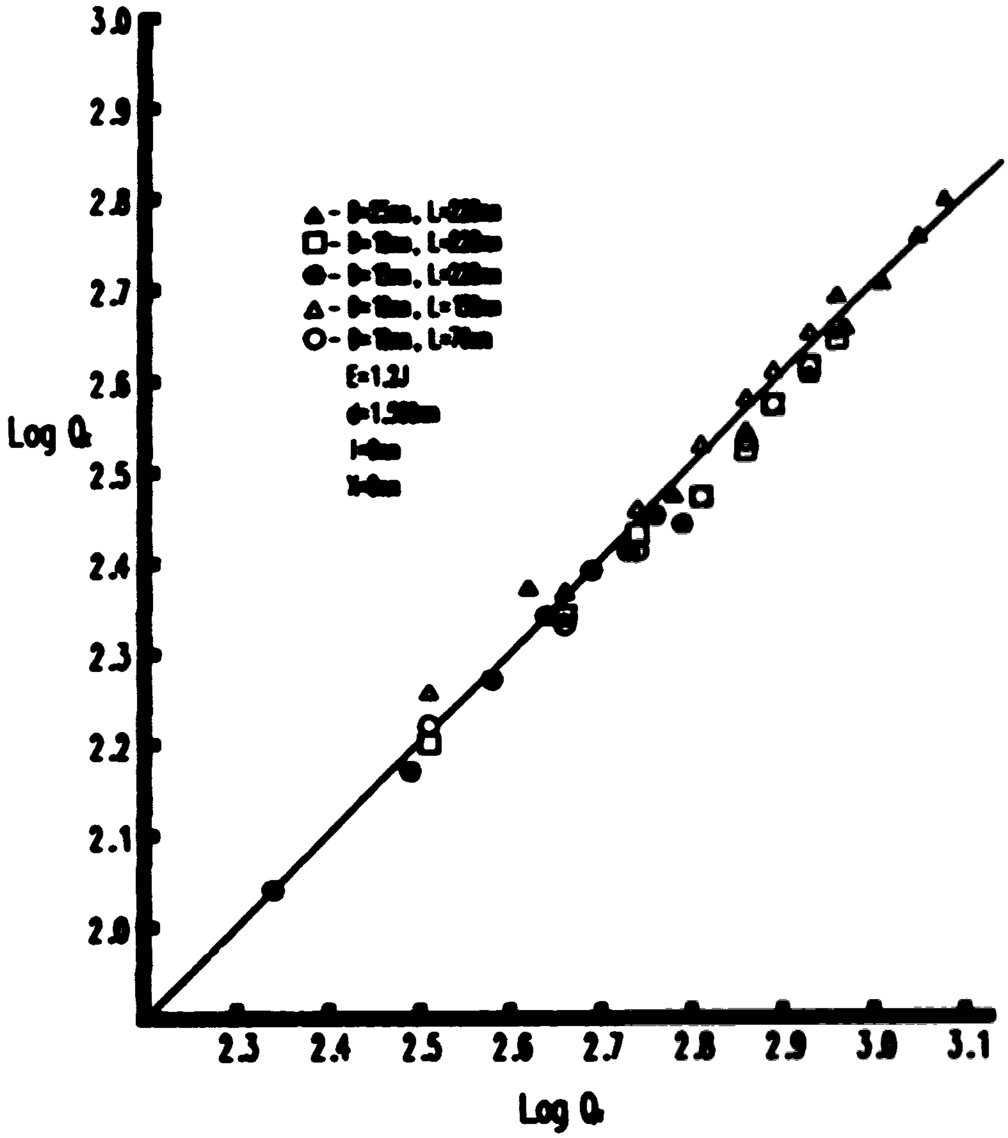

Figure 3.3 Volumetric Flow Rate: Experimental vs Theoretical

Topham et al. [7]. Figures 3.3, 3.4, and 3.5 are for an orifice diameter of 1.6 mm, a cavity length of 9 mm, and a stored discharge energy of 1.2 Joules.

Figure 3.3 depicts a log-log plot of volumetric flow rates; measured (Q_E=vA) versus calculated (Q_T, eqn.(4)), for various tube diameters and lengths positioned at the tube entrance plane Z=0 mm. Good data correlation and the linearity of the best-fit line produces a slope close to unity. This slope, however, is offset by a factor of 0.3 or a converted linear factor of two ($10^{0.3}$=2). This suggests that the original omission of viscous effects and other losses such as turbulence and air compression in equation (4) constitutes a 50% reduction in Q_E from the predicted values of Q_T. Therefore, a more practical equation for Q_T is:

$$Q = 0.4(\Delta f/\rho(Hm)^{0.5})^{0.5} \quad (Z=0mm) \quad (5)$$

Figure 3.4 illustrates volumetric flow rate versus frequency for the same parameters as Figure 3.3. The previous analysis of flow losses becomes immediately apparent by the gap in associated curves for Q_E and Q_T (eqn.(4)). Larger tube diameters permit increased flow velocities since the increased cross-sectional area of the tube inlet reduces flow resistance (created by the fraction entrance area occupied by the plasma jet igniter at Z=0 mm).

