Experimental investigation of a liquid-gas dual-swirl coaxial injector under self-pulsation

Isheeta Sunil Ranade
EXPERIMENTAL INVESTIGATION OF A LIQUID-GAS DUAL-SWIRL COAXIAL INJECTOR UNDER SELF-PULSATION

by

Isheeta Sunil Ranade

A THESIS

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We, the undersigned members of the Graduate Faculty of the University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements of the degree of Master of Science in Aerospace Systems Engineering.

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ABSTRACT
The School of Graduate Studies
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Degree Master of Science College/Dept. Engineering/Mechanical and Aerospace Engineering

Name of Candidate Isheeta Sunil Ranade
Title Experimental Investigation of a Liquid-Gas Dual-Swirl Coaxial Injector Under Self-Pulsation

Liquid-gas swirl coaxial injectors in liquid rocket engines can produce self-excited, and self-sustained oscillations called self-pulsations that result in spray oscillations and high-intensity pressure fluctuations. The objective of this thesis is to determine the onset of self-pulsations, marked by a stability boundary over a range of liquid and gas momentum flux values. Cold-flow injector tests are performed to investigate the self-pulsation phenomenon in a dual-swirl coaxial injector using water and nitrogen to simulate liquid and gas propellants used in liquid rocket engines. Three geometric configurations are tested: non-recessed, and recesses of 1 mm and 2 mm. The recess length is the length that the inner swirl post is recessed from the injector face. The parameter space investigated encompasses propellant momentum flux values from 12.67 to 71.83 kPa for the liquid, and 6.7 to 648 kPa for the gas. Sound measurements and high-speed videography images are used to determine the onset of self-pulsations, which marks the lower stability boundary.

Self-pulsations are observed for the dual-swirl coaxial injector element for both, recessed and non-recessed configurations. For the two recessed configurations, as the recess length increases, the self-pulsation zone becomes wider because the onset of self-pulsations is observed at lower gas momentum flux values. For 1 mm recess, the gas to liquid momentum flux ratio at the stability boundary covers a range of 2.6 to 8.0, while for
2 mm recess, the gas to liquid momentum flux ratio at the stability boundary covers a narrower range of 1 to 3.5. Thus, between the two recessed configurations, the 1 mm recess configuration is preferable as it provides a wider range of stable operating conditions. The lower stability boundary for the non-recessed configuration lies between the boundaries of the recessed configurations, with gas to liquid momentum flux ratios ranging from 2.5 to 4.4 at the boundary. The trend with increasing liquid momentum flux is similar to that recorded for the 2 mm recess configuration, however, unlike the 2 mm recess configuration, the gas momentum flux value for the non-recessed configuration has to be at least twice that of the liquid momentum flux value in order to incite self-pulsations. This allows for a marginally wider stable zone, resulting in more stable operating conditions. The uncertainty of the water and nitrogen momentum flux measurements were calculated to be 7% and 14% respectively.

The inner swirl post is modeled as a quarter-wave resonator to determine if it has potential to incite and exacerbate self-pulsations due to resonance. The calculated first quarter-wave resonant frequency, 1420 Hz, lies within the dominant acoustic frequency range of 1000 to 3400 Hz, which is determined by an FFT analysis of the sound emissions across the self-pulsations zone for the recessed configurations. The swirl post, therefore, may act as a potential internal oscillator that could act by itself or through coupling with other internal/external oscillators to excite and sustain self-pulsations.
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<tr>
<td>$A_{ortifice}$</td>
<td>Orifice area</td>
</tr>
<tr>
<td>$A_{tang.holes}$</td>
<td>Area of tangential entry holes</td>
</tr>
<tr>
<td>$A_{ann}$</td>
<td>Gas annulus area</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>$c_{mix}$</td>
<td>Mixed acoustic velocity in the swirl post</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Coefficient of discharge</td>
</tr>
<tr>
<td>$d_{ann,out}$</td>
<td>Fuel post diameter</td>
</tr>
<tr>
<td>$d_{ann,in}$</td>
<td>LOX swirl post shaft diameter</td>
</tr>
<tr>
<td>$d_{in}$</td>
<td>Diameter of inlet channels</td>
</tr>
<tr>
<td>$d_n$</td>
<td>Nozzle diameter</td>
</tr>
<tr>
<td>$d_{vc}$</td>
<td>Vortex chamber diameter</td>
</tr>
<tr>
<td>$f_{cut}$</td>
<td>Acoustic cut-off frequency</td>
</tr>
<tr>
<td>$f_n$</td>
<td>Swirl post quarter-wave resonant frequency</td>
</tr>
<tr>
<td>$f_{sp}$</td>
<td>Self-pulsation frequency</td>
</tr>
<tr>
<td>$h$</td>
<td>Liquid film thickness</td>
</tr>
<tr>
<td>$K$</td>
<td>Fluid bulk modulus</td>
</tr>
<tr>
<td>$L_{1 \rightarrow 2}$</td>
<td>Recess Length</td>
</tr>
<tr>
<td>$L_{in}$</td>
<td>Length of inlet channels</td>
</tr>
<tr>
<td>$L_{inj}$</td>
<td>Overall length of the swirl post</td>
</tr>
<tr>
<td>$L_{vc}$</td>
<td>Length of vortex chamber</td>
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$n$ Mode; whole number multiple of fundamental frequency

$P$ Pressure

$P_v$ Vapor pressure of water

$R$ Universal Gas Constant

$Q$ Momentum flux

$q$ Dynamic pressure

$T$ Temperature

$x_{atten}$ Axial attenuation distance

$\rho_L$ Density of water

$\rho_G$ Density of nitrogen gas

$u_L$ Velocity of water

$u_G$ Velocity of nitrogen gas

$m_{water}$ Mass flow rate of water

$m_{nitrogen}$ Mass flow rate of gas

$\mu_L$ Dynamic viscosity of water

$\gamma$ Specific heat ratio

$\Delta P$ Pressure drop

$\phi$ Propellant momentum flux ratio

$\varphi$ Nozzle fullness coefficient

$\eta_1$ Acoustic admittance function of the gas manifold

$\eta_2$ Acoustic admittance function of the combustion chamber

$\forall$ Void faction

$\zeta$ Hydro-resistance of the injector
\[ \mu \quad \text{Mass flow discharge coefficient} \]

\[ \Lambda \quad \text{Depth of the liquid sheet penetration in the gas stream} \]
CHAPTER 1. INTRODUCTION

Combustion in liquid propellant rocket engines (LPREs) consists of sub-processes that include propellant injection, atomization, evaporation, and turbulent mixing, and combustion. Of all these, propellant injection is of great importance. The injector is composed of multiple elements that are responsible for introducing fuel and oxidizer into the combustion chamber according to the designed mass flow rates, spray angles, and the desired mixture ratio in order to maintain the integrity of the combustion process. Any hydrodynamic instabilities present in the injection process can excite instabilities in the processes that follow and result in destructive pressure oscillations and enhanced heat fluxes in the combustion chamber. The injector is thus a key component that couples the injection process with the combustion chamber in a feedback loop. It is therefore essential to design a robust injector to avoid inciting any form of intrinsic instability, and to avoid any hydrodynamic instabilities resulting from the propellant injection process.

1.1 Combustion Process in LPREs

It is crucial to understand the combustion process in liquid propellant rocket engine thrust chambers before delving into a discussion on combustion instabilities. The combustion process is composed of multiple elementary processes that occur simultaneously, while other processes that lead to the combustion process occur sequentially. Figure 1.1 shows the main physicochemical processes that take place in a liquid rocket thrust chamber and the interactions between these processes for a swirl-coaxial injector.
Figure 1.1: Fundamental Processes and Coupling Between them in Liquid Rocket Thrust Chambers [1]

Depending on the type of engine cycle, and injector design, the propellants are injected into the chamber individually in either liquid or gaseous form. The injected propellant jets, or sheets disintegrate rapidly into ligaments, and then into small droplets, i.e. atomize. The liquid disintegration mechanism depends on the type of injector, and the physical state of the propellants and may be achieved due to impingements of jets, intrinsic instabilities characteristic of liquid sprays, or due to the interaction with the surrounding gases at different temperature, pressure and velocity [2]. The droplets upon vaporization, mix and chemically react at extremely high temperatures, causing any remnant droplets to vaporize. The hot gases produced due to turbulent mixing and chemical reactions are then expanded and ejected through a converging-diverging exhaust nozzle to supersonic velocities.
For ease of analysis and to understand the coupling between the fundamental processes, the combustion chamber may be separated into zones depending on the process: injection, primary atomization, secondary atomization, primary mixing, primary reaction, and expansion as is shown in Figure 1.1. While these processes are considered to be basic and are found in most engines, in the case of gaseous propellants, atomization and vaporization does not occur [1]. The size, behavior and transition points of the zones is ultimately dependent on the physical states of the fuel and oxidizer combination, the operating conditions, the chamber geometry, and the injector design. The boundaries between the zones, however, cannot be explicitly defined as they are dynamic in nature. It is important to note that the creation of these zones merely simplifies the analysis. In real rocket engines, the fundamental processes are not isolated to any specific zone of the chamber, rather they occur simultaneously in various parts of the chamber and may play a role in exciting and sustaining combustion instabilities [3].

1.2 Combustion Instabilities in LPREs

Combustion instabilities have been a cause for concern since the development of liquid propellant rocket engines. The ability of these instabilities to manifest into catastrophic rocket failures if left unchecked is what makes combustion instability an important problem that needs to be addressed in the engine development process.

The combustion process is always accompanied by some pressure, temperature, and velocity fluctuations, even during stable operation. The problem arises when these seemingly regular fluctuations couple with the natural frequencies of the fuel and oxidizer feed system, or the chamber acoustics [2]. The frequency spectrum of the fluctuations present during normal operation appears continuous, with barely any detectable peaks. However, in the presence of combustion instability, periodic peaks at one or multiple frequencies in the spectrum are easily observed.
against the random-noise background, and these peaks are representative of large concentrations of vibratory energy [2, 4].

Propellant mixing results in the conversion of the propellants’ chemical energy into different forms of energy. Acoustic energy is one such form that affects combustion instability due to close coupling with unsteady heat release. Unsteady heat release generates acoustic energy, and the unsteady heat source disperses acoustic energy [5]. Combustion instabilities are likely to propagate through the combustion chamber if more acoustic energy is generated in comparison to acoustic losses. Figure 1.2 shows the interactions between the various mechanisms that drive combustion instability.

Figure 1.2: Mechanisms and the Interactions Responsible for Thermo-acoustic Instabilities. Based on a similar schematic in Ref. 5

Lord Rayleigh, in 1878, formulated a mathematical model, called the Rayleigh criterion, which attributes the growth of thermo-acoustic instabilities to the coupling between acoustic oscillations and unsteady heat release during the combustion process. The model concludes that when the rate of unsteady heat release and the pressure oscillations are in phase, acoustic disturbances in the system increase, resulting in the onset of combustion instabilities [5]. Several modes of combustion instabilities may be excited and sustained within the combustion chamber.
Depending on the frequency range of the oscillations, combustion instabilities may be categorized into three types. The most dangerous form of instability is the high frequency (also called screaming, or screeching) type with frequencies greater than 1,000 Hz, caused by the interaction between the combustion process in the chamber and the acoustic and resonance properties of the combustion chamber [2]. High-frequency instabilities are assumed to occur due to gas dynamic pulsations which interact with the propellant injection, and mixing process, resulting in excess heat transfer rates that may cause the injector to burn through, allowing the propellants to mix behind the injector face, causing to explosions, resulting in a disastrous failure of the entire system [4].

Intermediate frequency instabilities (also called buzzing) are typically in the 400-1,000 Hz frequency range and are normally the result of interaction between the combustion process and the propellant feed system flow dynamics. The presence of this type of instability may result in secondary major failures as prolonged exposure to buzzing may cause material fatigue and may also negatively affect engine performance and reliability [4]. The last type of instability is the low-frequency (also called chugging) instability, which falls in the 10-400 Hz frequency range and typically is a result of coupling between the propellant feed system and the combustion process. Low-frequency combustion instability may not pose a serious threat to the combustion chamber, but prolonged chugging may cause sensitive payloads to suffer from structural damage, and it may also potentially induce high-frequency instability [4, 6]. Design parameters of the combustion chamber, the injector and the propellant feed lines along with the propellant injection conditions greatly influence low-frequency instability. Engines using gas-liquid type injectors run the risk of the presence of acoustic instabilities, and instabilities caused by the high amplitude coupling of the feed system. Due to the compressible nature of the gaseous propellants, any increase in the
pressure from the chamber at the injector face may result in a reverse flow of the gases from the combustion chamber into the liquid/gas manifolds. If any unvaporized liquid droplets are entrained into these backflowing gases, it could result in detonations in the injector manifolds leading to failure [6].

From a preliminary discussion, it is evident that combustion instability mainly occurs due to coupling between the combustion and the unsteady fluid dynamics processes of the system, with the combustion process providing the oscillatory energy required to sustain the oscillations [7]. Since the injector determines this coupling to a great extent, designing a robust injector is important to avoid inciting any injector-coupled instabilities [8].

1.3 Types of Injector Designs

Several factors influence the choice of injector for a specific rocket engine. These factors include but are not limited to: the choice of propellants (liquid/liquid, liquid/gas, and gas/gas), engine cycle (staged combustion, gas generator, pressure fed), chamber pressure, required thrust and performance. There exist several injection schemes in literature that may be selected depending on the requirements. Figure 1.3 depicts the spray structure for all the injector types.
Impingement type injectors rely upon momentum exchange between propellant streams impinging upon each other at specific angles. Impinging injectors can be used in various configurations depending upon whether the impinging propellant streams are the same (like-on-like), or different (oxidizer and fuel). Depending upon the number of impinging streams, this type of injector can be classified into doublets, triplets, or pentads. In shear coaxial injectors, both the propellant streams are injected in a concentric pattern. Usually, the fuel is injected on the outside, while the oxidizer is injected through the center. Shearing between the two streams due to the difference in velocities of the two streams leads to atomization.

Swirl coaxial injectors add the element of swirl to the shear coaxial configuration to form finer and more uniform droplets, which enhance atomization quality and mixing efficiency. Swirl is imparted to the propellant/s by injecting them through tangential passages or using a mechanical swirler [9]. Swirl coaxial injectors exist in multiple configurations depending upon the physical properties of the propellants (liquid- liquid, liquid- gas, gas- gas), swirling propellant (liquid or gas), location of each propellant (liquid- centered, gas- centered), and also on the location of the swirling propellant (central/outer liquid or gas swirl).
Double-swirl coaxial injectors, as the name suggests, impart swirl to both the propellants, which may both be in liquid or gaseous state respectively, or may be a combination of liquid-gas. The direction of the swirl is also a factor that could be the same or different for both propellants. This thesis will focus on a dual-swirl liquid-gas coaxial injector, where the liquid is swirled through the center, and the gas is counter-swirled on the outside.

1.4 **Swirl Injectors**

Swirl injectors have been predominantly used in Russian liquid rocket engines as they exhibit wider stability margins for a range of mass flow rates, and offer superior performance, as compared to jet injectors operating at the same flow conditions [10, 11]. In terms of design, compared to jet injectors operating at similar flow rates, swirl injectors have a larger flow passage. Because of this feature, inaccuracies in manufacturing do not have a significant impact on the atomization quality, and they are less likely to experience cavitation or choking [6]. In addition to all these advantages, swirl injectors enhance the atomization quality due to the formation of finer, uniform droplets, which promote mixing efficiency, thus making them viable candidates for use in liquid rocket engines.