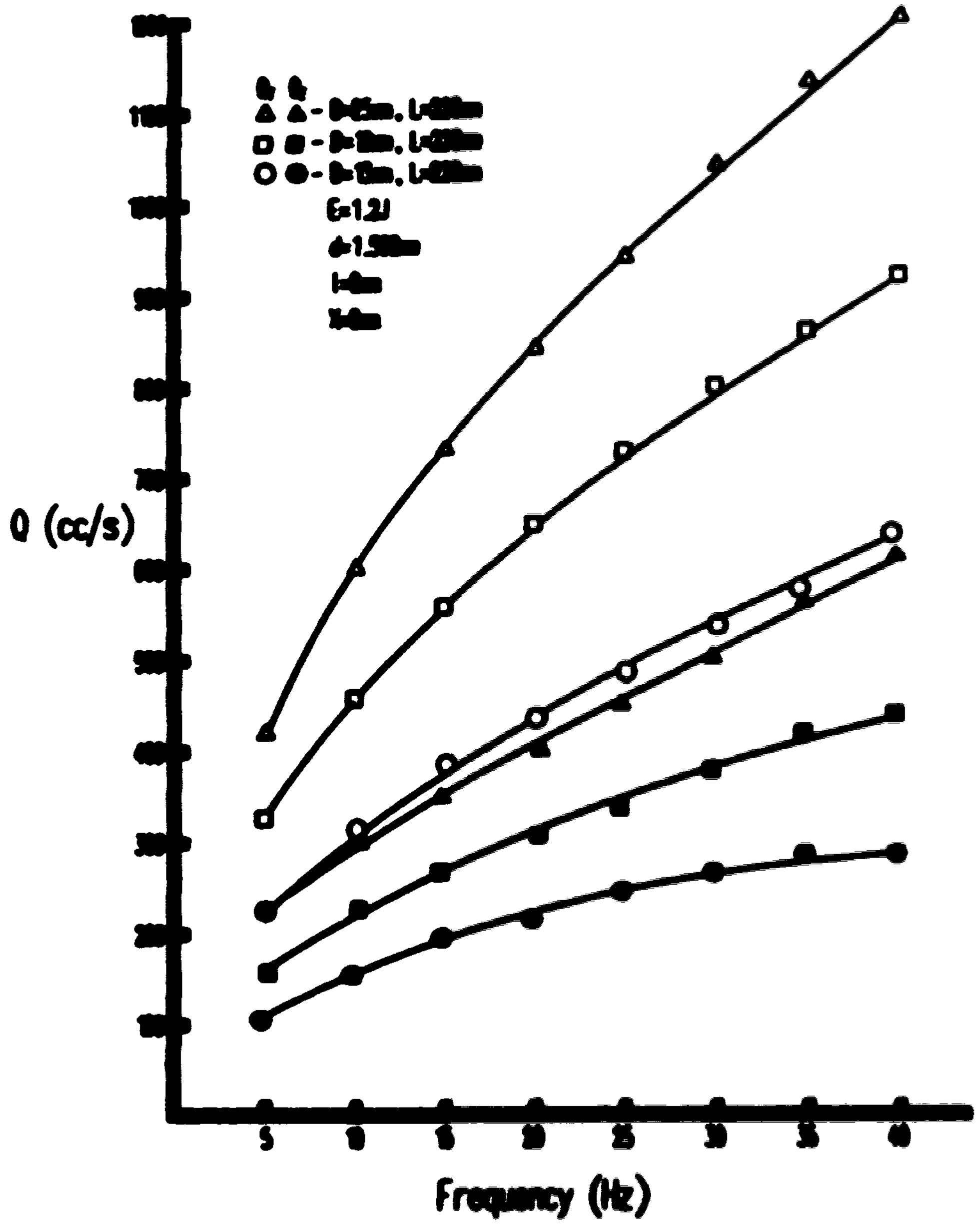

Figure 3.4 Volumetric Flow Rate vs Frequency

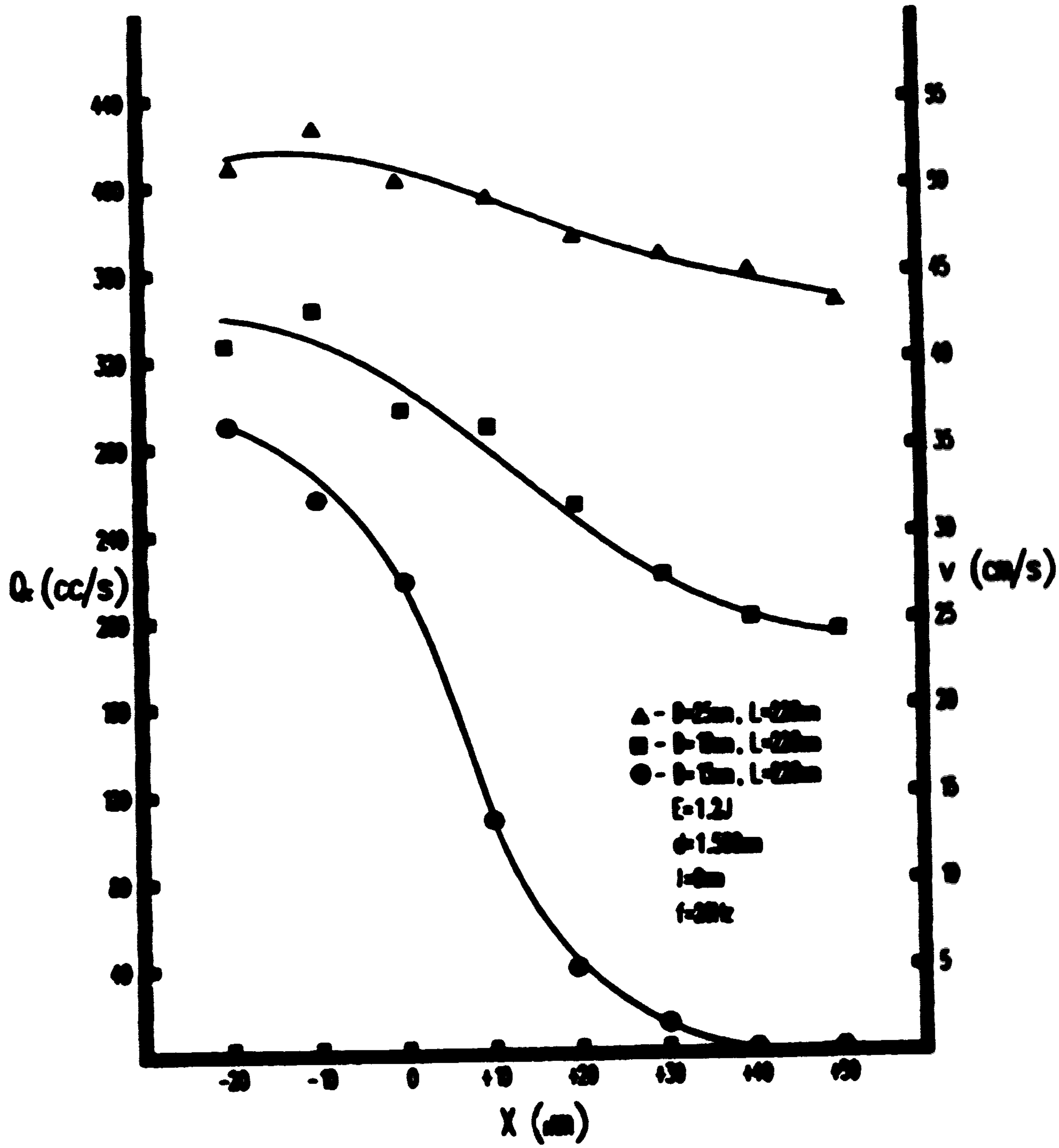

Figure 3.5 Volumetric Flow Rate vs Position

The results of Figure 3.5 indicate the importance of igniter position on flow volume and velocity (v). Maximum flows were obtained for positions outside the tube entrance plane (X=0 mm). Decreasing igniter position X (moving the igniter towards the tube entrance), produced a decline in flow generation. This resulted from greater igniter obstruction of the circulating flows captured by the restricting tube. Small tube diameters displayed very rapid declines in flow generation as the igniter approched the tube entrance. This was due to a larger fraction of tube cross-sectional area obstructed by the igniter.

It was also noted that for igniter positions greater than 20mm and tube lengths shorter than 10mm, virtually no exhaust flow was detected. The absence of detectable flow was due to insufficient control of ignition induced flow patterns. Igniter displacements larger than the scale of local flow patterns would prevent the restricting tube from capturing and redirecting flow energy. Inadequate tube length hampered the conversion of circular flow behaviour into linear flow motion.

3.4 Summary

It has been shown that repetitive plasma jet operation within restrictive boundaries is able to produce a significant gas pumping action. This property is affected by igniter geometry, energy deposition, repetition rate, igniter position, and the dimensions of the restrictive boundary (tube). Measurements indicate a substantial increase in flow volume for increased repetition rates and tube diameters. Optimized flows require the igniter to be positioned outside the boundary entrance but within the physical limits of induced circulating flows. Similar considerations are also required for the length of the restricting tube.

From the momentum imparted to the local gas, an expression for volumetric flow rate (Q) was derived based on ignition parameters and the dimensions of the restrictive tube. This expression was experimentally verified and corrected to compensate for flow losses.

The success of repetitive plasma jet operation in "transporting" local gases, supports the proposed application of implementing this feature to transform incombustible, fuel-rich mixtures into combustible states. Similarly, this pumpng process could also be used for incombustible mixtures beyond the lean flammability limit.

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4. FLARE GAS IGNITION

The ignition of petroleum waste gases is a common method of gas disposal in the petrochemical industry. Combustion provides a safe and efficient method of destroying these gases which are often toxic. The actual combustion procedure varies depending on whether the unwanted gases originated underground or from a refining process. The process of open flame, atmospheric combustion is known as flaring.

Unlike the controlled ignition environments of an automobile engine or a furnace, conditions for flare ignition and combustion are generally unpredictable. The primary reason is inadequate control over such factors as gas composition, flow dynamics, and climate conditions. Current flare designs and ignition methods have failed to show significant improvements or solutions to control these problems (Environment Canada, [3]).

Of the many igniter designs presently employed, few rely solely on electical methods of ignition. This lack of popularity is due primarily to poor ignition reliability of chaotic gas flows, typical of most flaring installations. Apart from this, electronic ignition systems provide distinct advantages over pilot gas systems, particularly in the economics of operation.

Introduced in this chapter is a combustion system designed to explore the ignition performance of plasma jets in a flaring environment. This presents an opportunity to compare both repetitive and single pulse plasma jet ignition performance against conventional electrical ignition. The surface gap igniter was chosen to represent conventional open electrode ignition designs. Single pulse operation is of interest as the majority of electrical systems rely on this mode of operation. Increased flow velocities and near-stagnant flows are investigated for ignition improvement by repetitive ignition.

4.1 INDUSTRY BACKGROUND

Current flaring practices generally involve the destruction of two principle forms of waste gas: sour gas, which typically contains high concentrations of toxic hydrogen sulfide, and sweet gas, whose primary component is methane. Compared to most combustible gases, especially methane, hydrogen sulfide is very flammable. Consequently, sweet gas is generally more difficult to ignite and maintain than sour gas, given equivalent conditions.

Most regulations pertaining to flaring are concerned with destruction or combustion efficiency. It has been established that, given a reasonably stable zone for combustion (with a minimum heat standard of 9 MJ/m^3), efficiencies approaching 98-99% can be achieved (Environment Canada [3]). Although climatic conditions have the greatest influence over flare combustion, the method of ignition is also of importance (Environment Canada [3]).

Flaring as a whole can be categorized into two areas; intermittent and continuous (Leahey et al. [6]). Intermittent flaring involves the random release of waste gas and is generally associated with production facilities. Random releases can be a result of production processes, service shut-downs, or emergency releases due to a fault in the production system. Whatever the case, it is of extreme importance that any ignition system employed be extremely reliable in igniting the flared mixture, with little regard for the aforementioned combustion standards. Continuous flares, however, must abide by such regulations, although their ignition performance can be somewhat relaxed.

The flare system employed for experimentation is modelled after an elevated flare stack. Elevated flares present the best compromise between economics and performance. Coupled with low installation, operation and maintenance costs, these flares provide the safest dispersal of burnt/unburnt gases. Moreover, they require little ground space and possess minimal visibility, noise, and radiation levels.

4.2 EXPERIMENTAL APPROACH

As illustrated in Figure 4.1, the experimental arrangement consisted of a scale model flare stack complete with wind shroud, slip-stream combustor, gas source, and

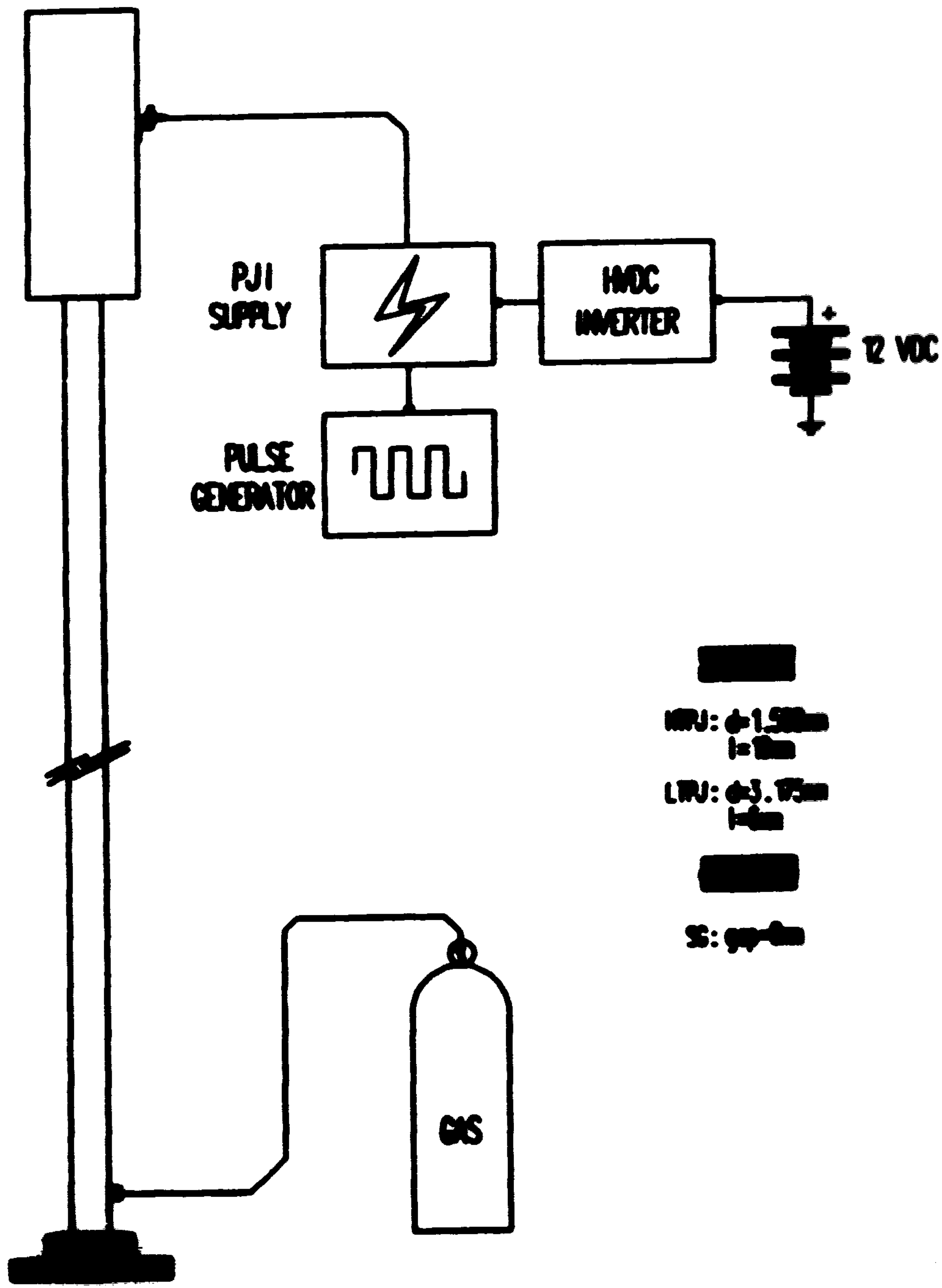

Figure 4.1 Elevated Flare Stack Model

ignition supply. The combustion system was assembled on top of a six storey building, providing the test apparatus with unobstructed exposure to the effects of wind. The model itself was two metres in height with an inside flare tube diameter of 7.62 cm. A simple wind shroud tube was fabricated from rolled stainless steel (Figure 4.2) and was supported by cross members attached to the flare tube. Wind shrouds are often incorporated to provide several important functions such as prevention of flame blow-out, providing a stable zone for ignition, and increasing combustion efficiency through flame stabilization. The grating at the shroud tip as shown in Figure 4.2 is to help subdue the effects of wind and to aid in flame stabilization.