In liquid-centered swirl coaxial injectors, the liquid propellant is injected with an added element of swirl into the swirl chamber. Without the coaxial gas flow, this configuration is called a pressure swirl/simplex atomizer. Due to the tangential velocity imparted to the liquid, a thin swirling liquid film is formed along the inner wall along with a hollow gas core. The liquid film emerges from the swirl chamber with tangential and axial velocities, resulting in the formation of a thin conical sheet at the exit [12]. This sheet can self-atomize, as it degenerates into ligaments and then forms droplets as can be seen in Figure 1.4.
To accelerate breakup and atomization, the conical sheet is exposed to aerodynamic forces from gases introduced by a concentric tube that surrounds the swirling water, which contributes to the self-atomization of the liquid sheet. The shear layer interaction between liquid and the ambient air promotes Kelvin-Helmholtz wave growth which affects the stability of the liquid sheet and generates surface waves of small amplitudes on the liquid sheet. The amplitude of these waves increases as they propagate downstream from the injection plane. Once a critical amplitude is reached, the liquid sheet disintegrates into ligaments [13].

While the liquid sheet is able to self-atomize, the presence of the coaxial gas flow accelerates the breakup of the liquid sheet due to momentum exchange between the liquid and the gas, which gives rise to disturbances and hence leads to quick disintegration of the contiguous liquid sheet. The coaxial gas may be injected as a jet or may have an element of swirl to it. Depending upon whether the gas is swirled or not, the spray characteristics will change, and there may be different instabilities at play that aid the breakup of the liquid sheet and thus influence the atomization and mixing process.
1.5 Self-Oscillations in Liquid-Gas, Swirl Injectors

During cold-flow tests conducted at the Propulsion Research Center, liquid-centered swirl coaxial injectors in single and dual-swirl configurations were found to be susceptible to self-oscillations at certain operating conditions [13, 14]. This self-oscillating behavior has been termed as self-pulsation in literature and is commonly observed in liquid-gas swirl injectors [10, 15-17]. Self-pulsations are usually characterized by periodic oscillation of the generated spray, strong pressure and flow rate fluctuations in the propellant feed lines [14]. Figure 1.5 shows an example of how the spray changes its structure as it evolves from pressure-swirl injection, to dual-swirl coaxial without and with spray oscillations. From left to right, the liquid mass flow rate is held constant, while the mass flow rate of gas is increasing steadily. The spray oscillations are more distinct in the injection plane, and not so much downstream because of the coaxial gas swirling in the opposite direction to the central liquid swirling stage. Compared to the easily observable spray oscillations for a liquid-centered swirl coaxial injector under self-pulsation, the spray features for the dual-swirl coaxial injectors appear more chaotic and therefore are difficult to observe.

![Figure 1.5: Instantaneous Spray Images Captured during Testing for Pressure Swirl Injection, Stable Spray without Self-Pulsations, and Oscillating Spray with Self-Pulsations (from L-R) for a Liquid-Gas Dual-Swirl Coaxial Injector](image)

While high-speed imagery is useful to observe the evident changes in the spray as it goes from stable to self-pulsating [13], this thesis will not rely too much on the high-speed cinematography of the spray to calculate the frequency of spray oscillations. Instead, this thesis will use acoustic measurements made in the near-field of the injector to extract acoustic
frequencies during self-pulsation. Figure 1.6 shows spectral analysis of sound emissions where the injector element was under self-pulsation and screeching sound emissions were perceived/recorded during testing. The acoustic frequency recorded for this case was 1,588 Hz, which lies in the expected range between 1,000-4,000 Hz.

Another important feature of an injector element under high-frequency self-pulsation is that it causes pressure and mass flow rate fluctuations in the liquid and gas propellant feed lines. Pressure fluctuations are measured by outfitting the liquid and gas manifolds each with dynamic pressure transducers. The data collected from these are analyzed to extract the frequency content to measure the extent of these pressure oscillations.

1.6 Research Objectives and Scope

The research effort discussed in this thesis attempts to map the stability boundary for self-pulsations for a liquid-gas, dual-swirl, coaxial injector. The study uses water and gaseous nitrogen as simulants. The tests will be conducted at atmospheric pressures and instrumented to measure line pressure fluctuations, sound emissions, and high-speed images. Creating a stability boundary
map primarily provides a basic framework for stable and unstable operating conditions and it usually includes the frequency spectrum of oscillations across the unstable range.

There exists a variety of literature for a liquid-centered swirl coaxial injector under high-frequency self-pulsation. In comparison, a detailed record of the phenomenon as it occurs in a dual swirl injector is very sparse. Due to the paucity in available data, a dual-swirl coaxial injector was selected as the test article of interest to study the self-pulsation phenomena. For the test campaign, the simulant propellants were throttled over a range of pre-determined flow momentum and momentum ratio values, and the injector was configured with three different recess lengths to understand the effect of propellant throttling and varying recess on the stability boundary.

Various mechanisms have been proposed for the development of self-pulsations in liquid-gas swirl coaxial injectors. The self-oscillations also depend extensively on operating conditions and injector design parameters. To orient the reader to the nuances of the self-pulsation phenomenon, the next chapter includes a literature review that will discuss the mechanisms of self-pulsation and summarize the various research efforts made in this area and set the context for this study.
CHAPTER 2. LITERATURE REVIEW

Self-pulsations were likely first observed in the mid-1970s in Russia while testing a liquid oxygen (LOX)/hydrogen rocket engine under off-nominal rating conditions [10]. These pulsations resulted in high-frequency pressure oscillations in the liquid and gas feed-lines, and low amplitude pressure fluctuations in the combustion chamber. The origin of these pulsations could not be traced to the acoustic characteristics of the combustion chamber since the observed pulsations were of frequency 5,500 Hz, which was far from the longitudinal (3,100 Hz) and transverse (3,240 Hz) frequencies of the chamber [15]. The discovery of the self-pulsations phenomena prompted special studies of the dynamic characteristics of liquid-gas coaxial injectors which posited that self-pulsations were a result of interaction of liquid and gaseous propellants inside the injector leading to hydrodynamic instabilities. These instabilities are a result of time-delayed feedback coupling of the conical liquid sheet and the surrounding gas flow [16]. The conical liquid sheet forms transient hydro-resistance to the gaseous flow which incites pressure oscillations in the propellant feed lines, mass flow rate fluctuations, and low amplitude oscillations in the combustion chamber.

Numerous experimental and analytical studies have been published over the years that seek to explain the mechanism of self-pulsation to understand the phenomena better. Through these studies, several mechanisms that could potentially incite self-pulsations have been identified. In addition to that, several experimental studies have also been successful at identifying important factors that influence the excitation of self-oscillations: injector geometry, operating conditions, and ambient conditions. The self-pulsations phenomenon encompasses a wide range of aspects that need to be considered to fully understand it. This chapter reviews the multitudes of published research related to self-pulsations in liquid-gas swirl coaxial injectors.
2.1 Anatomy of a Swirl, Coaxial Injector

Since majority of the literature covers self-pulsations in liquid-centered swirl coaxial injectors, the structure, and the important design parameters of a swirl-coaxial injector are discussed in this section.

Coaxial injectors are typically used in bi-propellant rocket engines, where the two propellants have to be injected into the combustion chamber via separate passages. Swirl-coaxial injector is one such type that is of particular interest for use in staged-combustion cycles, since in these cycles, one propellant exists in a liquid state, and the other in a gaseous state. In these injectors, one propellant is typically swirled (inside or outside), while the other propellant is delivered as a jet that is parallel to the swirling propellant’s axial flow. Swirl-coaxial injectors may exist in two configurations depending on which propellant is injected through the center tube: liquid-centered, gas-centered. Distinction may also be drawn on the basis of which propellant is swirled.

Of particular interest is the liquid-centered swirl coaxial injector, in which a conical liquid sheet is generated due to the liquid swirled through the center post. This liquid film is atomized by the coaxially delivered gaseous jet through the outer tube. The difference in the kinetic energies between the two flows allows for improved atomization and mixing.

The design of a swirl-coaxial injector element depends on various factors including, but not limited to required injection propellant drop, mass flow rate, and spray cone angle. Another important design parameter that is the swirl number, which is a measure of the strength of swirl that is imparted to the swirling propellant. The flow is considered to be a highly swirling flow if the swirl number is greater than 0.5. The swirl number is solely a function of the injector geometry [17].
Figure 2.1 shown below is a schematic of a liquid-gas swirl coaxial injector that shows the swirling liquid entering the swirl injector through tangential entries at the injector inlet, the liquid film with the gaseous vortex core inside the swirl injector, the coaxial gas jet which aids the atomization process, and the conical sheet formed at the injection plane.

![Figure 2.1: Swirl Coaxial Injector with Recess [18]](image)

A crucial design parameter that is shown in Figure 2.1 is the recess chamber, which is formed due to the swirl injector being located at some distance inward from the gas injector’s exit. The length of how much the central post is recessed from exit of the outer annulus is called the recess length, and is typically introduced to promote internal mixing of propellants, which has been showed to improve the mixing efficiency, and flame stabilization [19]. An increase or decrease in the recess length influences the level of liquid and gas interaction occurring inside the recess chamber, which alters the spray characteristics further downstream at the exit of the injector. Bazarov and Yang [10, 15, 16] identified the recess length to be an important parameter that is related to the onset of self-pulsations. The authors concluded that an increase in the recess length intensifies self-pulsations, and that with no recess, self-pulsations practically disappear. However, Eberhart et al. [11, 13] observed strong self-pulsations in a non-recessed swirl coaxial injector.

This suggests that while the interactions between the swirling liquid and gas in the recess chamber may play an important role in the excitation of self-pulsations, there are several other
mechanisms that are responsible for causing the injector to self-oscillate. The next section discusses some of the potential mechanisms that have been investigated so far and may be responsible for the onset self-pulsations in swirl-coaxial injectors.

2.2 Self-Pulsation Mechanisms

Understanding the underlying mechanisms for the occurrence of self-pulsations is important to avoid the onset of injection-coupled instabilities. Preliminary studies conducted by Bazarov and Yang suggest the time-delayed feedback coupling of the conical liquid sheet that blocks the coaxial gas flow is responsible for exciting self-pulsations [10, 15, 16]. Across all studies, the inner post recess has been identified as an important parameter that contributes to the onset of self-pulsations due to gas velocity fluctuations in the recess chamber. Interaction between the liquid-gas spray formed in the injection plane is also an important factor to consider when assessing the mechanisms responsible for the excitation of self-pulsations. Therefore, it is reasonable to separate the factors that trigger self-pulsations into external oscillators and internal oscillators.

2.2.1 External Oscillators

The presence of external oscillators is usually a result of the interaction of the liquid sheet with the co-annular gas in the spray field. The swirling liquid film upon exiting the injector forms an unrestrained conical liquid sheet that is contiguous in the injection plane. Waves originating from inside the injector propagate downstream and cause oscillations on the surface of the sheet. In addition to this, the interaction of the liquid sheet with the surrounding gas jet or swirling gas gives rise to dominant waves on the liquid sheet, which is implied similarly as in Kelvin-Helmholtz instability, induced by aerodynamic and hydrodynamic instability, which affects the frequency of self-pulsation [20]. Depending on the relative velocity between the two propellants,
and the gas viscosity, the liquid sheet contains intrinsic asymmetric and symmetric waves that are similar to the wave growth observed in cylindrical sheets [21].

Experimental studies conducted by Eberhart et al. [11, 22] for recessed and non-recessed elements identified the presence of Kelvin-Helmholtz (K-H) type instabilities at the self-pulsation boundary and found similar values for the oscillation frequency and the self-pulsations. The wave speed of self-pulsations at the stability boundary were found to be identical to the wave-speed of the quasi K-H instabilities found just prior to the stability boundary, thus concluding that K-H type instabilities may be responsible for exciting self-pulsations.

Im et al. [23] reported that self-pulsations are a result of the dominant wave of the liquid sheet, identifying that the frequency of K-H type instability is related to the frequency of the dominant wave, which in turn affects the self-pulsation frequency, thus identifying K-H instability as a mechanism of self-pulsation.

Kang et al. [18] studied the effect of recess length on the self-pulsation characteristics of a liquid-centered swirl coaxial injector element and found self-pulsation frequencies in the range of 1,000-4,000 Hz in the low-frequency range which is characteristic of K-H instability. It was further concluded that even though K-H instability always exists in liquid-gas swirl coaxial injectors, self-pulsations only occur when the K-H vortex is strong enough to be able to overcome the liquid inertia [18].

Spray interactions between the liquid sheet and the gaseous jet in the injection plane may be considered to be the external factors responsible for excitation of self-pulsations. External oscillators may potentially act as an unsteady boundary condition that while acting exterior to the injector element, might excite oscillations of internal fluid oscillators present within the swirl coaxial injector element [24].
2.2.2 Internal Oscillators

Eberhart and Frederick [24] conducted an extensive study to identify fluid oscillators internal to the swirl injector element that may be factors that incite self-pulsation under certain operating conditions. The dynamics of a liquid-centered swirl coaxial injector play an important role in the identification and contribution of these fluid oscillators to the self-pulsation phenomena. Depending on the geometry, flow properties, and thermal and physical properties of the fluids, the fluid oscillators may have inherent natural modes of oscillations. Figure 2.2 is a representation of the potential internal fluid oscillators as identified by the authors: swirl post and annulus acoustics, and liquid film hydrodynamics. The potential list of oscillators shown in Fig. 2.2 is by no means exhaustive, and there may be other fluid oscillators internal to the injector.

![Figure 2.2: Notional Representation of Potential Internal Fluid Oscillators Responsible for Excitation of Self-Pulsations [24]](image)

Acoustic eigenmodes of the fluid-resonant liquid swirl post, and the gas annulus, and the hydrodynamics of the liquid film act as potential fluid oscillators. Any downstream fluctuations in the liquid sheet or any oscillations in the gas ducts may excite eigenmode oscillations in the gas
annulus. Huang et al. [25] proposed a theoretical model to explain injector acoustics that may cause self-oscillations and found that self-pulsations may be excited by resonance between the gas core in the swirl post and the annular gas flow.

The swirl post itself contains a minimum of two oscillators: gas core acoustics, and the oscillations of the liquid film. The gaseous vortex core in the swirl post is susceptible to acoustic oscillations incited by internal or external factors. Ismailov and Heister suggested that a standing wave pattern may emerge in the swirl injector’s vortex chamber, and the amplitude of these waves is maximized at the natural frequencies of the swirl injector [26]. The coupling between the swirl injector and the combustion chamber may result in resonance when the natural frequencies of the swirl injector coincide with the combustion instability frequency. Figure 2.3 is a representation of the resonance phenomenon in swirl injectors.

Figure 2.3: Schematic of a Standing Wave Pattern at Swirl Post Resonance [26]

Eberhart and Frederick [24] identified through analytical and experiments that vortex chamber surface waves were the controlling fluid oscillator for the parameter space they tested in.
They also identified that swirl post-normal modes were important parameters that aided the excitation of self-pulsations. Bazarov [15] also suggests that self-pulsations are amplified by the gas cavity that is contained within the liquid swirl post and serves the function of a resonator for the pulsations. Another important oscillator is the liquid film contained within the swirl injector which is susceptible to oscillations caused by hydraulic disturbances, cavitation, and perturbations of the gas vortex core [24].

It is understood that self-pulsations, as the name suggests are self-excited, and self-sustained. There is no one single factor that may be the source of the driving mechanism of self-pulsations. A combination of two or more fluid oscillators may also exist that could cause the injector to self-pulsate. Both the internal and external factors depend on the injection conditions, ambient atmosphere, and injector geometric parameters. Mapping the stability boundary for the injector as a function of these parameters is useful to obtain a clear idea of which potential oscillator/s (internal or external) might drive the injector to self-pulsate at different points in the self-pulsation domain. Since each point in the self-pulsation domain is a function of varying operating conditions, it is a useful exercise to map the stability boundary as dynamic characteristics of the injector may change across the domain.

2.3 Stability Boundary of Self-Pulsations

The self-pulsation mechanism can be explained by the pulsation mechanism observed in vocal cords or petal valve [10]. The liquid film can be considered as a flexible petal valve that oscillates due to interaction with the surrounding gas flow. Figure 2.4 shows a schematic of a petal valve model with the liquid film at the exit. Exit of the central swirling liquid post is marked as 1, and the injector exit is marked as 2. For constant pressure drop across the injector, the liquid film forms a passage for the co-annular gas to flow [15]. The area of the passage at the injector exit
fluctuates with time delay as the gas velocity fluctuates at the exit of the central liquid post, which promotes pressure oscillations in coupled systems upstream (feed lines) and downstream (combustion chamber) of the injector. The self- pulsation frequency of the injector depends on the gas flow oscillations in the recess chamber.

Figure 2.4 Schematic of Petal Valve Acoustic Impedance Model. Based on a Similar Diagram Presented in [10, 15]

If the liquid sheet exiting the injector is assumed as a thin, deformable membrane, and isentropic gas flow, the acoustic admittance functions at stations 1 and 2 is obtained as shown in Eq. (1) as derived by Bazarov in Ref 16.

\[
\eta_2 = \frac{u_{G1}}{u_{G2}} \left(1 - \frac{2A}{\xi - A} e^{i\omega t}\right) \eta_1
\]  

(1)

Acoustic admittance functions essentially define the ratio of the gas velocity to the pressure fluctuation [10]. In Eq. (1), \( \eta_1 \) and \( \eta_2 \) are the acoustic admittance functions of the gas manifold and the combustion chamber respectively [15], while \( u_G \) is the gas velocity at stations 1 and 2 respectively. Depth of the liquid sheet penetration in the gas stream, \( \Lambda \), is a dimensionless quantity and is a function of the ratio of the liquid momentum flux to the gas momentum flux, \( \Lambda = f(\rho_L u_L^2/\rho_G u_G^2) \). The hydro- resistance of the injector, \( \xi \), which is also a non- dimensional quantity is defined as \( \xi = \partial F_2/\partial(\Delta P) \), where \( \Delta P = P_1 - P_2 \). The self- pulsation boundaries can be
calculated by varying the hydro-resistance and assuming $\eta_1 = \eta_2 = 0$ since the injector can be modeled as having open exits [16]. Figure 2.5 shows the theoretical domain of self-pulsation for a coaxial liquid-gas injector plotted as a function of the liquid sheet penetration depth and the gas momentum flux ratio.

![Figure 2.5: Theoretically Calculated Self-Pulsation Boundaries for a Liquid-Gas Swirl-Coaxial Injector as a Function of Varying Hydro-Resistance [10]](image)

Since self-pulsations depend significantly on injector geometry, pressure drop at the liquid and gas stages, and ambient pressure, stability boundaries that are representative of all these factors can be mapped. Figure 2.6 is an example of the effects of propellant momentum flux, and pressure drops on the stability boundary of self-pulsations for different ambient pressures, and recess lengths [10]. Both the graphs show self-pulsation that is similar to the parabolic pattern that is seen in Figure 2.5. An increase in the gas mass flow rate results in an increase in the self-pulsation domain, and therefore throttling the gas flow allows marking the left-hand boundary. To mark the right-hand boundary, the gas mass flow rate is held constant, and the liquid flow is increased which results in an occurrence of self-pulsations, however a further increase in the liquid flow results in the disappearance of self-pulsations. Another general trend that is observed is that the
self-pulsations frequency increases for a constant liquid flow rate, while the gas flow rate is steadily increased. Trends observed in Figure 2.6 suggest that the self-pulsation zone increases for lower ambient pressure and for increasing recess lengths. This observation agrees well with several experimental studies that have identified the recess length as the important parameter that exacerbates self-pulsations.

Mapping the stability boundary divides the parameter space into zones of self-pulsation and no self-pulsation and enables the injector designer to obtain stable and unstable operating points for the injector. Noticeable changes have been observed in the spray characteristics for injectors under self-pulsation, thereby influencing atomization and mixing characteristics of the injector. Several experimental studies have been conducted and are available in the open literature that have probed the effect of various parameters on the spray characteristics, and on the stability boundary. These studies are summarized in the next section to provide a basis for the research covered in this thesis.
2.4 Experimental Studies

Several cold-flow experimental studies using simulant propellants have been conducted by several researchers to understand the self-pulsation phenomenon. Bazarov and Yang [10, 15, 16] made pioneering contributions to experimental studies of self-pulsations, which lay the groundwork for all future studies. The authors noted the pressure drops across the liquid and gas stages, and the liquid nozzle recess length as the important parameters that have an influence on the onset of self-pulsations as well as on the self-pulsation zone. It was noted that self-pulsations practically disappeared with no inner post recess. Considering that the resonance between the gas core and the gas flow in the gas annulus is a potential mechanism for self-pulsation, the influence of the width of the gas-annulus was also studied. Stronger self-pulsations were found for a narrow gas annulus whose width was up to one-sixth of the original dimension, and the self-pulsation zone became wider. Another variation to the design was to close a part of the tangential entries that reduced the liquid mass flow rate, and the result was a broader self-pulsation zone with a decrease in the pulsation amplitude.

Eberhart et al. [11] reported the presence of self-pulsations even for a flush-mounted (configured with no recess) injector element. The authors suggested the presence Kelvin-Helmholtz instability as the reason for the occurrence of self-pulsations for a flush-mounted element [11, 22]. This idea was backed by Kang et al. [18] who suggested that Kelvin-Helmholtz type instability is always a necessary condition, and that this type of instability is always present in liquid-gas swirl coaxial injectors. The authors concluded that self-pulsations only occurred when the Kelvin-Helmholtz vortex was significantly stronger and capable of overcoming the liquid inertia.
Im et al. [27] studied the effect of varying propellant injection velocities and geometric parameters such as the recess length and the gap size between the inner and outer annulus. The frequency of spray oscillations was observed to remain unchanged with an increase in gas velocity, and an increase in liquid velocity caused self-pulsations to cease. Short recess lengths, and an increase in the gap size caused the self-pulsation phenomenon to disappear. Furthermore, as the recess length increased, the self-pulsation boundary was found to shift to the right.

Im et al. [28] studied the effect of increasing the recess length on the acoustic frequency and found that an increase in the recess length, increases the acoustic frequency. The acoustic frequency was also found to be a function of the injection velocities of the liquid and gas. Cold-flow experiments were conducted by Sasaki et al. [29] using water and nitrogen gas as simulants and observed that for an injector under self-pulsations, spray oscillations were accompanied with high-frequency sound emissions. They also reported the presence of self-pulsations for an injector configured without recess and observed that the recorded sound emissions for the flush-mounted case were of lower intensity compared to the recessed injector element case.

Im and Yoon [23], studied the effect of different ambient pressures and recess lengths and found that self-pulsations disappear which results in the decay of the dominant wave of the liquid sheet. The authors also conclude that with an increase in the recess length, the interaction between the liquid and the gas also increases which intensifies self-pulsation.

Kang et al. [30] focused on studying the spray characteristics for a liquid centered swirl coaxial injector under self-pulsation and observed that the phenomenon has negative effects of the atomization and mixing. However, Bazarov [10] notes that self-pulsations may intensify the atomization and mixing characteristics of the injector by allowing uniform distribution of the propellants in the combustion chamber. It is also noted that self-pulsations may be considered
detrimental to the operation of the engine only if they cause high amplitude pressure oscillations in the combustion chamber which give rise to high-frequency combustion instability, which must be fervently avoided in liquid rocket engines.

Table 2.1 shown below summarizes the various parameters that influence the self-pulsation phenomenon or are influenced by it, the type of parameter and the reference number that provides more information about it.

**Table 2.1: Literature Review Summary of Swirl Coaxial Injectors**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Type</th>
<th>References</th>
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<td>Recess length</td>
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<td>Injector Design</td>
<td>10, 15</td>
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<td>Effect on Atomization</td>
<td>30</td>
</tr>
<tr>
<td>External Oscillators (K-H type instability)</td>
<td>Self- Pulsation Mechanism</td>
<td>11, 18, 22, 23</td>
</tr>
<tr>
<td>Internal Oscillators</td>
<td>Self- Pulsation Mechanism</td>
<td>13, 24, 25, 26</td>
</tr>
</tbody>
</table>

2.5 Self-Pulsations in Liquid-Gas Dual Swirl Coaxial Injectors

Most of the available literature about the self-pulsation phenomenon is about liquid-centered swirl coaxial injectors in which the liquid is swirled through the center post, and the gas
is injected through the outer annulus as a jet. However, the injector configuration used for analysis in this thesis is a liquid- gas dual swirl coaxial injector where the liquid (center) and gas (outer annulus) are both swirled. One important feature of this injector is that the gas is counter- swirled through the outer annulus, which increases the shear between the liquid and the gas thus promoting atomization. The spray characteristics of this type of injector are noticeably different from those observed for swirl coaxial injectors.

For certain operating conditions, this injector element undergoes self- pulsation which is accompanied by spray oscillations, feed- line pressure oscillations, and mass flow rate oscillations as is typically associated with the excitation of the self- pulsation phenomena. Bazarov studied the effect of swirling the gas using two- nozzle swirl coaxial injectors and found that the self- pulsation zone was rather narrow and self- pulsation was accompanied by high amplitude pressure and mass flow rate oscillations [15].

Considering there is not much information available in the literature that attempts to study a liquid- gas dual- swirl coaxial injector under self- pulsation, this injector element was selected as the test article for experimental studies. Understanding the stability boundary of self- pulsation of this kind of injector will help injector designers obtain a set of stable and unstable operating points specific to this kind of injector. Additionally, it will give researchers an insight into the potential instabilities that arise due to self- pulsations when both liquid and gas are swirled.

A preliminary experimental investigation was conducted to map the stability boundary for the selected injector element under self- pulsation [14]. The next chapter describes the cold- flow experiment setup which includes brief discussions on injector geometry variation, operating conditions parameter space, instrumentation, and data analysis.
CHAPTER 3.  EXPERIMENT DESCRIPTION

3.1 Overview

Cold-flow experiments were conducted at the Johnson Research Center to investigate the self-pulsation stability boundary of a liquid-gas dual-swirl coaxial injector using water and gaseous nitrogen as propellant simulants. From the literature, it is evident that the recess length is an important parameter that influences the width of the stability boundary, and therefore the injector was tested for two different recess length (1-2 mm), and also in the flush-mounted configuration without recess. Since self-pulsations typically occur when the injector operates at off-nominal operating conditions, the mass flow rate of the simulants was throttled between 45%-90% of the nominal design point for the injector element.

3.2 Non-Reactive Spray Experiments (Cold Flow)

Non-reactive (cold-flow) spray experiments separate the injection process from the thermochemical processes that follow. This de-coupling between the two processes allows for extensive experimentation in a laboratory setting as the harsh environment that is typical of combustion is avoided. Cold flow tests also have the advantage of being able to run continuously for long durations, as compared to most hot-fire tests that last only for few seconds. Additionally, cold flow experiments have low costs associated with it, are easy to execute, and are relatively safer for the personnel involved and for the hardware.

De-ionized, filtered water at standard temperature and pressure is used as a simulant for liquid oxygen, and the fuel is simulated using gaseous nitrogen. Due to the incompressible nature of water, the density of water and liquid oxygen is similar at an assumed subcritical injection pressures and temperature of ≈ 90K. A comparison of some thermophysical properties of water and liquid oxygen are given in Table 3.1, the format of which is based on a similar table found in
Ref 1. The similar densities of LOX and water makes it a suitable simulant for cold-flow tests. Gaseous nitrogen being inert can be safely used to simulate gaseous fuel such as GH₂ or gaseous hydrocarbon.

<table>
<thead>
<tr>
<th>Table 3.1: Comparison of Thermophysical Properties for Water and LOX [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Liquid Properties</strong></td>
</tr>
<tr>
<td>Density (\frac{kg}{m^3})</td>
</tr>
<tr>
<td>Viscosity (Pa-s)</td>
</tr>
<tr>
<td>Surface Tension (\frac{N}{m})</td>
</tr>
</tbody>
</table>

It must be noted that while water and GN₂ have been widely used for cold-flow tests, the fluid properties of each of the simulants will limit accurate representation of real operating conditions. Since the injection and atomization processes are not greatly affected by the chemical reaction, using simulants to conduct cold-flow tests is acceptable [1].

Since this is a preliminary study attempting to probe the stability boundary of self-pulsation for a dual-swirl coaxial injector, the sprays are issued into the atmosphere at standard pressure and temperature.

### 3.3 Injector Design

The Modular Injector for Scientific and Educational Research (MISER) was designed for a LOX/LCH₄ propellant combination for use in future lunar ascent engines [17]. The injector element was designed to be modular to accommodate three separate configurations: shear-coaxial, swirl-coaxial, and dual-swirl coaxial, that could be easily altered to suit a desired experiment [31]. To change from single-swirl to dual-swirl, the fuel jet sleeve with four radially-drilled holes is replaced with a fuel swirling sleeve with four tangentially-drilled holes. In the dual-swirl
configuration, the liquid was swirled centrally, and the gas was counter-swirled through the outer annulus. The dual-swirl coaxial injector within the cube is shown in Figure 3.1.

![Figure 3.1: Dual-Swirl Coaxial Injector within the Miser Cube](image)

The recess length may be changed by inserting spacers in the configuration. The purple and blue bands in Figure 3.1 are the 1 mm and 2 mm spacers that may be inserted to change the recess length. Figure 3.2 shows an exploded view of the assembly with all the parts labeled.

![Figure 3.2: Exploded View of the Miser Assembly](image)
The internal swirl element is designed according to the ideal hydraulic design methodology outlined by Bazarov et al. [6]. All the design parameters are related to each other through Bernoulli’s equation and the principle of conservation of mass, energy, and angular momentum [6]. The element is designed for a nominal design flow rate of 82 g/s, a total free cone spray angle of 90°, and liquid film thickness of 473 μm [17]. The internal swirler uses four tangentially-drilled holes to impart swirl to the fluid. The exterior swirling element was designed for a nominal mass flow rate of 0.027 kg/s for LCH4. This element was also designed in accordance with the classic design methodology outlined by Bazarov et al. [6]. Figure 3.3 is a schematic of the flow passages of both the oxygen and the fuel through the interior and exterior swirler. The fuel is counter-swirled external to the oxidizer post.

**Figure 3.3: Flow Paths of Oxygen and Fuel Through Interior and Exterior Swirlers**

Important design parameters for the interior and exterior swirler elements are summarized in Table 3.2 and the design procedure is outlined in detail in Appendix A.
From other research work conducted using the same LOX swirl element, it is noted that there is a minor inconsistency between the designed geometry and the manufactured geometry of the LOX post [13]. The nozzle tube and its base are welded together to obtain a single component, which is then attached to the vortex chamber. A special weld tack was placed on the outside diameter of the base-to-tube edge to avoid any geometric discontinuities. However, a small gap remains at the interface of the nozzle and the vortex chamber piece. The length of this gap is estimated to be approximately 0.01 mm and is depicted in Figure 3.4. It is believed that the gap is likely smaller when the injector assembly is under compression, as is required.
It is important to note the presence of the inconsistency between the design and the manufactured component, however, the presence of the gap is considered insignificant as it neither affects the fluid dynamics of the liquid within the vortex chamber, nor does it have a negative influence on the liquid film fluid mechanics within the nozzle and the resulting liquid sheet and spray cone [13].

While this injector is designed for a liquid-liquid dual swirl type of injector, the propellant simulants used for this research work are in the liquid-gas state. Previously, this injector has been used in the swirl-coaxial configuration for hot-fire tests using gaseous oxygen and gaseous methane [17]. The use of this propellant combination has been justified by the author on the basis that at high chamber pressures, and at high temperatures, gaseous propellants more accurately simulate the liquid propellants’ physical properties [17].

Using a combination of liquid-gas propellants may be justified if the engine uses a regenerative cycle, in which case one or both the propellants may be injected in the gas phase. Additionally, it is considered valuable to investigate the application of this injector design for a liquid-gas propellant combination as is typically used in an engine employing the staged combustion cycle. Therefore, the use of water and nitrogen gas as propellant simulants for this injector design is reasonable.
3.4 Test Conditions

Preliminary testing revealed that the dual-swirl coaxial injector experienced self-pulsations when tested for varying liquid and gas pressure drops. Hence, a parameter space was set up to explore the stability of the injector over a range of liquid and gas mass flow rates, for two different recess lengths, and in the flush-mounted configuration.