Figures 4.2 and 4.3 illustrate the arrangement of components employed to direct, mix, and manipulate combustion gases. A combustion tube assembly was located a short distance above the flare tube exit to catch and divert a small portion of the flare gas (slip stream) towards an ignition zone. Separated from main stream, this slip stream travelled up the ignition tube until it encountered a group of orifice holes (turbulence plate). Positioned downstream and perpendicular to this plate was the test igniter, projecting from a viewport entrance. Once ignited, the ensuing combustion wave would propagate up the flame tube where it was redirected towards the main stream flow thereby creating ignition of the main stream gases.

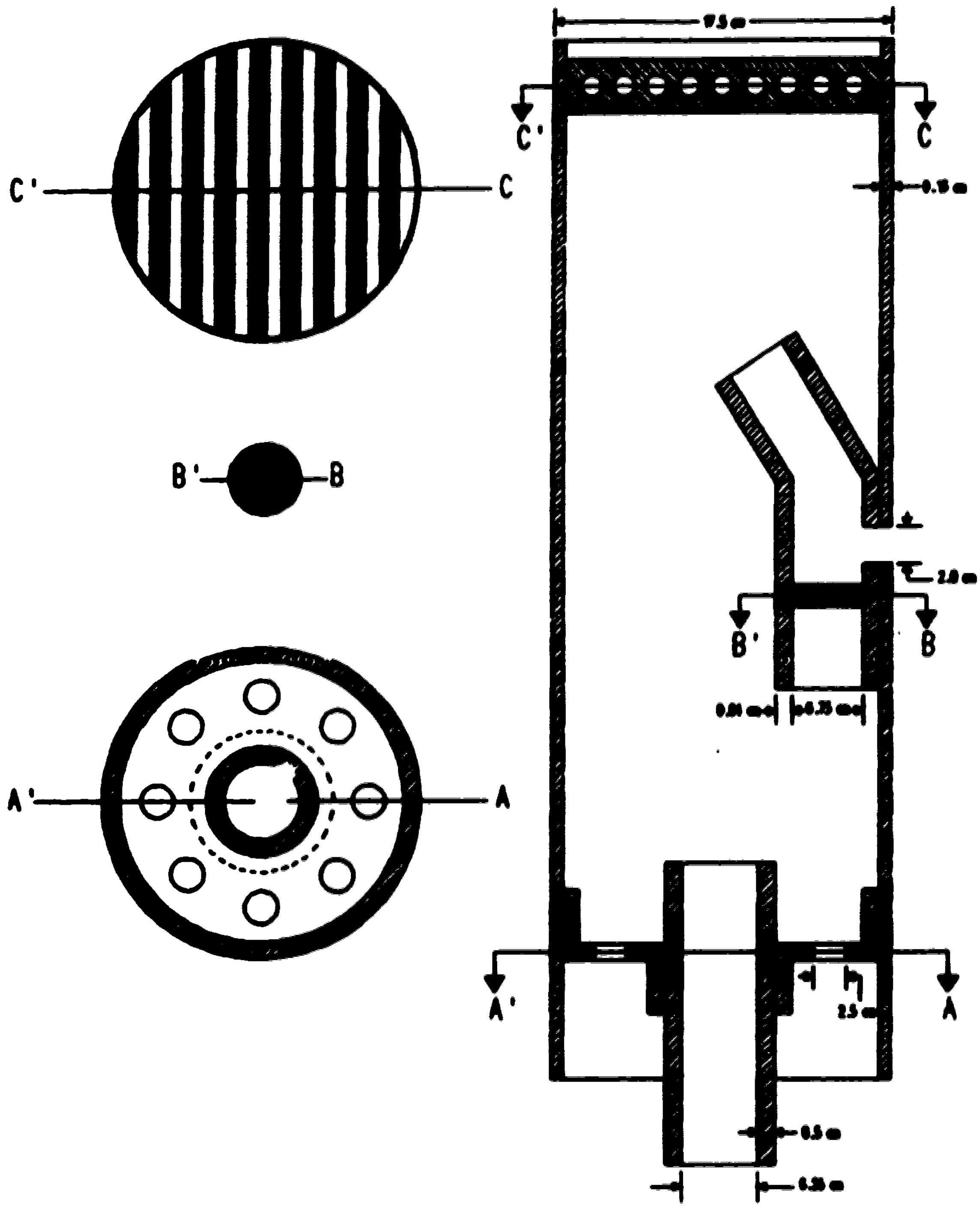

Figure 4.2 Wind Shroud Assembly

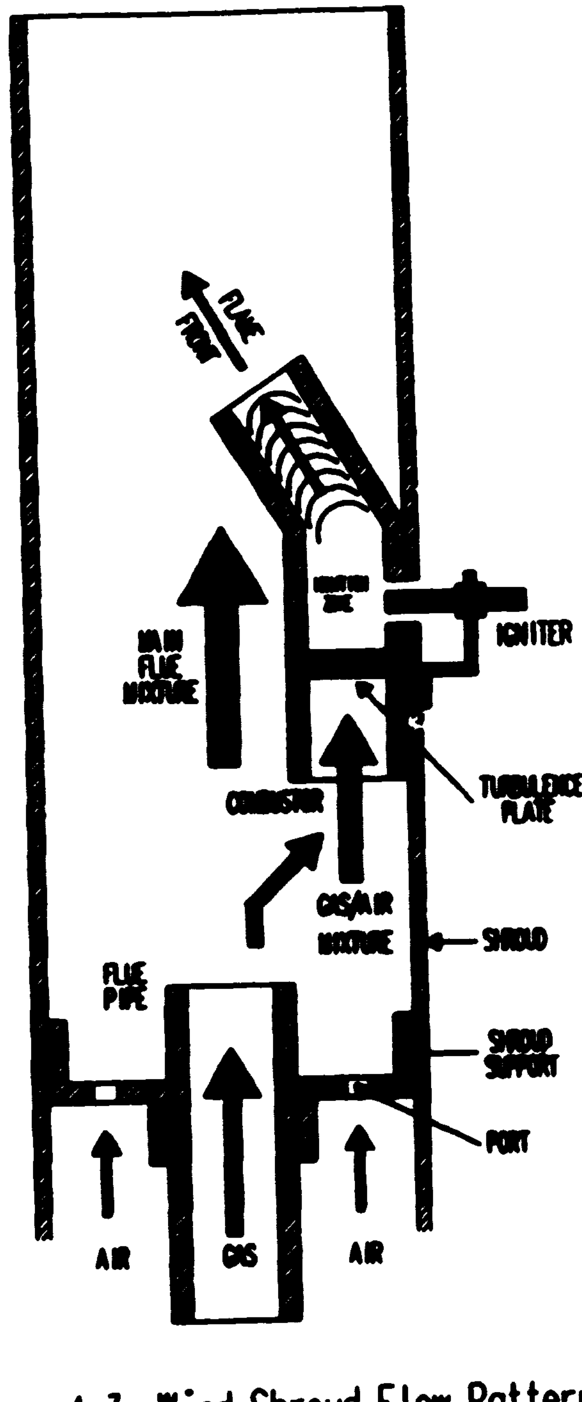

Figure 4.3 Wind Shroud Flow Patterns

This system is an example of slip stream, flame front ignition, a popular method for both electrical and pilot gas systems.

The purpose of the turbulence plate was to initiate mixing in the ignition zone. Gases passing through this plate obstruction would produce multiple turbulent zones upon exit, promoting mixing with air inside the flame tube or air "injected" by plasma jet operation at the time of ignition (Lewis [7]). The turbulence plate also served to slow down the slip stream gases for improved ignition reliability and to protect the igniter from carbon contamination from combusting gases passing up through the combustor entrance.

Unlike a field test site, actual sour/sweet gas mixtures were not available for direct study. Propane was selected as a model gas to simulate some of the conditions encountered by sour gas installations. Commonly used as pilot gas fuel, low propane flows behave in a similar fashion to low flow sour gas situations. Inside a wind shroud, the heavier-than-air gas "chokes" the combustion zone with an over-rich incombustible mixture. Unlike current electrical methods, repetitive plasma jet igniter operation may produce eventual ignition success by "agitating" the mixture, statistically improving the chances of obtaining ignition (Kono et al. [4]).

Methane was chosen for simulating sweet gas conditions since methane is usually the major component. High flows were only available using methane, since its vapour pressure is much higher than that of propane. The increased vapour pressure also allowed for experimentation at sub-zero temperatures.

With the narrow flammability limits of methane (5.3-14% by volume) and propane (2.2-9.5% by volume), ignition success under these conditions would suggest substantial ignition improvements for sour gas flaring given the wide flammability range of H_2S (4.3-45% by volume, Matheson [5]). Sweet gas flaring would also benefit if plasma jet ignition performance surpassed conventional (surface gap) ignition.

4.3 DATA COLLECTION

The repeatability of the data collection process, apart from prevailing climatic conditions, was primarily dependent upon the time required for the test gas to establish steady flow conditions. This delay time was approximated by a series of ignition tests for three flow categories; low (<100 cm/s), medium, and high (>200 cm/s). Experimentation revealed approximate delay times of 60, 30, and 20 seconds respectively, producing satisfactory repeatability for mild climatic conditions. Stronger wind conditions and random gusts required increased times.

Data was collected and assessed according to two criteria: number of single pulse attempts to achieve ignition, and ignition success of repetitive igniter operation over a given time frame. These methods of evaluation were chosen after considerable experimentation and examination of preliminary test results. To the author's knowledge, they are presented here for the first time.