3.4.1 Test Matrix

Considering that self-pulsations typically occur during off-nominal scenarios, the liquid mass flow rate was throttled over a range of 41%-83% of the designed mass flow rate of 82 g/s. There was no specific parameter space for throttling the mass flow rate of gas. Rather, the set-points obtained from the preliminary investigation were used as a baseline to determine the point of onset of self-pulsations for each liquid mass flow rate, which is marked by the lower stability boundary. Once the lower boundary was marked, the gas flow rate was increased further to record at least five more data points in the self-pulsation region for each configuration, as long as the gas flow rate was within the pre-determined range.

The upper limit for the mass flow rate of gas was decided to be approximately 10.94 g/s as during some previous experimental tests, the LOX swirl post was subject to high-cycle fatigue which resulted in the structural failure of the component during two preliminary test campaigns. The high-cycle fatigue may have been a result of repeated testing over the years, or due to the rapid oscillations experienced by the component during this test campaign. Therefore, to exercise abundant caution and to maintain the structural integrity of the test article, 10.94 g/s was selected as the upper limit to which the gas mass flow rate could be throttled. This limit also matched well with previous experimental work that was conducted by Eberhart et al. [13, 20, 22]. Table 3.3 summarizes the target flow conditions that form the parameter space.
<table>
<thead>
<tr>
<th>SP</th>
<th>( \dot{m}_L ) (g/s)</th>
<th>( \dot{m}_G ) (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>54</td>
<td>1.11 – 10.94</td>
</tr>
<tr>
<td>6</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>

### 3.4.2 Flow Conditions Control

Liquid flow rate was controlled using an orifice. To ensure that the flow cavitates at the orifice, and not at any point in the injector, the smallest area of the LOX swirl post was determined and depending on that an appropriately sized orifice was selected to control the flow. Different liquid flow rates were achieved by controlling the upstream pressure to the orifice. Calculation of the cavitation number enabled to determine the limiting value of the upstream pressure, which was calculated to be 82 psi. For all pressure values greater than 82 psi, the flow cavitated only at the orifice, therefore enabling flow control.

Catch and weigh tests were used to calibrate the orifice. For each upstream pressure value, water flowed through the orifice, and was discharged into a bucket. The collected mass of water was weighed on a scale, and this value was divided by the total collection time recorded using a
stopwatch (60 s). A total of three trials were conducted for each upstream pressure, and the average of all these values yielded the various mass flow rates.

Figure 3.5 shows the calibration curve for the liquid mass flow rate as a function of the upstream pressure. The trendline is exponential since the mass flow rate is a function of the square root of the difference between absolute upstream pressure, and the vapor pressure of water at standard atmosphere. The same test was repeated with the orifice and the LOX swirl post in the fluid circuit, to ensure the same mass flow rates were measured as those without the LOX swirl post.

![Figure 3.5: Calibration Curve for Measured Mass Flow Rate](image)

Using the measured average mass flow rate values, the discharge coefficient was calculated for each mass flow rate using Eq. 1 rearranged for solving the discharge coefficient, instead of mass flow rate. The average discharge coefficient across all set points was calculated to be 0.59. Using this discharge coefficient, the mass flow rate of water was calculated as a function of the discharge coefficient and upstream pressure using Eq. 1. Since the flow experiences cavitation at the orifice, the mass flow rate is a function of the square root of the pressure difference between the upstream pressure and the vapor pressure of water. Since the vapor pressure of water is very
small compared to the upstream pressure value and is constant, the mass flow rate of water can be controlled by varying the upstream pressure.

\[ \dot{m} = C_dA_{orifice}\sqrt{2\rho(P_1 - P_v)} \quad (1) \]

A linear relationship is obtained between the calculated mass flow rate and the square root of the differential pressure as is shown in Figure 3.6.

To measure the mass flow rate of the gas, it is assumed that the flow chokes at the tangential holes of the exterior swirler. A coefficient of discharge of 0.77 is assumed. The mass flow rate is then calculated as a function of the injection pressure upstream of the exterior swirler using Eq. 2.

\[ \dot{m}_{gas} = 4A_{tang.holes}C_dP_1\sqrt{\frac{y}{RT}}\sqrt{\frac{2}{y+1}} \quad (2) \]

The exterior swirler has a total of tangential entry inlets, thus, the area is multiplied by four to calculate the total gas flow rate.
3.4.3 Recess Length Modifications

Considering the recess length is an important parameter that is thought to drive self-pulsations, two different recess lengths were tested. Figure 3.7 below is a schematic that shows the recess length ($L_{1\rightarrow2}$) as is typically calculated for swirl coaxial injectors.

![Figure 3.7: Schematic of the Inner Swirl Post Recessed from the Outer Annulus. Gaseous Nitrogen is Swirled through the Outer Annulus (shown in black) and Water is Swirled through the Inner Post (shown in blue)](image)

For the MISER, spacer rings measuring 1 mm and 2 mm respectively may be integrated with the LOX swirl post assembly to change the recess configuration. Only two recess lengths were tested as it was observed while preliminary testing that for recess lengths greater than 2 mm, this injector is unable to generate a suitable spray.

3.4.4 Testing Strategy

The same strategy was employed for all points in the test matrix. A total of six steps are outlined below:

1) Set a liquid mass flow rate and ensure nominal pressure-swirl flow.
2) Once, pressure swirl flow is achieved, gradually sweep the gas flow rate until the lower self-boundary of self-pulsation is reached.

3) To avoid the hysteresis effect, decrease the gas mass flow rate slightly until no self-pulsation sound emissions are audible, then steadily increase the gas flow rate to the point of the onset of self-pulsation.

4) Record data for the lower stability boundary

5) Continue increasing the gas, while at the same liquid mass flow rate, and record data points at specific intervals. Increase the gas mass flow rate to record at least five more points if the upper limit of the gas flow rate is not breached.

6) Repeat 1-5 for the next liquid mass flow rate test points.

3.5 Facility Description

Cold-flow tests were conducted at the Johnson Research Center’s Cold Flow Spray Facility. Figure 3.8 shows a general schematic of the Cold Flow Test Facility and the Atmospheric Spray Facility is marked by a dashed red square. The facility was designed to accommodate full-scale cold flow injector characterization studies. Simulants may be delivered to a pressurized chamber that allows a backpressure of up to 500 psi, or to the atmospheric spray bench where the flow discharges into ambient pressure environment.

Propellant simulant flow is controlled through two circuits: 1) for the liquid simulant, 2) for the gaseous simulant. Liquid flow rates of up to 1.36 kg/s and gas flow rates of up to 2.4 kg/s can be maintained using nitrogen K-bottle packs. A 60-gallon run tank is used to pressure feed de-ionized, filtered water to the atmospheric spray bench. High-speed imaging and laser diagnostic techniques are available to use depending upon the experimental requirements.
For the experiments conducted for this thesis, spray was issued into an open-air environment and a catch basin was used to drain the water discharged by the injector. All experiments are controlled through an approved Standard Operating Procedures document, a copy of which can be found in Appendix B. Once the facility is brought up to the available system pressure, and the valve checkouts are performed, the Run Tank Dome and the Gas Sim Dome may be pressurized as per experimental requirements. Experiment specific procedure is followed from this point onward.

3.6 Instrumentation

The Spray Facility is equipped with a data acquisition (DAQ) system to measure, monitor, and record steady and dynamic pressures, temperature, and other flow parameters used for experiments within the facility. The DAQ card can be controlled by a computer that runs the National Instruments LabVIEW software. The software samples, and records data at pre-specified
sampling rates and writes it to an LVM file which can be used later for data analysis. For dynamic pressure measurements, an additional connection had to be made as the data must first pass through a signal conditioner, and then through system containing an NI model USB-6363, which then connects to the main computer that runs the LabVIEW software. The dynamic pressure measurements can be integrated with the main code to allow for recording the steady and dynamic pressure data at the same time.

The injector is outfitted with a pair of steady and dynamic pressure transducers at the liquid and gas manifold. Piezoelectric dynamic pressure transducers (PCB model 106-B) were used to record any pressure oscillations in the liquid and gas feed lines. Figure 3.9 marks the location of the static and dynamic transducers pair for the liquid and gas feed lines. Dynamic data from both the transducers is sampled at a rate of 50,000 Hz. Appropriate sampling frequency was selected based on literature survey which has detected pressure oscillations typically of the value 3,000 Hz [13]. Nyquist criterion, which states that the sampling rate must be at least twice the highest frequency to be resolved was considered when selecting the sampling frequency. Under-sampling results in aliasing which causes frequencies that are higher than the sampling rate to be represented as being less than half the sampling rate. Selecting a sampling frequency at least ten times the frequency of interest aids in accurately measuring the shape of the signal [36].
A Panasonic dynamic microphone is placed at a distance of 240 mm from the injector to measure acoustic emissions that are typically perceived when the injector is under self-pulsation. Sound emissions are recorded using a MATLAB script at a sampling frequency of 50,000 Hz. The code saves each audio recording into a .mat file, which can be loaded later and analyzed to find the sound frequencies.

To capture the spray characteristics, high-speed images were recorded using one Vision Research Phantom Micro v4 camera. Data from the camera is recorded using the Phantom Camera Control (PCC) 3.4 software, which allows the user to control the recording parameters like frame rate, exposure, and resolution. All images were recorded at a rate of 10,000 frames per second with an exposure of 1.51 $\mu$s. Figure 3.10 shows the overall setup including the camera and the microphone.
This chapter discussed the experimental setup and the test matrix that was used to acquire sound, pressure oscillations, and high-speed videography data to meet the test objectives. The next chapter discusses the results in detail and attempts to map the stability boundary for the liquid-gas dual-swirl coaxial injector element.
CHAPTER 4. RESULTS

This section presents and discusses the experimental results obtained during the test campaign. The self-pulsation boundaries are marked for the three different recess length configurations tested, along with the acoustic frequencies that were recorded. A qualitative account of the spray characteristics and the observed spray instabilities are also included. Additionally, the role of the inner swirl post as a potential internal oscillator is considered and discussed.

4.1 Flow Scaling

The propellant momentum flux ratio is an important non-dimensional scaling parameter for liquid rocket engines. Bazarov and Yang [10] suggest that the stability boundaries can be scaled with the momentum flux, and that the onset of self-pulsations is affected by the propellant momentum flux. The commonly used equation for propellant momentum flux and the ratio of the propellant momentum flux for liquid-gas swirl coaxial injectors is given by Eq. 1, and 2.

\[
Q = 2q = \rho u^2
\]  
\[
\Phi = \frac{Q_G}{Q_L} = \frac{\rho_G u_G^2}{\rho_L u_L^2}
\]  

The unit for momentum flux is the same as the unit of pressure. The propellant momentum flux is also related to the dimensionless depth of liquid sheet penetration into the coaxial gas stream, \( \Lambda \), which is defined as \( \Lambda = 1/\Phi \). This is an important parameter that features in the hydro-resistance equation used to calculate the stability boundaries (refer to section 2.2.2 in chapter 2).

Calculation of the axial velocity at the nozzle exit for the liquid involves first calculating the liquid film sheet thickness at the injection plane. An empirical relation developed by Suyari and Lefebvre [32, 33] is used to calculate this parameter as

\[
h = 2.7 \left[ \frac{\mu_L \Delta P_L}{\rho_L u_L} \right]^{0.25}
\]  

44
which is then used to calculate the axial velocity

\[ u_L = \frac{\dot{m}_L}{\rho_L \pi h (d_n - h)} \] (4)

The axial liquid velocity is a function of the liquid film sheet thickness, \( h \), mass flow rate of the liquid, \( \dot{m} \), liquid dynamic viscosity, \( \mu_L \), liquid density, \( \rho_L \), the nozzle diameter, \( d_n \) which is the diameter of the oxidizer swirl post shaft, and the pressure drop across the liquid stage of the injector, \( \Delta P_L \). The velocity of the gas is calculated using

\[ u_G = \frac{\dot{m}_G}{\rho_G A_{ann}} \] (5)

It is important to account for the hydraulic diameter while calculating the area of the annulus \( A_{ann} \) term [13] in Equation 5. This term can be calculated

\[ d_{ann} = \left\{ \left( d_{ann,out} + d_{ann,in} \right)^2 \left( d_{ann,out} - d_{ann,in} \right)^3 \right\}^{0.2} \] (6)

In which the outer annulus diameter, \( d_{ann,out} \) is the diameter of the fuel post, and the inner annulus diameter, \( d_{ann,in} \), is the diameter of the oxidizer swirl post shaft.

Since the objective of this thesis is to map the stability boundary, the parameter space included multiple gas flow rate values for the same liquid flow rate as was shown in the test matrix in the previous chapter. Therefore, while the propellant momentum flux is the scaling parameter of choice, its value is not constant across the parameter space. However, the test conditions cover the same liquid and gas momentum flux space that has been previously investigated for liquid-gas swirl coaxial injector elements [11, 13, 22].

Using the liquid mass flow rates from section 3.4.1 in chapter 3, the corresponding liquid momentum flux values can be calculated using equations 1, 3 and 4. Table 4.1 below summarizes the calculated liquid momentum flux values at each set point.
Table 4.1: Liquid momentum flux values calculated at each mass flow rate set point

<table>
<thead>
<tr>
<th>SP</th>
<th>( \rho_L u_L^2 ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.67</td>
</tr>
<tr>
<td>2</td>
<td>15.48</td>
</tr>
<tr>
<td>3</td>
<td>23.43</td>
</tr>
<tr>
<td>4</td>
<td>32.00</td>
</tr>
<tr>
<td>5</td>
<td>41.53</td>
</tr>
<tr>
<td>6</td>
<td>51.77</td>
</tr>
<tr>
<td>7</td>
<td>61.43</td>
</tr>
<tr>
<td>8</td>
<td>71.83</td>
</tr>
</tbody>
</table>

All set points in this chapter will be referred to in terms of the liquid momentum flux.

4.2 Dominant Frequency Determination

For test cases that had a low signal to noise ratio, the spray frequency was determined using the high-speed videography data. All high-speed data was sampled at 10kHz. The high-speed video was first converted into “.jpg images”, which were analyzed using the Image Processing Toolbox in MATLAB [36]. An analysis routine was developed in MATLAB to process the images to focus on the injector near-field area because spray pulsations were observed in that region.

Each image corresponded to one frame. The total number of pulses and the corresponding number of frames were counted, using this the self-pulsation frequency can be calculated using

\[
 f_{sp} = \frac{\text{No.of pulses}}{\text{No.of frames required}} \times \text{(Sampling Frequency)} \quad (7)
\]

This technique was mainly used to determine the dominant frequencies at the self-pulsation lower boundary for the non-recessed injector configuration.
4.3 Self-Pulsation Stability Boundary

Typically, the self-pulsation boundary may be characterized as shown in Figure 4.1, which is a conceptual self-pulsation domain as a function of the liquid and gas momentum flux [13]. The lower boundary sketched in Figure 4.1 indicates that as the liquid momentum flux increases, the gas momentum flux required to incite self-pulsations also increases, and the lower boundary appears to be linear, experimental results for the injector element used for this thesis yielded a non-linear relationship between the liquid and gas momentum flux values, which has been observed previously by other researchers [10,13].

4.3.1 Identifying and Characterizing Different Self-Pulsation Behaviors

The characteristics of self-pulsations just below the lower boundary, that is during the transition from no pulsation to pulsation, may be labelled as “intermittent”. At the transition near the lower boundary, it is difficult to gauge whether self-pulsations exist based on the sound emissions or from the spray characteristics. Qualitatively, the spray field may be devoid of any instabilities, and thus globally stable. The intermittent self-pulsations have been termed as “faint” in this study. Once in the faint self-pulsation zone, it was observed that even a slight increase in
gas flow rate would mark the onset of consistent self-pulsations. The point of transition from intermittent to continuous pulsations is the condition where the lower boundary was identified.