Single pulse performance was judged by recording the number of pulse attempts (two second intervals) required to achieve ignition, to a maximum of ten. The data illustrated in Figures 4.4-4.6 are the average of five trials. In an attempt to obtain data from comparable conditions (eg. wind), many are the result of experiments performed weeks apart. The majority of results to be discussed are based on this criterion. This method was chosen for similarities with convention ignition methods (electronic) and reduced error probability (Birch et al. [1]).

Repetitive igniter operation was studied for three frequencies (2, 5, 10Hz), over a time frame of five seconds. Ignition was recorded as "successful" if ignition occurred within the specified time. Judging ignition success over this time period was more practical and accurate than attempting to ascertain the true time of ignition. For example, operating at a frequency of 10Hz, it was nearly impossible to visually judge which pulse initiated ignition.

Once a steady flow of gas was established through the flare stack prototype, the igniter under test was operated until ignition occurred or specific time/pulse limits were exceeded. If ignition was successful, the gas supply was removed. This allowed the resultant flare to eventually extinguish itself as it consumed the remaining gas in the flare pipe.

4.4 DISCUSSION

With the exception of intentional flame extinction, the above procedure is similar to actual flare ignition. Most field systems, however, will continue to attempt ignition indefinitely until success is achieved. The response of the model system to both ignition and climatic variances was quite realistic. Its behaviour in wind, for example, despite the consistency of gas flow and composition, displayed the common effects of periodic blow-out, flow stagnation, and delayed ignition. These effects become more pronounced for increased wind velocities and especially so for low gas flows. Increased gas flows produced more stable flares under strong wind conditions but were more difficult to ignite (Figure 4.5). It is understandable that compounding wind effects with other uncontrollables (gas composition, flow, etc.) presents a difficult challenge for reliable and predictable ignition success in field applications. Despite the aforementioned, plasma jet ignition was able to enhance ignition reliability over conventional ignition (surface gap).

4.4.1 Repetitive Operation

The investigation of repetitive igniter operation was conducted using only one plasma jet geometry for comparison against surface gap ignition. Figure 4.4 illustrates the performance results of the two igniters for both model gases. Comparing either methane or propane ignition results, the plasma jet displayed improved performance over its surface gap counterpart in achieving successful ignition for higher flow velocities. Although a low wind was present, the experimental error introduced is considered minimal (est. ±10%) given the general consistency of the data collected not only for this experiment but also for other tests under similar climatic conditions.

Progressive increases in operational frequency produced a sharp advancement in plasma jet response, a proportionally greater improvement than for the surface gap. Although only the methane data supports this, the increased advancement is plausible considering the influence of plasma jet ignition on local flows. It has been shown (Chapter Three) that increasing the frequency of plasma jet operation elevates the device's influence over local flow patterns. Given this added control, improved ignition reliability would be possible for larger global flows and/or

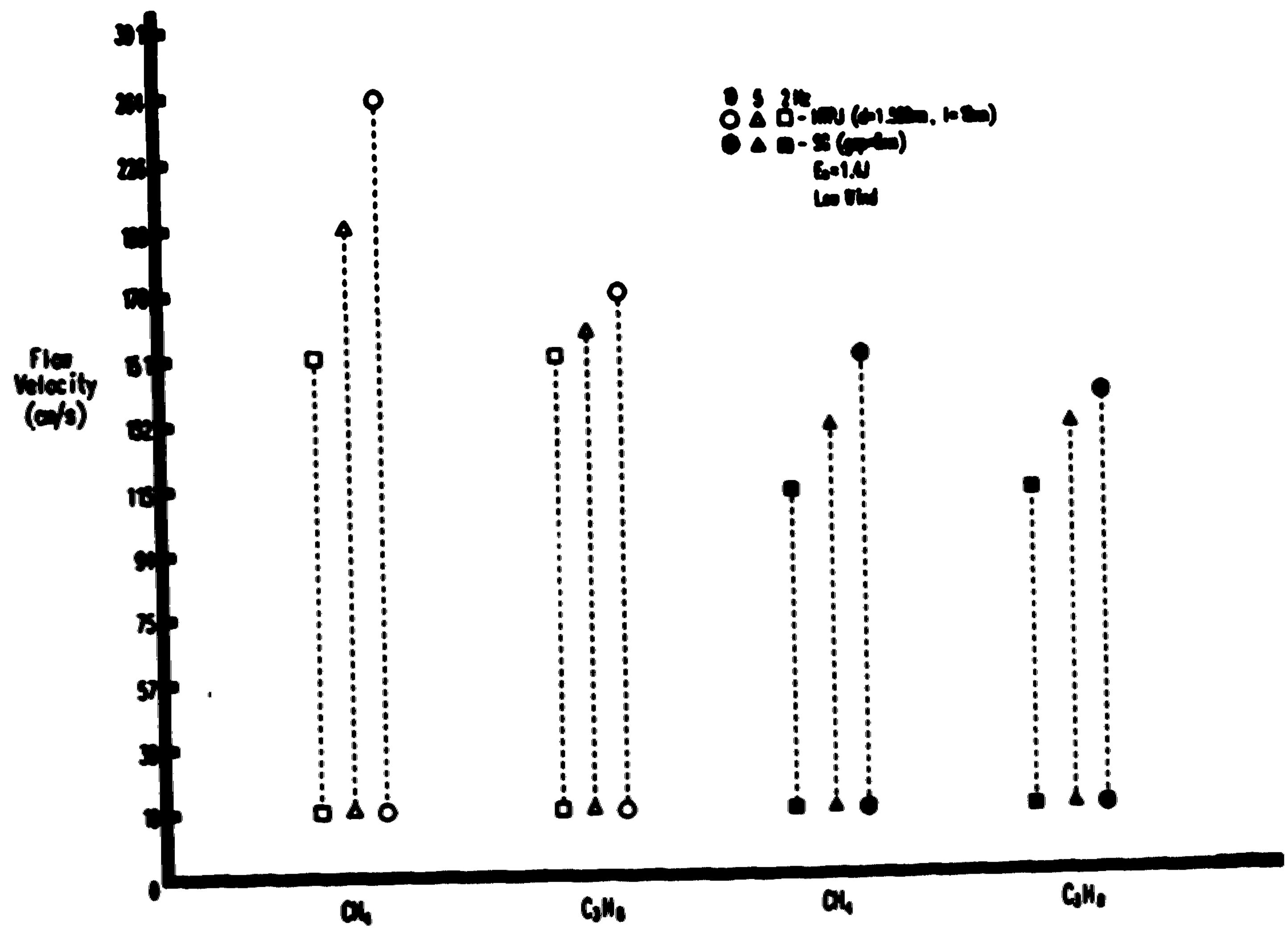

Figure 4.4 Repetitive Ignition Performance

stronger wind conditions. The propane ignition results are different primarily because of climatic variations between the experiments (wind, temperature, humidity) as opposed to chemical composition (since the flammability limits of the two gases are close; 5.3-14% (CH_4), 2.2-9.5% (C_3H_8) by volume.

To investigate the phenomenon of wind shroud "choking", a propane flow of approximately 5 cm/s was allowed to fill the test model shroud for several minutes (slip stream combustor removed). Visual observations from beneath the shroud indicated that this flow rate was adequate to continuously choke a large portion of the shroud volume. The test igniter was then energized repetitively at a frequency of 10Hz.

With this near-stagnant, incombustible condition, repetitive plasma jet (HTPJ) operation was able to create ignition in three of five attempts (one minute maximum). Repetitive surface gap ignition failed in each of its five attempts, even after the fifth attempt was continued for more than a minute. Flow inconsistencies within the shroud are suspected for the two plasma jet failures as well as the mixture limits of C_3H_8 (2.2 - 9.5% by volume). Under H_2S conditions, significantly better results would be expected for both igniters given the wider flammability range of H_2S (4.3 - 45% by volume).

The success of repetitive plasma jet ignition is credited to the recirculating flow patterns induced by the device. These flows would begin to influence the pooled gas on a large scale, slowly agitating the gas to mix with resident air in the shroud. Eventually, the mixture would transform into a combustible mixture. The improved energy conversion capabilities of the plasma jet (Section 2.2.1) would also be a factor, delivering more energy per pulse.

Although not investigated, it is doubtful that single ignition attempts would achieve similar results. If the time span between successive pulses was too large, individual pulse contributions would fail to collectively induce global gas mixing. The initial condition of inflammability would persist, unaffected by ignition source operation. Single pulse operation would also deliver less energy to the local gas than repetitive ignition, reducing ignition reliability (Kono et al. [4]).

4.4.2 Single Pulse Performance

Illustrated in Figure 4.5 is a single pulse performance comparison of the high turbulence plasma jet (HTPJ), low turbulence plasma jet (LTPJ), and the surface gap igniter (SG). All three igniters were operated from a conventional plasma jet supply utilizing methane as the test gas. The sharp rise at the end of the SG and LTPJ curves indicates a dramatic increase in the number of