One way to distinguish between intermittent or “faint” self-pulsation behavior and continuous self-pulsation behavior is to observe the spray pattern for both cases. In the intermittent self-pulsation zone, the spray cone maintains a conical shape, with minor noticeable disturbances as is shown in Figure 4.2 below for test case SP7 ($\rho_{LuL^2} = 61.43 \text{ kPa}$) for 1 mm recessed configuration, with the red rectangle marking the region of interest. The black marks in all the frames should be neglected as they represent water droplets splashed on the camera during testing.

![Figure 4.2: Steady Behavior for 1 mm Recessed Configuration for Test Case SP7 ($\rho_{LuL^2} = 61.43 \text{ kPa}$) for a $\dot{m}_{n_{nitrogen}} = 9.35 \text{ g/s}$](image)

For a case where continuous self-pulsations are observed, the spray cone is visibly unstable as is shown in Figure 4.3 for test case SP7 ($\rho_{LuL^2} = 61.43 \text{ kPa}$) for the 1 mm recessed configuration. The red rectangle marks the region of interest. In addition to the instability in the spray cone, there is a stream of large droplets downstream in the spray field. Presence of these droplets can be attributed to the unsteady mixing caused by continuous self-pulsations.
Figure 4.3: Spray Behavior for 1 mm Recessed Configuration for Test Case SP7 
\( \rho_{LuL}^2 = 61.43 \text{ kPa} \) for a \( \dot{m}_{\text{nitrogen}} = 9.94 \text{ g/s} \)

Detailing the lower boundary for a constant liquid momentum flux value is not easy as the self- pulsations are very sensitive to the gas momentum flux. A slight increase in the gas flow resulted in continuous self- pulsations, and therefore, recording the exact gas momentum flux level where the self- pulsations start was a difficult task. Sensitivity of the onset and intensity of self- pulsations to an increase in gas mass flow rate has been observed and recorded in literature by other researchers [10, 13, 15]. Once the lower boundary is mapped, it is comparatively easy to navigate through the self- pulsation region. For each liquid momentum flux value, the lower boundary point was marked, after which the gas flow rate was increased in steps to explore the weak and strong pulsation zones within the self-pulsation region. This process was repeated for all liquid flow test points for all recess configurations.
4.3.2 Self-Pulsation Region

The self-pulsation region is further divided into weak and strong pulsation zones. Dramatic spray instability is observed through high speed videography that allows observations that can distinguish the self-pulsations zone into strong and weak self-pulsations as spray patterns differ in these two zones. For the dual-swirl coaxial injector tested in this study, two different forms of spray instabilities (axisymmetric, and swirling) were observed in the high-speed videos for test conditions within the self-pulsation region which will be elaborated upon later in this chapter.

In addition to visual spray instabilities, distinct sound emissions are also observed in the self-pulsation region and are used to distinguish between strong and weak self-pulsations. Fast Fourier Transform (FFT) analysis was used to deduce the acoustic frequency spectrum levels from the recorded sound data. The amplitude value of the FFT analysis for the dominant frequency observed was the deciding factor that determined whether a test condition displayed strong or weak self-pulsations.

The acoustic frequencies for test conditions showing weak self-pulsations cannot be readily inferred due to low signal to noise ratio. This was the case across all the recess and non-recessed configurations. The transition from weak to strong self-pulsations is marked by a sharp amplification in the amplitudes of the recorded sound. For cases classified as weak self-pulsations, the amplitude value is low. As the gas flow rate increases, the amplitude of the sound signal also increases, thus classifying the test case as strong self-pulsation type. Figure 4.4 shows test case SP6 \((\rho_{Lu}L^2 = 51.77 \text{ kPa})\) for the 1 mm recess configuration, for which self-pulsations at two different gas flow rates are recorded for a constant liquid mass flow rate.
The FFT data represented in blue is a case of weak self-pulsation, where the amplitude is recorded to be 56.74 and the dominant frequency is 1,531 Hz. The amplitude of broadband noise was observed to be approximately 20, which makes the amplitude of the weak pulsations case 184% greater than the broadband noise. The data represented in red is a case of strong self-pulsation, recorded at a higher gas flow rate. The amplitude is observed to be almost 2,208% greater than broadband noise, and the dominant frequency recorded is 1,588 Hz. This is an example of a common trend that was observed across all configuration for all test points. At each constant liquid flow rate (SP1-SP8), an increase in gas flow rate causes a significant increase in the amplitude of the signal.

For all configurations, the observed difference in the amplitudes between weak and strong pulsation cases was similar. For a constant liquid flow rate, the amplitude values of the FFT data can be seen increasing as the gas flow rate is increased in steps. In addition to acoustic emissions, the visual spray instabilities may also be used to make the distinction as was mentioned earlier.
The type of data used, and the criteria used to classify the all test cases into various zones is summarized in Table 4.2.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Data Used</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2. No distinct dominant sound frequency detected in FFT, only broadband noise, as detected by the microphone</td>
</tr>
<tr>
<td>Intermittent (Stable in graphs)</td>
<td>Sound</td>
<td>1. Distinct dominant frequency present in FFT with primary amplitude, at least ten times of the broadband noise amplitude observed in the FFT for that test.</td>
</tr>
<tr>
<td>Weak Pulsations (Defines the lower self-pulsation boundary)</td>
<td>Sound, Visual</td>
<td>1. Unstable spray behavior exhibited a presence of axisymmetric instability.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Distinct dominant sound frequency observed accompanied by a steady “screaming” sound noted by the test conductor which is a typical feature of self-pulsations behavior. In case of low signal to noise ratio in a data set, weak pulsations were confirmed through high-speed videography data.</td>
</tr>
</tbody>
</table>
1. Unstable spray behavior with a presence of swirling instability observed in high-speed videos. For some strong pulsation cases, the spray could be observed swinging sideways, possibly due to a similar movement of the inner swirl post.

2. Distinct dominant sound frequency observed in an FFT with an amplitude that is at least 100 times the noise level accompanied by a steady “screaming” sound, with a distinction that loudness of the sound is amplified compared to the weak self-pulsation region. Harmonics of the dominant frequency are also detected in the FFT.

The conceptual map of the self-pulsation and no self-pulsation zones may be applicable to all types of liquid-gas swirl coaxial injectors. However, in this study, the upper boundary was not mapped to avoid structural failure of any component of the injector assembly and to stay within the limitations of the test facility.

4.4 Lower Stability Boundaries

Using the criteria specified Table 4.2, the lower stability boundaries are marked for all the configurations that were tested for this study.

4.4.1 Flush-Mount Configuration

Several researchers have observed that self-pulsations practically disappear when the LOX swirl post is not recessed from the fuel post. However, with the MISER injector element, self-
pulsations have been observed by Eberhart [12] over off-nominal design conditions. Since the same hardware, except for the exterior swirler is used for this test-campaign, it was determined to be a productive exercise to probe the injector’s self-pulsation characteristics in the flush-mount configuration. Like the swirl-coaxial injector configuration, self-pulsations were observed for the dual-swirl coaxial configuration as well.

The self-pulsation stability boundary for the flush-mount configuration, for which the inner swirl post is not recessed from the outer gas annulus, is shown in Figure 4.5. Self-pulsation was observed for all test cases. The red dots in the figure represent the lower boundary points at which the onset of self-pulsations was recorded based on sound emissions recorded by the test observer. The propellant momentum flux ratios that enclose the lower stability boundary are also marked.

![Figure 4.5: Lower Stability Boundary of Self-Pulsations for the Non-Recessed Configuration](image)

The propellant momentum flux ratios calculated for the lower boundary points for each test case were within the range 2.5 - 4.4. Thus, for all the test cases (SP1-SP8) for the non-recessed
configuration, the gas momentum flux was required to be at least two times the liquid momentum flux to cause self-pulsations.

Sound data that was recorded did not register distinguishing frequency values for this configuration as compared to the recessed configurations. Some cases did register frequencies of up to 6,000 Hz, however, these were very low in amplitude, which indicate that this was mostly white noise that the microphone may have picked up. A potential source of noise besides the test process is the sink into which the spray is exhausted. This is true of all cases, recessed and non-recessed.

The cause of self-pulsations may be attributed to the presence of Kelvin-Helmholtz instability in the spray field. As suggested by Kang et al. [20], Kelvin-Helmholtz instability is always present due to the interactions between the liquid and gas phases in the injection plane. Another reason for the lower stability boundary may be attributed to the absence of the recess chamber. Since the LOX post is not inwardly recessed from the fuel post, there is no interaction between the liquid and the gas internal to the injector. Therefore, internal mixing can be ruled out in this case. External mixing between the liquid and the gas streams may result in Kelvin-Helmholtz instability due to the chaotic interaction between the swirling liquid sheet, and the counter-swirling gas on the outside.

### 4.4.2 Recess = 1 mm

When the injector is in the first recess configuration (recess = 1 mm), the observed self-pulsations boundary can divide the parameter space into clear zones of pulsation and no pulsation. Figure 4.6 displays the lower stability boundary of self-pulsations as observed for this configuration. The red dots in the figure represent the lower boundary points at which the onset
of self-pulsations was recorded based on sound emissions recorded by test observer. The propellant momentum flux ratios that enclose the lower stability boundary are also marked.

![Figure 4.6: Lower Stability Boundary of Self-Pulsations for the Recess = 1mm Configuration](image)

The propellant momentum flux ratio for the lower boundary was calculated to be in the range $2.6 - 8.0$. This indicates that for self-pulsations to start, gas momentum flux has to be at least twice than the liquid momentum flux, and for test cases SP4 - SP8 ($\rho_G u_G^2 = 32 \text{kPa to } 71.83 \text{kPa}$) the gas momentum flux ratio has to be significantly higher than the liquid momentum flux. This can also be seen in Figure 4.6 as the lower boundary shifts up as liquid momentum flux increases. This is the only configuration for which the lower stability boundary lies between a wide range of propellant momentum flux ratios.

The boundary exhibits an almost linear trend and for most cases, an increase in the liquid mass flow rate results in a delay for the onset of self-pulsations. In this configuration, the recess chamber is present, albeit, it is not very long. However, there is still some interaction between the liquid and the gas internal to the injector in the recess chamber. Thus, while Kelvin-Helmholtz
instability may drive self-pulsations externally to the injector, the recess chamber may play an active role in driving self-pulsations internally.

The frequencies recorded were in the range of 1,000-2,000 Hz, which was expected, with some strong pulsation cases recording up to second order harmonics of the dominant frequency. Table 4.3 summarizes the frequency values recorded in the FFT at the lower stability boundary.

**Table 4.3: Frequency Values Recorded at the Lower Stability Boundary for the Recess = 1 mm Configuration**

<table>
<thead>
<tr>
<th>Set Point</th>
<th>$\Phi$</th>
<th>Dominant Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>2.6</td>
<td>1166</td>
</tr>
<tr>
<td>SP2</td>
<td>2.8</td>
<td>1302</td>
</tr>
<tr>
<td>SP3</td>
<td>2.7</td>
<td>1446</td>
</tr>
<tr>
<td>SP4</td>
<td>5.1</td>
<td>1444</td>
</tr>
<tr>
<td>SP5</td>
<td>5.9</td>
<td>1215</td>
</tr>
<tr>
<td>SP6</td>
<td>8.1</td>
<td>1438</td>
</tr>
<tr>
<td>SP7</td>
<td>7.7</td>
<td>1505</td>
</tr>
<tr>
<td>SP8</td>
<td>8.0</td>
<td>1624</td>
</tr>
</tbody>
</table>

Figure 4.7 shows a three-dimensional scatter graph of the recorded frequency of the dominant sound modes at the lower stability boundary.
Figure 4.7: Three-Dimensional Display of the Recorded Acoustic Frequencies Across the Lower Boundary of Self-Pulsations for Recess = 1 mm

As the liquid momentum flux increases, the dominant frequency at the lower boundary also increases, except for SP5 – SP6 ($\rho_{L}u_{L}^{2} = 41.53 \text{ kPa to } 51.77 \text{ kPa}$) which did not follow a linear pattern. The propellant momentum flux ratio values do not offer a reasonable explanation for the deviation from the trend for these two cases, and therefore, these cases are considered anomalies.

An interesting phenomenon was noted while testing this configuration. At some liquid and gas mass flow rates, the sound frequency was perceived to change without any increase in the gas mass flow rate. Similarly, the spray was also prone to display more than one instability. A common form of spray instability is the pulsing kind, which is axisymmetric in nature. A cluster of droplets appears to be pushed out of the injector in pulses, thus resulting in axisymmetric instability. However, at a certain point, the spray starts to display swirling instability. The spray cone in the injection plane appears to swirl during this kind of instability. While the swirling instability was commonly observed for higher gas mass flow rates, this was the only configuration in which two different instability modes were on display without increasing the liquid or gas mass flow rates.
4.4.3 Recess = 2 mm

For this configuration, self-pulsation region is wider as compared with the non-recessed and 1 mm recessed configurations. This agrees with the observations made by Bazarov and Yang [9]. There is no clear linear trend at display for this configuration. Compared to the previous configuration, the onset of self-pulsation starts at much lower gas mass flow rates. Figure 4.8 displays the lower stability boundary of self-pulsations as observed for this configuration. The red dots in the figure represent the lower boundary points at which the onset of self-pulsations was recorded based on sound emissions recorded by test observer. The propellant momentum flux ratios that enclose the lower stability boundary are also marked.

![Figure 4.8: Lower Stability Boundary of Self-Pulsations for the Recess = 2 mm Configuration](image)

The propellant momentum flux ratios calculated for the lower boundary are within the range of 1.0 – 3.5, which indicates that the gas momentum flux should be at least equal to the liquid momentum flux for the onset of self-pulsations. The propellant momentum flux ratios at the stability boundary for this configuration display the narrowest range, compared to other
configurations. Therefore, the onset of self-pulsations is premature for this configuration. Table 4.4 summarizes the frequency values recorded in the FFT at the lower stability boundary.

**Table 4.4: Frequency Values Recorded at the Lower Stability Boundary for the Recess = 2 mm Configuration**

<table>
<thead>
<tr>
<th>Set Point</th>
<th>Φ</th>
<th>Dominant Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>1.9</td>
<td>1013</td>
</tr>
<tr>
<td>SP2</td>
<td>2.8</td>
<td>1089</td>
</tr>
<tr>
<td>SP3</td>
<td>1.2</td>
<td>1251</td>
</tr>
<tr>
<td>SP4</td>
<td>1.1</td>
<td>1371</td>
</tr>
<tr>
<td>SP5</td>
<td>1.1</td>
<td>1520</td>
</tr>
<tr>
<td>SP6</td>
<td>2.8</td>
<td>1675</td>
</tr>
<tr>
<td>SP7</td>
<td>3.3</td>
<td>1715</td>
</tr>
<tr>
<td>SP8</td>
<td>3.5</td>
<td>2072</td>
</tr>
</tbody>
</table>

Figure 4.9 shows a three-dimensional scatter graph of the recorded sound frequencies. The frequencies recorded were in the range of 1,000-2,072 Hz, with some with some strong pulsation cases recording up to second order harmonics of the dominant frequency, similar to the first recessed configuration. As compared with the previous recessed configuration, the sound frequencies for this configuration followed a linear pattern wherein, as the liquid momentum flux increases, the dominant frequency at the lower boundary increases.
For this configuration as well, it may be assumed that Kelvin-Helmholtz type instability is present due to the liquid and gas interaction that occurs externally. Internally, the increased interaction between the liquid and gas may be a factor that may cause spray instabilities. Since the inner swirl post is slightly more recessed than the previous configuration, the recess chamber is slightly longer. Therefore, there is more potential for internal mixing of the flow. The interaction between the liquid and the gas inside the recess chamber may lead to instabilities that may propagate downstream into the spray that is injected in the injection plane.

Similar to the previous recess configuration, spontaneous change in the frequency of the sound without any increase or decrease in the liquid and gas mass flow rates was observed. This seemed to be a common feature at the lowest liquid mass flow rate, and the highest gas mass flow rate. This also resulted in a change in the spray structure and two different instabilities were apparent in the spray. One was the axisymmetric type instability and the other one, swirling type.