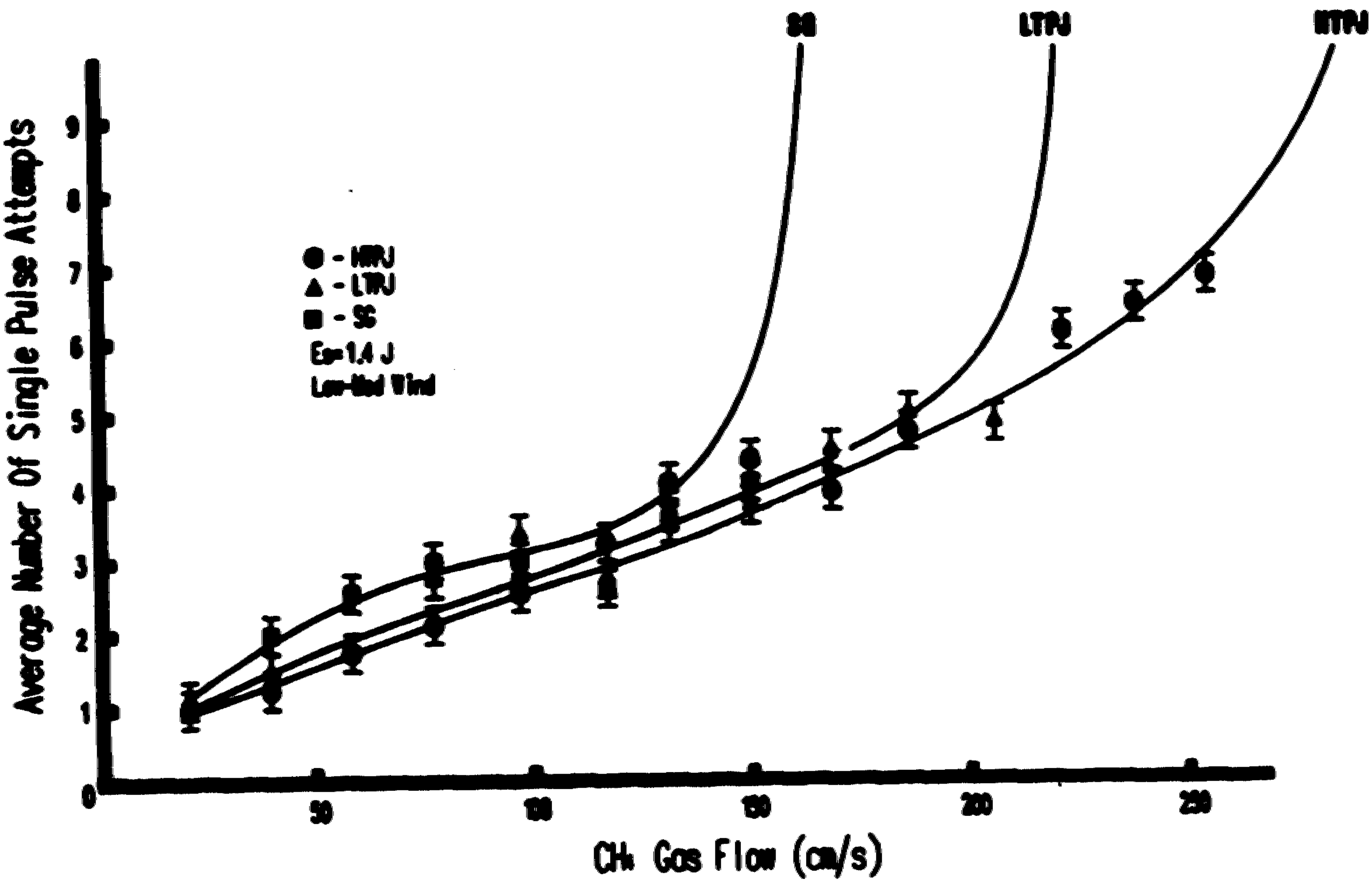

Figure 4.5 Ignition Success vs Gas Flow

ignition attempts required to achieve ignition for the next flow increment (19 cm/s). This behaviour is not illustrated for the HTFJ since 250 cm/s was the flow limit for the methane source. The data presented was compiled from experiments performed weeks apart in an effort to accumulate results under similar climatic conditions.

The ability of the HTFJ device to ignite higher flow rates is directly related to the increased intensity of induced local flows. For a given gas flow, the turbulence generated by the HTFJ would be affected to a lesser degree by flow parameters than LTFJ turbulence. This would enable the HTFJ to have continued ignition success as flow velocity increased. Chomiak [2] observed similar results and concluded that establishing a small scale turbulent zone near the point of ignition was the most efficient method of improving the ignition of turbulent mixtures. The larger energy conversion efficiency of the HTFJ also contributes to improved performance. Similar explanations of turbulence and conversion efficiency support the increased ignition success of the LTFJ device over surface gap ignition.

Figure 4.6 illustrates the ignition performance of the HTFJ under medium (10-20 kmh) and high (>20 kmh) wind conditions for single pulse operation. Despite the presence of the wind shroud, changes in wind velocity were able to significantly influence ignition success. This suggests

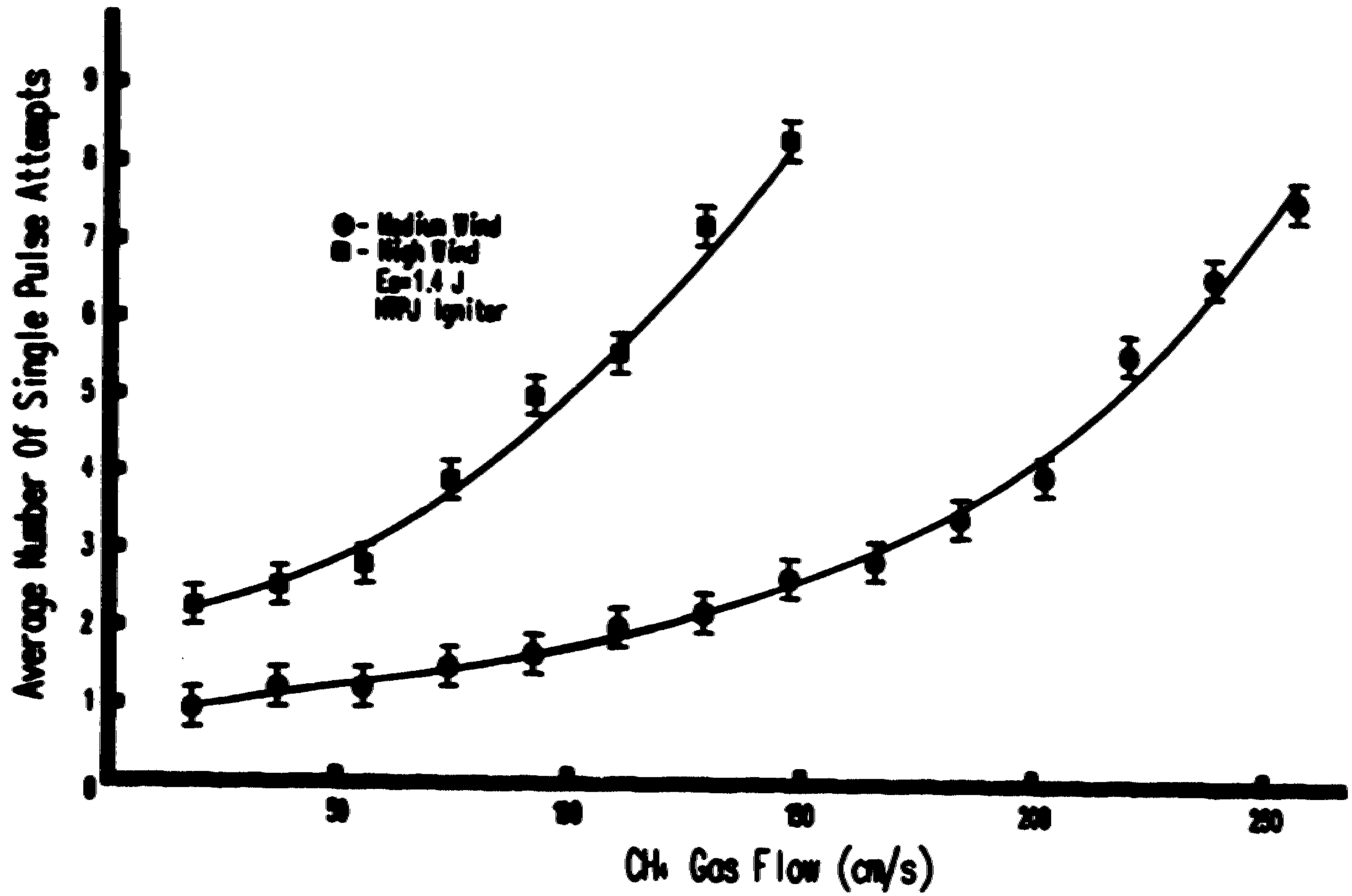

Figure 4.6 Wind Effects On Ignition Success

that to improve ignition performance under such conditions, attention must be focused towards effective wind shroud design as well as of alternate ignition sources.

The chaotic behaviour of the prevailing winds did provide evidence of how some ignition attempts, whether single pulse or repetitive, fail. By observing ignition attempts up through the bottom of the wind shroud, it was seen that ignition sometimes occurred successfully within the ignition zone, only to be extinguished as the flame propagated up the flame tube. Sometimes the flame front did manage to reach the main flare gases only to be extinguished by highly turbulent and/or incombustible flare gases.

4.5 Summary

Despite improvements in ignition reliability, the level of success achieved by plasma jet ignition (or any other source) was directly dependent upon wind conditions. A substantial reduction in ignition performance was detected for moderate increases in wind velocity. Further research is necessary to discover methods of reducing wind effects.

The investigations of this chapter have indicated that plasma jets provide improved ignition performance over conventional flare ignition methods. Repetitive ignition of flowing mixtures revealed that through its hydrodynamic properties, plasma jet ignition was able to establish control over local flow patterns. This allowed the device to ignite mixtures of higher velocity than those for surface gap ignition.

The generation of local flow patterns was also responsible for successful ignition of low flow conditions. Repetitive plasma jet operation was eventually able to ignite a fuel-rich zone of gas, a failure for surface gap attempts. The level of energy deposited to the local gas by the plasma jet is also suspected as a contributing factor.

Investigation of single pulse ignition again revealed the benefits of plasma jet operation. The HTPJ displayed ignition success for larger gas velocities than the LTPJ. The LTPJ provided a similar performance improvement over the surface gap ignition. As before, the hydrodynamic properties associated with plasma jets are responsible.

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5 SUMMARY & CONCLUSION

The studies of the previous three chapters lead to several important conclusions regarding the effects of plasma jet hydrodynamics on combustion.

It has been shown that for moderate mixtures, the plasma jet igniter is capable of increasing combustion speed and performance over conventional ignition methods. An important factor in this process is the turbulent nature of the ejected plasma plume. Near the lean flammability limit, however, this turbulence has been found to inhibit flame development in the early phases of combustion. Combustion enhancement with plasma jet ignition rapidly declines near the lean flammability limit, eventually displaying inferior performance to that generated with conventional surface gap ignition. The surface gap igniter successfully produced ignition and partial combustion beyond plasma jet limitations. Optimization of plasma jet operational and geometric parameters is essential in reducing turbulence generation to achieve ignition success and combustion of lean mixtures. Turbulence reduction is possible by increasing plasma jet orifice diameters and/or reducing its cavity length.

The improved ignition reliability of surface gap ignition over plasma jet ignition suggests the importance of igniter characteristics in the determination of the lean flammability limit. Both the "position" of the lean boundary and the range of partial combustion are affected by igniter characteristics. A description of the lean flammability limit for igniters of negligible turbulence generation may be best represented as a "transition" region, instead of a discrete boundary. This would also provide an illustration of the partial combustion characteristics associated with individual igniters.

Partial combustion with surface gap ignition was investigated as a function of igniter deposition energy. Under these conditions of low turbulence, it was shown that the energy delivered to the local gas by the igniter was able to heat the gas sufficiently to provide a temporary combustible mixture. The volume of the heated gas was found to be directly related to the amount of energy delivered by the igniter. Partial combustion persisted until external heat losses forced its extinction.

Observations of early stage combustion pressures and pre-combustion mixtures were greatly enhanced by using interferometric techniques. This optical pressure detector provided a significant improvement in measurement sensitivity and accuracy over mechanical transducers. Optical distortions, however, produced by latter stage combustion, limited the useful range of optical pressure detection. Consequently, a piezoelectric pressure transducer was used to record pressure fluctuations in the latter combustion stages. A complete combustion pressure profile was assembled from early stage interferometer data and latter stage pressure information detected by the piezoelectric transducer.

While previous studies of plasma jet hydrodynamics have focused on the ignition aspects of the device, the hydrodynamics of the plasma jet may be harnessed to provide gas pumping. As a result of a plasma jet igniter's momentum transfer characteristics, it was shown that if operated repetitively and placed near the entrance of a restrictive tube, the plasma igniter is capable of transporting air (or fuel) from one region to another. This action could be used to transform a previously incombustible mixture into one capable of ignition and sustained combustion.

Measurements confirmed the standard relationship of increased flow volume (and velocity) for increased repetition rates and tube diameters. Altering igniter geometry (supportive of high turbulence fields) and increased discharge energies also produced increases in gas flow. A practical expression relating volumetric flow rate (Q) to the aforementioned parameters was derived ($Q = 0.4(Af/p(Em)^{0.5})^{0.5}$). Optimal flows required the igniter to be positioned outside the entrance of the surrounding tube but within the physical limits of local flow patterns produced by plasma propagation.

A final study was conducted to examine both the pumping and ignition aspects of plasma jet hydrodynamics in a practical environment. The hostile environment posed by elevated waste gas flaring was chosen to test the plasma jet igniter for improvements in ignition reliability. Current methods of electrical ignition have displayed poor ignition performance, plagued by unpredictable variances in flow velocity, fuel composition, and the influences of wind. Low flow and/or near-stagnant gas flows in wind shrouds also present a barrier to ignition, producing an incombustible zone of gas, resulting from inadequate fuel/air mixing.

Repetitive plasma jet operation was used to significantly improve ignition reliability in the above situation. The plasma jet provides direct transport of outside air to the fuel-rich zone, inducing a more flammable ignition situation. Mixture fluctuation and a net increase in energy delivered to the ignition zone would statistically improve ignition reliability. Both a plasma jet igniter and a surface gap device (representative of current ignition designs) were operated repetitively within a wind shroud, choked with an incombustible, fuel-rich mixture. The plasma jet was successful in achieving ignition in three of five attempts. The surface gap device failed in all attempts to achieve ignition.

It is generally the practice of most electrical ignition methods to deliver ignition energy in single bursts rather than repetitively over a long time span. A study of single pulse ignition reliability revealed that the plasma jet igniter was able to produce ignition for higher gas flow velocities than surface gap ignition. The ability to ignite faster moving flows is attributed to the hydrodynamic properties of the plasma jet device, establishing control over local flow patterns.

In short, results indicate that partial combustion occurs over a range of mixtures and is dependent on the ignition characteristics of the igniting source. The degree of combustion achieved is greatly affected by turbulence local to the combustion zone. The degree of combustion also indicates the characteristics of the region between full and no combustion, the limit region of lean flammability. It has been shown that the hydrodynamics of plasma jet operation inherently produces a pumping action which has proved useful in mixture control. Plasma jet hydrodynamics have also been found to improve the ignition of flowing mixtures.

Results indicate that the hydrodynamic properties of plasma ignition can be both productive and destructive under different environmental and operational conditions. The necessity of igniter induced turbulence for local flow control versus its destructive properties towards ignition, presents a difficult design problem for applications requiring both flow control and a gentle ignition environment. The implementation of plasma jet ignition requires not only consideration of the operational parameters and physical attributes of the device but also the desired goal to be achieved by its use. This goal will dictate which operational and physical parameters are chosen and how each is utilized for optimized performance.