Another important observation that can be made for the spray developed for this recess configuration is that it appears to exit the injector at an angle. The angled spray feature was also observed for higher recess values of 3 mm and 4 mm. Therefore, it may not be due to self-
pulsations, but rather due to the interaction between the liquid and gas inside the recess chamber that may cause the liquid film to impinge on the wall at an angle, and thus spray at an angle as well.

4.5 Dynamic Pressure Data for all Configurations

Dynamic pressure data was recorded for both liquid and gas feed lines. An FFT analysis of the recorded data yielded information about the frequency of pressure oscillations in the feedlines. It is important to note that the gas spectrum does not register significant oscillations. This is attributed to the choking of the tangential holes of the exterior swirler at all the gas flow rates explored for this study. As a result, any downstream gas pressure fluctuations caused by the onset of self-pulsations do not propagate upstream at the location of the dynamic pressure transducer. Any minor oscillations that are observed may be the reason of variations in flow conditions.

For the non-recessed configuration, the pressure oscillation frequency was typically in the range of 1,500-3,000 Hz. Figure 4.10 is an example for the lower self-pulsation boundary for the first liquid set-point. The amplitude of the pressure oscillations increases as the test cases traverse through the strong self-pulsation region.
Pressure oscillations recorded for both the recessed configurations were of very low amplitude. It was concluded that there was a calibration error on the day of testing, which renders the recorded dynamic pressure data for the recessed configurations unusable for analysis. Figure 4.11 and 4.12 are examples of the kind of data recorded for dynamic pressures for recessed configurations.
Figure 4.12: Liquid and Gas Pressure Oscillations Recorded for Recess = 2 mm

The pressure oscillations that are detected in Figures 4.11 and 4.12 can be attributed to the liquid and gas flow conditions and are not related to the injector under self-pulsation. Since accurate dynamic pressure data was available only for the flushed configuration, dominant frequencies were not determined from the feedline dynamic pressure data to be consistent. The data may instead be used to confirm the presence of oscillations in the liquid feedline (for the non-recessed configuration), which has been mentioned in literature as a manifestation of the injector under self-pulsations.

4.6 Analysis of Self-Pulsation Region

Monte Carlo Method for uncertainty propagation was used to determine the uncertainty propagation of all variables in the liquid and gas momentum flux equations [38]. Appendix C provides more detail about the Monte Carlo approach used to calculate the uncertainties. Additionally, the calculated errors, and the uncertainties associated with each point on the stability boundary are documented in Appendix C. Figure 4.13 shows a comparison of the lower stability boundaries for all configurations. The uncertainty of the water and nitrogen momentum flux measurements were calculated to be 7% and 14% respectively. Error bars for the water and
nitrogen momentum flux values are marked for all the points on the lower stability boundary in Figure 4.13. Since the self-pulsation boundary for the non-recessed and 2 mm recessed configuration lie close together, the error bars for the nitrogen momentum flux overlap for SP6-SP8.

![Figure 4.13: Lower Stability Boundaries for all Test Configurations. Regions Above Each Boundary Correspond to Self-Pulsation Zones](image)

The area under the self-pulsation region is different for each configuration. For lower liquid momentum flux values, the lower stability boundaries lie within a narrow range, and only begin to diverge after the first three set points. The boundaries for the 2 mm and the non-recessed configuration lie close to each other, while the boundary for the 1 mm configuration diverges significantly post SP4 ($\rho_Lu_L^2 = 32 \text{ kPa}$).

The self-pulsation zone is the widest for the 2 mm configuration, and therefore, the total number of points in the stable zone is low. The non-recessed configuration follows a similar pattern, with a marginally wider self-pulsation zone compared to 2 mm. The lower boundary for the 1 mm configuration accommodates for the most stable set points. Comparing the boundaries
for the recessed configurations to available literature, the trends observed are reasonable. According to Bazarov and Yang [10, 15, 16], the self-pulsation region becomes wider with an increase in recess, which is observed in this study. However, in the same studies, the authors have mentioned that self-pulsations disappear with the absence of recess, which is not applicable to this study.

Eberhart [13] has observed self-pulsations for a non-recessed injector and the stability boundary pattern observed in terms of width of stable region was recorded as: non-recessed > 1 mm > 2 mm. The same injector hardware is used in this thesis, the only difference being the exterior gas swirler. Therefore, for the non-recessed configuration, in addition to the common potential internal oscillators, external oscillators may play a significant role since the liquid and gas interaction occurs external to the injector.

Another possible external oscillator that may have contributed to the differences in the stability boundaries and the width of the stable region, between the two studies, may be the liquid flow metering element that was used. This study uses an orifice to meter the flow, and standard orifices are prone to cause a whistling type noise in the system [37]. The noise from the orifice may have coupled with the fluid oscillators internal to the injector, and with the external oscillators caused by the interactions between the liquid and gas, therefore causing the difference in the lower stability boundaries.

4.6.1 Recess = 1 mm

Frequency distribution of a portion of the self-pulsation region for the 1 mm recess configuration is shown in Figure 4.14. While self-pulsations were observed across the parameter space summarized in Table 3.3, only a few data points were recorded to determine the frequency distribution. Mapping the frequencies across this region allows to deduce important relationships
between the variation of the dominant frequency with an increase in the liquid and gas mass flow rates, respectively. An increase in the propellant flow rates correlates to an increase in the propellant momentum flux values.

For all constant liquid momentum flux cases, as the gas mass flow rate is throttled, the dominant frequency increases steadily, while a sharp increase in amplitude is observed. Similarly, with an increase in the liquid momentum flux, the registered dominant frequency also increases. For the upper band containing test points \( \rho_g u_g^2 > 400 \text{ kPa} \), the frequency falls in the upper range of 1,400-1,650. Across all liquid momentum flux test points, SP1-SP8 the dominant frequencies at low gas momentum flux range from 1,100-1,630 Hz.

The dark colored bands at lower liquid momentum flux points, and for gas momentum flux values in the range of 200 kPa to 350 kPa, show higher frequencies because for these cases the registered dominant frequencies, with the highest amplitudes are multiples of the fundamental frequency, which was in the range of 1,300-1,400 Hz. Therefore, the frequency values are in the range of 2,000-2,750 Hz in this region. An example of such a case is shown in Figure 4.15.
Multiples of the fundamental frequency were also observed for other cases shown in the frequency distribution. Most cases, however, other than the ones marked in Figure 4.14, registered up to the second harmonic of the fundamental frequency, but with a lower amplitude; an example of such a case is shown in Figure 4.16. This was observed across all liquid momentum flux test points.
The upper band with the higher frequency values also corresponds to loud pulsations as was observed and noted on test day. The amplitude that was registered for these cases was at approximately 100 times the recorded broadband noise. In addition to the sound amplitude, the spray was highly unstable, which when observed in the high-speed video appears to be so due to the inner swirl post oscillate from side to side within the injector element. The oscillations of the swirl post likely cause the spray to swirl in the spray field. This type of instability was observed in the upper range of all liquid mass flow rate setpoints.

All dominant frequencies recorded for this configuration at the lower boundary and in the self-pulsation region are summarized in Appendices F and G, respectively. Additionally, sound frequency graphical data for this configuration is recorded in Appendix D.

4.6.2 Recess = 2 mm

Frequency distribution of the self-pulsation region for the 2 mm recess configuration is shown in Figure 4.17. While self-pulsations were observed across the parameter space summarized in Table 3.3, only a few data points were recorded to determine the frequency distribution, similar to the previous recessed configuration.

![Figure 4.17: Frequency Distribution in the Self-Pulsation Region for Recess = 2 mm](image)
Frequency distribution for this configuration mainly falls in the range of 1,000-3,400 Hz. At low liquid and gas momentum flux values, the registered dominant frequency is the lowest and is in the range of 1,000-1,200 Hz. An increase in gas mass flow rate at a constant liquid mass flow rate, results in an increase in the dominant frequency.

The dark colored regions in the upper band of the plot represent multiples of the fundamental frequency. All frequencies recorded above 1,800 Hz, are higher order harmonics of the fundamental frequency, and are included in Figure 4.17 because they registered the highest amplitudes compared to the fundamental frequency. This is mostly observed for test cases where \( \rho_g d_t g^2 > 250 \text{ kPa} \), and dominant frequencies \( > 3,000 \text{ Hz} \) are recorded. This behavior of the self-pulsation frequency to jump to a multiple of the fundamental frequency has been observed and recorded in literature [18]. Figure 4.18 shows an example of such a case, with the harmonics of the fundamental frequency clearly recorded.

![Figure 4.18: Example of Self-Pulsation Frequency Jump to a Multiple of the Fundamental Frequency for Recess = 2 mm at SP6 (\( \rho_1 u_1^2 = 51.77 \text{ kPa} \)) for \( \dot{m}_{\text{nitrogen}} = 8.84 \text{ g/s} \)](image)
Compared to the 1 mm recessed configuration, this configuration recorded more test points that registered higher order harmonics of higher amplitudes. The self-pulsation frequency at the second harmonic is also greater than the one observed for the 1 mm recessed configuration.

Highly unstable spray displaying similar inner swirl post behavior as that mentioned for the previous configuration is observed for the 2 mm configuration as well. Test conditions with higher propellant momentum flux ratios are more susceptible to this type of spray instability.

All dominant frequencies recorded for this configuration at the lower boundary and in the self-pulsation region are summarized in Appendices F and H, respectively. Additionally, sound frequency graphical data for this configuration is recorded in Appendix E.

4.7 Qualitative Account of Spray Instabilities

Due to the swirling motion imparted to both the liquid and the gas flows, the typical spray structure associated with self-pulsations was not observed. Additionally, the spray field was chaotic, which prevented from the usage of traditional techniques such as Proper Orthogonal Decomposition (POD) analysis to determine the spray frequency. Some unique spray structures were captured using high-speed videos for test conditions falling in the self-pulsations zone. As was mentioned earlier, the spray structure displayed at least two modes of instability: axisymmetric and swirl. This section provides an extensive account of the peculiar spray patterns that were observed when the injector was under self-pulsations.

4.7.1 Axisymmetric Instability

Axisymmetric instability is primarily characterized in this thesis as that which is associated with a “flapping” motion of the spray. The spray can be seen being ejected from the injector face in pulses, which causes the spray cone to expand and contract. In swirl-coaxial injectors, this expansion and contraction propagates downstream in the spray field. However, for the dual-swirl
coaxial injector, the counter-swirling gas atomizes the inner liquid cone before the pulse propagates downstream. This prevents the formation of spray patterns associated with self-pulsations that have been recorded in literature [10,13,15].

Figure 4.19, 4.20, and 4.21 show a typical cycle of self-pulsation at different liquid and gas momentum flux conditions. In the first row from left to right, the spray cone begins to form and starts expanding before collapsing (second row from left to right, spray area of interest is marked by red squares) after which this cycle is repeated.

Figure 4.19: One Cycle of Self-Pulsation for the Non-Recessed Configuration at Test Case SP 4 ($\rho_{LuL}^2 = 32 \text{ kPa}$) for $m_{nitrogen} = 7.00 \text{ g/s}$
Figure 4.20: One Cycle of Self-Pulsation for Recess = 1 mm at Test Case SP 1 (\(\rho_L u_L^2\) = 12.67 kPa) for \(\dot{m}_{\text{nitrogen}}\) = 7.03 g/s

Figure 4.21: One Cycle of Self-Pulsation for Recess = 2 mm at Test Case SP 3 (\(\rho_L u_L^2\) = 23.43 kPa) for \(\dot{m}_{\text{nitrogen}}\) = 4.89 g/s

Axisymmetric instability was seen in all the configurations that were tested, recessed and non-recessed, and was limited to the weak self-pulsations zone. It was possible to estimate the spray self-pulsation frequency by counting the pulses and implementing equation 7 discussed in
Section 4.2. Spray self-pulsation frequency was typically estimated to be in the range of 1,200-1,600 Hz, which matches the bandwidth of the acoustic frequencies.

4.7.2 Swirling Instability

Swirling type instability was the second type of instability observed for flow conditions experiencing strong self-pulsations and was always accompanied by very loud sound emissions. Due to the fixed position of the high-speed camera, it was not possible to capture the swirling motion of the spray.

On close observation of the high-speed videography data, it was observed that the inner swirl post may be oscillating violently within the injector element, thus imparting swirling motion to the spray. However, in the absence of visual access to the inner swirl post, the likelihood of the swinging movement of the inner swirl post causing swirling instability, remains a conjecture.

Figures 4.22, 4.23, and 4.24 are representative of the swirling type instability for different test conditions for the non-recessed and recessed configurations, and the area of interest is marked by red rectangles.

Figure 4.22: Representation of Swirling Instability for the Non-Recessed configuration at Test Case SP 8 ($\rho_L u_L^2 = 71.83 \text{ kPa}$) for $\dot{m}_{\text{nitrogen}} = 8.77 \text{ g/s}$
Figure 4.23: Representation of Swirling Instability for \textit{Recess} = 1 \textit{mm} at Test Case SP 8 (\(\rho_{LU}L^2 = 71.83 \text{ kPa}\)) for \(\dot{m}_{\text{nitrogen}} = 10.94 \text{ g/s}\)

Figure 4.24: Representation of Swirling Instability for \textit{Recess} = 2 \textit{mm} at Test Case SP 8 (\(\rho_{LU}L^2 = 71.83 \text{ kPa}\)) for \(\dot{m}_{\text{nitrogen}} = 8.08 \text{ g/s}\)

In all the figures, the spray cone can be seen swinging sideways, which may be a result of the oscillatory motion of the inner swirl post within the injector. Additionally, for both the recessed configurations, there is a stream of large droplets that propagates downstream, which will result in unsteady mixing if implemented in a liquid rocket engine. For the \textit{recess} = 2 \textit{mm} configuration, the spray is angled to the right, compared to the spray in Figures 4.22, 4.23.

On close observation of the high-speed videos, it was noted that for sufficiently high mass flow rates of liquid and gas, the swirl direction of the spray changes in random intervals. There is an important interaction that occurs between both the swirling flows where the flow
swirling with a higher momentum appears to change the swirling direction. However, it isimportant to note that there is a possibility that the observed swirl direction change may be a resultof aliasing. The sampling rate used for recording high speed data was 10,000 Hz. In case the sprayoscillations exceed 5,000 Hz, the current sampling rate is deemed inadequate which may havecaused the spray to appear to change swirling directions due to aliasing.

Only one swirl number was tested for both liquid and gas. The swirl number dependsprimarily on the geometry of the injector, and in this case, no changes were made to the geometryspecifically pertaining to the swirl number and changing the recess length does not have anyinfluence on the swirl number. Considering that the swirling spray behavior under some conditionswas observed across all test cases, the presence or absence of the recess chamber had no majorrole to play in eliminating swirling instability that was observed.

4.7.3 Self-Pulsation Zone-Specific Spray Instabilities

The two different modes of instabilities are present separately for some cases, while insome cases the spray is issued in pulses, and a swirling motion is also observed. The differentmodes of spray instabilities that were observed may be marked on the stability boundaries recordedfor the recessed and non- recessed configurations as is shown in Figure 4.25. The pattern of theonset of each kind of instability was common across all configurations tested in this study.
Swirling instability is typically found for cases where \( \rho_g u_g^2 > 450 \text{ kPa} \), and for all cases less than 450 kPa, axisymmetric instability was observed.

### 4.8 Potential Internal Oscillator

Section 2.2.2 of chapter 2 briefly discussed potential fluid oscillators internal to the injector that may potentially excite self-pulsations due to resonance. These internal oscillators experience natural oscillations due to their structure, flow conditions, and the physical and thermal properties of the fluid flowing through these structures. These oscillators may show potential to oscillate under certain conditions, and potentially couple with other oscillators in the system to induce the injector into experiencing self-sustained oscillations. While multiple fluid oscillators have been discussed briefly in the previous chapter, this section will only discuss the potential of the longitudinal acoustic eigenmodes of the swirl post to incite self-pulsations.

The reason for selecting the swirl post for analysis is the apparent oscillatory motion of the spray where it appears to swing from side to side under certain operating conditions. It is suggested that this may be due to the swirl post oscillating within the injector. Another reason for focusing
on the swirl post eigenmodes is the structural failure of two swirl post tubes during the test campaign. It is imperative to reiterate that the failure may have been caused by repeated use of the swirl posts over the years for the self-pulsation study and may not be due to test conditions it was subjected to on the day. However, it may be determined that the repeated failure justifies considering the role of the swirl post as one of the many potential oscillators internal to the injector. Eberhart [13, 24] presents a comprehensive assessment of the swirl post eigenmodes, and the same assessment is applied to this thesis, since the swirl post hardware was the same for both studies. The model used to calculate the quarter-wave frequencies of the swirl post is briefly described, and the frequency values are listed. For analyzing the quarter-wave frequencies, the swirl post is considered independently and is decoupled from the fuel annulus. Hence, the calculations only concern the liquid volume and the gas core formed inside the swirl post.

Huang et al. [35] have proposed that the self-pulsation frequency may be defined through the longitudinal acoustic resonance model. Since during testing within the self-pulsation zone, high-intensity sound emissions are recorded, it is important to consider the potential implications of resonance on the self-pulsation frequency.

The swirl post may be modeled as a quarter wave resonator with a closed at one end, and open at the other boundary condition. The fluid volume in the swirl post is assumed to be a constant radius cylinder and length. The longitudinal eigenmodes may be approximated using equation 8 shown below, which is a general equation for a simple quarter wave resonator.

$$f_n = \frac{(2n-1)c}{4L_{inj}}$$  \hspace{1cm} (8)

The $L_{inj}$ term includes the overall length swirl post, including the vortex chamber, nozzle, and swirl post [24]. It is important to remember that the inside the swirl post, the flow is heterogenous since swirling liquid film creates a gaseous vortex core in the center. Therefore, it is
required to consider the propagation of pressure waves through the liquid-gas heterogenous medium. The liquid film is rotational in nature and has mean flow in the axial direction, unlike the gaseous core. An acoustic cut-off frequency is defined such that at a certain axial distance, the fundamental mode pressure waves attenuate by a factor of $e^{-1}$, within the liquid film. This cut-off frequency and the axial distance is defined by equations 9 and 10 [13].

$$f_{cut} = \frac{(2c+1)c}{4h}$$  \hspace{1cm} (9)

$$x_{atten} = \frac{2h}{\pi}$$  \hspace{1cm} (10)

The axial distance is primarily a function of the liquid film thickness, $h$, which is calculated using the empirical relation expressed in Equation 3. It can be inferred that low frequency pressure waves attenuate at an axial distance of approximately 64% of the liquid film thickness for each test condition. As the liquid flow rate increases, the axial attenuation distance reduces. There exist other factors that may attenuate the pressure waves within the liquid film even further: shear and viscous forces due to interaction with the wall and turbulence. Therefore, it is prudent to assume that most of the longitudinal propagation will occur through the gaseous core [34].

To calculate the quarter-wave frequencies, it is necessary to find the mixed acoustic velocity of the water-air medium. The acoustic velocity is approximated by assuming a constant gas void fraction throughout the cross-sectional area of the gaseous core and for the overall length of the swirl post [24]. The mixed acoustic velocity can be estimated using equation 11 shown below [13].

$$\frac{c_{mix}}{c_g^2} = \frac{\rho^* + \frac{(1-\gamma)}{\gamma^*} \rho^*}{\rho^* + \frac{(1-\gamma)}{K^*}}$$  \hspace{1cm} (11)

In the equation, $\rho^* = \rho_g/\rho_l$ and $K^* = K_g/K_l$ where $K$ is the fluid bulk modulus, $K = c^2/\rho$.

For standard pressures and temperatures, the mixed acoustic velocity can be plotted for a range of void fractions as shown in Figure 4.26 shown below.
For water-air mixture, and for the test condition region under consideration, the mixed acoustic velocity approaches close to the acoustic velocity of pure air. Therefore, it may be assumed that the mixed acoustic velocity in the liquid-gas medium is 343.2 m/s [24]. Using this value for the mixed acoustic velocity, longitudinal quarter-wave frequencies as calculated for the swirl post are shown in Table 4.5.

**Table 4.5: Acoustic Quarter-Wave Frequencies for the Swirl Post**

<table>
<thead>
<tr>
<th>n</th>
<th>( f_n ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(~1420)</td>
</tr>
<tr>
<td>2</td>
<td>(~4250)</td>
</tr>
<tr>
<td>3</td>
<td>(~7000)</td>
</tr>
</tbody>
</table>

As can be seen in Table 4.5, the first quarter wave resonant frequency falls within the bandwidth of the acoustic frequencies measured in all the tests. Furthermore, cases in which the dominant frequency was observed to be a multiple of the fundamental frequency, also fall within the range of the first and second quarter wave resonant frequencies of the inner swirl post. The
acoustic frequencies and the spray frequencies may represent damped frequencies in some cases that do not lie within the 1,420-4,250 Hz range. Thus, the swirl post may be considered to be one of the possible oscillators within the system that may incite and exacerbate self-pulsations.
CHAPTER 5. CONCLUSIONS

A liquid-gas dual-swirl coaxial injector was tested at varying water and nitrogen flow rates to determine the self-pulsation stability boundary. Since majority of the surveyed literature suggests that the recess length is an important parameter to consider that may influence self-pulsations, two recess length values, 1 mm and 2 mm, were tested, respectively. Some research also points to the presence of self-pulsations for even the non-recessed injector configuration, and therefore, the test article was also tested in the non-recessed configuration. The results presented mainly the stability boundaries detected for the three different configurations, and the acoustic frequencies recorded by a microphone placed in the near-field of the injector.

Some of the major conclusions drawn from this research effort for the conditions investigated are:

1) Self-pulsations are observed for the non-recessed configuration as well as for both the recessed configurations. While the interactions taking place between the liquid and gas within the recess chamber may be important, the presence or absence of the recess chamber may not necessarily be an important factor in inciting self-pulsations.

2) Self-pulsation stability boundaries recorded for the recessed configurations conform to the observations in literature, which suggest that as the recess length is increased, the self-pulsation, unstable region becomes wider. Conversely, this causes the stable region to become narrower.

3) Contrary to literature, self-pulsations did not disappear for the non-recessed configuration. The stability boundary for the non-recessed configuration lay between the boundaries recorded for the two recessed configurations.
4) For all configurations, the onset of self-pulsations for lower liquid momentum flux values (SP1-SP3) was recorded at low gas momentum flux values. However, as the liquid momentum flux increases (SP4-SP8), the lower self-pulsation boundary was recorded when the gas momentum flux was slightly higher than the liquid momentum flux, which during testing was characterized by the liquid and gas pressure drop values across the injector element.

5) The counter-swirling gas injected exterior to the inner swirling liquid sheet significantly alters the spray characteristics from those typically observed for swirl-coaxial injectors. Due to this difference, even under self-pulsations, the spray features observed are different and are considered chaotic in nature. Under self-pulsation, the spray displays two types of instabilities: axisymmetric, and swirling, and both. The spray exits the injectors periodically in the form of a cluster of droplets (“flapping motion”) when axisymmetric instability is present. In the presence of swirl instability, the spray field can be observed to be swirling. The change in swirl direction of the swirling spray may be attributed to aliasing due to a possibly low sampling frequency.

6) Propagation of pressure waves through the gas core contained within the swirl post is suggested as a possible internal oscillator responsible for the onset of self-pulsations. The first quarter wave frequency calculated for the swirl post is within the range of acoustic frequencies recorded during the test campaign. Therefore, resonance of the swirl post at those frequencies may be a factor by itself or may be coupled with another potential oscillator contained within the injector.
5.1 Recommendations

Several recommendations may be made to explore the self-pulsations phenomena further, in a liquid-gas dual-swirl coaxial injector, considering that not much self-pulsations literature is available for this kind of injector.

1) It would be beneficial to explore the spray characteristics of this kind of injector and understand the relation between propellant throttling and important spray features such as free cone spray angle, breakup length, and droplet sizes.

2) The current test matrix should be expanded to include higher gas mass flow rates to probe the upper stability boundary. It would suit well to expand upon the gas momentum flux values further to map the upper boundary of self-pulsation.

3) The external factor that may potentially excite and sustain self-pulsations is the presence of Kelvin-Helmholtz instability arising due to the interaction between the liquid and gas phases in the injection plane. Without any spray oscillation measurements, it is difficult the quantify the Kelvin-Helmholtz frequency range which is typically observed for both recessed and non-recessed injectors. However, spray oscillation frequency and acoustic frequency is often the same [27]. To definitively say if K-H instability is a factor to consider, it is recommended to setup a suitable visualization technique to record spray instabilities.

4) Studies may be conducted at varying ambient pressures to determine the self-pulsation boundary and spray characteristics during self-pulsation.

5) Studies to determine the possible coupling between a cavitating orifice in the feedline, and the self-pulsations experienced by the injector element should be conducted as it
would provide valuable insight into the coupling of self-pulsation frequencies with feed-line instabilities.

6) Manufacturing an injector of similar dimensions as the Miser but using a clear material like acrylic would provide optical access to the swirl post and other inner parts of the injector. This would help to explore the potential internal oscillators that may act by themselves or together to excite and sustain self-pulsations.
APPENDICES

Appendix A: Injector Element Design Process

The injector element is designed following the ideal hydraulic swirl injector design as outlined Bazarov [6]. Injector element design typically begins by taking into consideration mission design requirements such as thrust, burn time, mixture ratio, and choice of propellant. As per the mission requirements stated by Ikard et. al [31], the inner swirl stage and exterior swirl stage is designed.

The injector element was originally designed to operate at a nominal LOX mass flow rate of 82 g/s, and liquid methane mass flow rate of 27 g/s, at design pressure drops of 345 kPa for both propellants. Since the injector element was not designed for this experiment, the design calculations outlined below are summarized from the suitable references [6, 31].

Procedure to determine design parameters for the inner LOX swirl post:

1. Using the pressure drop and density value of liquid oxygen, the exit jet velocity is determined using Bernoulli’s equation.

   \[ V_{e,LOX} = \sqrt{\frac{2\Delta P_{LOX}}{\rho_{LOX}}} \]

2. Using the exit jet velocity, the exit cross-sectional jet area can be calculated

   \[ A_{jet,LOX} = \frac{\dot{m}_{LOX}}{\rho_{LOX} V_{e,LOX}} \]

3. A non-dimensional parameter, \( a \), is defined which is defined as the ratio of the vortex radius of the head end, \( r_{mk} \) and the nozzle radius, \( R_n \). Hydraulic parameters of the inner swirling stage are shown in Fig. A.1. Spray angle data can be used to calculate the parameter, \( a \).

   \[ a_{LOX} = \frac{\tan \frac{\alpha}{2}}{1 + \tan^2 \frac{\alpha}{2}} \]
4. Next, the non-dimensional parameter, $a$, is used to calculate the nozzle fullness coefficient is calculated which refers to area of the liquid in the passage. Using this coefficient, the mass flow coefficient is calculated, which is similar to the coefficient of discharge in orifices.

$$\sqrt{a_{LOX}} = (1 - \phi_{LOX}) \frac{2}{\sqrt{2-\phi_{LOX}}}$$

$$\mu_{LOX} = \frac{\phi_{LOX} \sqrt{\phi_{LOX}}}{\sqrt{2-\phi_{LOX}}}$$

5. Using the cross-sectional jet area and the mass flow coefficient, geometric parameters of the nozzle such as radius, diameter and area can be calculated.

$$A_{n,LOX} = \frac{A_{jet,LOX}}{\mu_{LOX}}$$

$$R_{n,LOX} = \sqrt{\frac{A_{n,LOX}}{\pi}}$$

$$d_{n,LOX} = 2R_{n,LOX}$$

Figure A.1: Schematic of Liquid Flow in the Inner Swirl Post; 1-Injector Casing; 2-Vortex Chamber; 3-Nozzle Passage; 4-Tangential Passage [6]
6. The nozzle fullness factor is then used to calculate the liquid film thickness in the nozzle, and it is normalized by the radius of the nozzle.

\[ \bar{h}_{\text{LOX}} = 1 - \sqrt{1 - \Phi_{\text{LOX}}} \]

\[ h_{\text{LOX}} = \bar{h}_{\text{LOX}} R_{\text{n,LOX}} \]

7. Geometric parameter defined by, \( A = \frac{\bar{r}_{\text{in}}}{A_{\text{in}}} \) is calculated using the non-dimensional parameter, \( a \). Next, the total inlet area and diameter are calculated using the geometric parameter.

\[ A_{\text{LOX}} = \sqrt{\frac{a_{\text{LOX}}}{\mu_{\text{LOX}}}} \]

\[ A_{\text{in,LOX}} = \frac{\bar{r}_{\text{in,LOX}} A_{\text{n,LOX}}}{A_{\text{LOX}}} \]

\[ d_{\text{in,LOX}} = \frac{4A_{\text{in,LOX}}}{\pi r_{\text{inj}}} \]

8. The sum of the inlet geometry is used to calculate the vortex chamber diameter

\[ d_{\text{vc,LOX}} = 2\bar{r}_{\text{in,LOX}} R_{\text{n,LOX}} + d_{\text{in,LOX}} \]

9. Next, the inlet channel length is calculated, which is suggested to be twice the inlet diameter

\[ L_{\text{in,LOX}} = 2d_{\text{in,LOX}} \]

10. The vortex chamber length is calculated, which is suggested to be 2.5 times the inlet diameter

\[ L_{\text{vc,LOX}} = 2.5d_{\text{in,LOX}} \]

This concludes the calculations procedure for the interior LOX swirl post. The CAD drawings of this part are shown in the Figures A.2-A.5.

Calculations for the exterior swirling stage:
1. Calculations for the exterior swirling stage begin by assuming a liquid film thickness of $h_{LCH4} = 0.3 \text{ mm}$.

2. Next, the minimum nozzle diameter is determined for the fuel nozzle, and it is the sum of the LOX post nozzle diameter, the LOX post wall thickness, desired gap between the LOX post and the outer annulus, and the film thickness, $h_{LCH4} = 0.3 \text{ mm}$. Using the diameter, the nozzle area can be calculated.

   $$d_{n,LCH4} = d_{n,LOX} + 2\delta_{wall} + 2\delta_{gap} + 2h_{LCH4}$$

   $$A_{n,LCH4} = \frac{\pi}{4}d_{n,LCH4}^2$$

3. Using Bernoulli’s equation, the jet velocity can be calculated, which can be used to calculate the jet cross-sectional area.

   $$V_{e,LCH4} = \sqrt{\frac{2\Delta P_{LCH4}}{\rho_{LCH4}}}$$

   $$A_{jet,LCH4} = \frac{m_{LOX}}{\rho_{LOX}V_{e,LCH4}}$$

4. Next, the nozzle mass flow coefficient and nozzle fullness coefficient can be calculated by rearranging the nozzle mass flow coefficient as shown below.

   $$\mu_{LCH4} = \frac{A_{jet,LCH4}}{A_{n,LCH4}}$$

   $$\mu_{LCH4} = \frac{\phi_{LCH4} \sqrt{\phi_{LCH4}}}{\sqrt{2 - \phi_{LCH4}}}$$

5. The previously assumed film thickness is recalculated using the nozzle fullness factor. This is an iterative calculation, and the process should be repeated until convergence is achieved.

   $$h_{LCH4,new} = \frac{d_{n,LCH4}}{2} \left( 1 - \sqrt{1 - \phi_{LCH4}} \right)$$

6. Next, the non-dimensional parameter, $a$, is calculated, which is then used to calculated the geometric parameter, $A$.  

89
\[
\sqrt{a_{\text{LCH4}}} = (1 - \phi_{\text{LCH4}}) \frac{2}{\sqrt{2 - \phi_{\text{LCH4}}}}
\]

\[
A_{\text{LCH4}} = \frac{\sqrt{a_{\text{LCH4}}}}{\nu_{\text{LCH4}}}
\]

7. Next, geometric parameters such as the total inlet area and the individual inlet diameter for the exterior stage can be calculated.

\[
A_{\text{in, LCH4}} = \frac{\bar{R}_{\text{in, LCH4}} A_{n, \text{LCH4}}}{A_{\text{LOX}}}
\]

\[
d_{\text{in, LCH4}} = \frac{4 A_{\text{in, LCH4}}}{\pi n_{\text{in, LCH4}}}
\]

8. Finally, the length of the inlet channels, diameter of the vortex chamber and the length of the vortex chamber is calculated.

\[
L_{\text{in, LCH4}} = 2d_{\text{in, LCH4}}
\]

\[
d_{v_{c, \text{LCH4}}} = 2\bar{R}_{\text{in, LCH4}} R_{n, \text{LCH4}} + d_{\text{in, LCH4}}
\]

\[
L_{v_{c, \text{LCH4}}} = 2.5d_{\text{in, LCH4}}
\]

This concludes the calculations procedure for the interior LOX swirl post. The CAD drawings of this part are shown in the Figures A.6-A.8.
Figure A.2: Miser Oxidizer Post Base

Figure A.3: Miser Interior Swirl Nut
Figure A.4: Miser Interior Swirl Press Plate

Figure A.5: Miser Oxidizer Post Shaft
Figure A.6: Miser Exterior Swirler

Figure A.7: Miser Fuel Post
Figure A.8: MISER Cube

Figure A.9: MISER Holder
Appendix B: Standard Operating Procedure for Atmospheric Spray Facility

UAH Propulsion Research Center

STANDARD OPERATING PROCEDURE FOR:

Atmospheric Spray Facility Test

SOP #: FRC - SOP - JRC-631-A2
Revision: A
Version: 2
Operation: Atmospheric Spray Facility Test
Test Location: JRC High Bay

Test Date: ____________
Test Time Start: ____________ Finish: ____________

Test Team

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<thead>
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<th>NAME</th>
<th>ROLE</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td></td>
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<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
__________________________

This Procedure Contains the following Hazards:

- Human Subjects
- Highly Toxic Chemicals
- Pressurized gases
- Microbial agents/products
- Lasers
- Radioisotopes or x-ray generating equipment
- Human blood, body fluid, tissue
- Animal Subjects
- Toxins or toxin products
- Explosives/Propellants
- Cell or tissue culture
- Selected Agents
- Carcinogenic/mutagenic/teratogenic chemicals
- Recombinant DNA/RNA molecules

Atmospheric Spray Facility Test
FRC - SOP - JRC-631-A2
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AUTHORIZED RED TEAM MEMBERS

Individuals identified below are authorized to participate in test operations as Red Team Members through the SOP approval signatures. By signing the document below, the individuals acknowledge that they have reviewed the procedure and understand the general and specific safety requirements personnel limits and work descriptions necessary to accomplish their part of the operation.

Additional Red Team Member may be added to this document without a procedure revision pending approval of the PRC Director or Laboratory Supervisor or Facility Engineer prior to participating in the experiment. Additional members require signatures of both the individual to be added and the approver.

Authorized test individuals agree to abide by and follow the procedure outlined in this document for conducting the described experiment. Any individual not following procedure during testing in a manner which jeopardizes other test members will be immediately removed from the red team and reported to the PRC director.

<table>
<thead>
<tr>
<th>RED TEAM MEMBERS</th>
<th>AFFILIATION</th>
<th>FIRST AID/CPR-AED CERTIFICATION DATES</th>
<th>PRC SAFETY TRAINING</th>
<th>SIGNATURES</th>
</tr>
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<tbody>
<tr>
<td>David Lineberry</td>
<td>PRC Staff</td>
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<td>2018</td>
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<td>Tony Hall</td>
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<td>Erik Korzon</td>
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<td>2018</td>
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</tr>
</tbody>
</table>

Atmospheric Spray Facility Test
PRC – SOP – JRC-032-A2
SECTION II. TEST PROCEDURES

PRETEST LABORATORY PREPARATION

☐ 1. Confirm a JRC Staff Member is in the area to support Testing

☐ 2. If guests are present, provide a safety briefing to include
   - Hazards specific to this operation: High Pressure, Debris
   - emergency procedures
   - staying outside the marked boundary, see Appendix D

☐ 3. Ensure all personnel are wearing personal protective equipment (PPE).

DAQ START-UP

☐ 4. Ensure DAQ connections (NI FXI-1052) for test conditions per Table 1:

☐ 5. Turn on DAQ

☐ 6. Open LabView.

☐ 7. Run: ______________.vi

<table>
<thead>
<tr>
<th>Name</th>
<th>Plug Ch</th>
<th>DAQ Ch</th>
<th>DAQ Card</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Press</td>
<td>Box 3 Ch 14</td>
<td>BNC2085 – a05</td>
<td>SCXI Slot 1</td>
</tr>
<tr>
<td>Run Tank Dome Press</td>
<td>Box 3 Ch 20</td>
<td>BNC2085 – a03</td>
<td>SCXI Slot 1</td>
</tr>
<tr>
<td>Run Tank Press</td>
<td>Box 3 Ch 19</td>
<td>BNC2085 – a10</td>
<td>SCXI Slot 1</td>
</tr>
<tr>
<td>Liquid Sim Press</td>
<td>Box 3 Ch 18</td>
<td>BNC2085 – a15</td>
<td>SCXI Slot 1</td>
</tr>
<tr>
<td>Injector Press 1 (right)</td>
<td>Box 1 Ch 1</td>
<td>BNC2085 – a00</td>
<td>SCXI Slot 1</td>
</tr>
<tr>
<td>Injector Press 2 (left)</td>
<td>Box 1 Ch 2</td>
<td>BNC2085 – a03</td>
<td>SCXI Slot 1</td>
</tr>
<tr>
<td>Feed Line Temp</td>
<td>Box 1 TC 1</td>
<td>TC2095 – a01</td>
<td>SCXI Slot 2</td>
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<tr>
<td>High Freq. Press. Transducer 1</td>
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<td>BNC2080 – a00</td>
<td>SCXI Slot 3</td>
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<tr>
<td>High Freq. Press. Transducer 2</td>
<td>Box 1 Ch 14</td>
<td>BNC2080 – a02</td>
<td>SCXI Slot 3</td>
</tr>
</tbody>
</table>

☐ 8. Verify nominal pressure readings of zero

☐ 9. Verify nominal thermocouple readings

☐ 10. Verify nominal dynamic pressure readings of zero

Atmospheric Spray Facility Test
FRC – SOP – JRC-032-A2

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TEST ARTICLE SETUP

11. Ensure all test components downstream of Atmospheric Spray Facility Loop hand ball valve (7.09) and Gas Sim three-way hand ball valve (8.01) are
   ○ Pressure-rated higher than Maximum Operating Pressure or
   ○ have appropriate relief mechanisms in place to protect components and operators (check the date of calibration of relief valve 15.03)

12. Secure feed lines and pressure relief lines to test stand apparatus

FACILITY START-UP

13. Loosen Cap on Water Holding Tank (16.03) so that the holding tank cannot hold pressure

14. Position Drain Line(s) under High Bay Door 1

15. Position caution boundaries as portrayed on facility footprint (Appendix D)

16. Position warning signs as portrayed on facility footprint (Appendix D)

RUN TANK FILL

17. Open ¼” Run Tank hand ball valve (7.04).

18. Close liquid line hand ball valve (7.05)

19. Open Run Tank to pump hand ball valves (7.06, 7.08)

20. Optional if using pump, energize Fill Pump (13.01) until tank is full

21. Optional if using pump, De-energize Fill Pump (13.01)

22. Close Run Tank to pump hand ball valves (7.06, 7.08)

23. Close ¼” Run Tank hand ball valve (7.04)

24. Open liquid line ball valve (7.05)

PRESSURE SOURCE STARTUP

25. Verify all three-way hand ball valves (8.02, 8.03, 8.04, 8.05) set to VENT

26. Verify all hand regulators fully backed out (14.03, 14.04, 14.05, 14.06) (CCW)
27. Verify PLC power

28. Insert "Enable Key" and arm the Control Panel

29. Disengage "Emergency Stop"

30. Verify nominal Control Panel switch positions as per Table 2:

<table>
<thead>
<tr>
<th>Switch</th>
<th>Valve Function</th>
<th>Switch Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fire</td>
<td>Closed</td>
<td>Down</td>
</tr>
<tr>
<td>Window/Curtain Fire</td>
<td>Closed</td>
<td>Down</td>
</tr>
<tr>
<td>Liquid Sim Fire</td>
<td>Closed</td>
<td>Down</td>
</tr>
<tr>
<td>Gas Sim Fire</td>
<td>Closed</td>
<td>Down</td>
</tr>
<tr>
<td>Run Tank Pressure/Vent</td>
<td>Vent</td>
<td>Down</td>
</tr>
<tr>
<td>Main Vent</td>
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<td>Down</td>
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<tr>
<td>Chamber Liquid Vent</td>
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<td>Down</td>
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<td>Chamber Gas Vent</td>
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<td>Down</td>
</tr>
<tr>
<td>Emergency Stop</td>
<td>Engaged</td>
<td>In</td>
</tr>
</tbody>
</table>

31. Set semaphore light at rear door to yellow

32. Open Air Source by following the appropriate steps below

   **K-Bottle Supply Source**
   - Open Isolation Valves between Bottle valve and system
   - Crack open bottle to let pressure slowly bleed into system
   - Once Pressure has equalized, Open all other k-bottles in supply manifold

   **Wind Tunnel Air Tanks**
   - Close Wind Tunnel Tank Vent Valve (9.01)
   - Verify pressure of Wind Tunnel Air Tanks with gauge
   - Open Wind Tunnel Tank Isolation Manual Ball Valves as required
     - MBV-7.01
     - MBV-7.02
33. Disengage the emergency stop.
34. Verify Operation of Main Vent Valve (10.02) by toggling the valve
35. Close Main Vent Valve (10.02)
36. Open Main Fire Valve (10.01)
37. Verify the pressure via the pressure transducer (12.01) and the analog gauge (1.02)

**VALVE ACTUATION**

38. Turn Valve Actuation Supply three-way ball valve (8.02) to pressurize
39. Set Valve Actuation Supply hand regulator (14.03) to 100 psig
40. Verify valve actuation
   - Close “Chamber Liquid Vent” (10.03) (switch)
   - Close “Chamber Gas Vent” (10.07) (switch)
   - Close Liquid Sim Fire (10.08)
   - Set Run Tank Pressure/Vent to Vent (10.04)

**RUN TANK PRESSURIZATION**

41. Set Run Tank hand regulator (14.06) to 100 psig, check transducer (12.06) for pressure
42. Rotate Run Tank Pressurization three-way hand ball valve (8.03) to Pressurize (CCW)
43. Toggle “Run Tank Pressure/Vent” (10.04) to PRESSURE (switch)
44. Run Tank Vent Check
   - Verify “Run Tank Pressure” via LabView, pressure transducer (12.03)
   - Fully Back Out Run Tank hand regulator (14.06), turn CCW
   - Toggle “Run Tank Pressure/Vent” (10.04) to VENT (switch)
   - Verify “Run Tank Pressure” via LabView reduces to 0 psig, (12.03)
45. Toggle “Run Tank Pressure/Vent” (10.04) to PRESSURE (switch)
46. Set in-line Run Tank hand regulator (14.06) to desired pressure max. 2000 Psi

47. Verify “Run Tank Pressure” via LabView

**LIQUID SIMULANT SPRAY**

48. Close Chamber Loop hand ball valve (7.03)

49. Verify the top part of the High-Pressure Spray Facility Chamber is secured or removed

50. Open Atmospheric Spray Facility Loop hand ball valve (7.09)

51. Open “Liquid Sim Fire” (10.08) (switch)

52. Open Injector Hand Ball Valve(s) (7.10, 7.11)

53. Adjust Run Tank hand regulator (14.06) to achieve mass flow rate as per test sheet

54. Proceed with test-specific experiments

55. In event of total run tank depletion:
   - Close “Liquid Sim Fire” (10.08) (switch)
   - Close Injector Hand Ball Valve(s) (7.10, 7.11)
   - Proceed to RUN TANK DEPRESSURIZATION
   - Proceed to RUN TANK FILL section
   - Proceed to LIQUID SIMULANT SPRAY
   - Repeat as necessary

56. After completing tests proceed to Run Tank Depressurization

**RUN TANK DEPRESSURIZATION**

57. Verify Chamber Liquid Vent (10.03) is closed

58. Verify Chamber Gas Vent (10.07) is closed

59. Inform personnel in the vicinity of venting, hearing protection optional

60. Toggle “Run Tank Pressure Vent” (10.04) to VENT (switch)
61. Verify “Run Tank Pressure” is zero via LabView & 12.03 and 1.07

FACILITY DEPRESSURIZATION

- 62. Verify Run Tank is depressurized
- 63. Back out Run Tank Pressure Regulator (14.06)
- 64. Set Run Tank Pressure Vent (10.04) to pressurize
- 65. Vent the line via Run Tank handball-valve (7.04)
- 66. Set ball-valve (10.04) to vent
- 67. Close Main Fire Valve (10.01)
- 68. Inform personnel in the vicinity of venting, hearing protection optional
- 69. Open Main Vent (10.02)
- 70. Open the hand valve to depressurize N₂ panel.
- 71. Verify “System Pressure” is zero via LabView & 12.01 and 1.02

72. Close Supply Tank Isolation Valves

   K-Bottle Supply Source
   - Close all K-Bottle Valves

Wind Tunnel Air Tanks

   - Close Wind Tunnel Tank Isolation Manual Ball Valves and lock the Valves
     - MBV-7.01
     - MBV-7.02

- 73. Open Supply Line Manual Vent (9.01)
- 74. Once all pressure is vented Close Supply Line Manual Vent (9.01)
- 75. If Running on a K-Bottle Pack, Close Bottle Pack Isolation Valves
- 76. Turn off facility amber
FACILITY SHUT DOWN

☐ 77. Reengage “Emergency Stop”

☐ 78. Disarm Control Panel and remove “Enable Key”

☐ 79. Return all Control Panel switches to nominal positions as per Table 4

☐ 80. Return all three-way hand ball valves (8.02, 8.03, 8.04, 8.05) set to VENT

☐ 81. Fully Back out Valve Actuation hand regulator (14.03) (CCW)

☐ 82. Reposition Drain Line

☐ 83. Recap tank

☐ 84. Remove warning signs on High Bay Entrance Door and JRC Exit to Test Stand

☐ 85. Close Bay Door 1

☐ 86. Back up Method: __________________________

☐ 87. Upon completion, the SOP needs to be signed by the participating Red Team Members, scanned, and saved on the Spray Facility Computer.
Appendix C: Uncertainty Analysis

Elemental standard uncertainty can be estimated using equation C.1. Standard uncertainty is a combination of all elemental standard uncertainties, which accounts for the effects of systematic, $b_i$, and random uncertainties, $s_i$. Uncertainty calculation provides an estimate of a range within which the actual value of an error lies [38].

$$u_X^2 = \sum_{i=1}^{n} b_i^2 + s_i^2 \quad \text{(C.1)}$$

Monte Carlo Method (MCM) is used to calculate the uncertainties in the measurement of the liquid and gas momentum flux. This method determines the uncertainty of each parameter that is used to calculate the momentum flux by applying an appropriate probability distribution for each variable in the equation. The flowchart in Figure C.1 explains the MCM method in detail for when random standard uncertainty values are used for individual variables [38].

![Figure C.1: Schematic of the Monte Carlo Method for Uncertainty Propagation](image_url)
First, mean values of each variable in the equation are determined. Next, elemental systematic uncertainties, $b_k$, and random standard uncertainties, $s$, are estimated for each variable in the equation of interest. Random uncertainties in the measured variables are assumed to be zero since the standard deviation of the final result is calculated. For each source of error in the equation, an appropriate probability distribution function is assumed. Random values for each systematic error and random error are calculated using a random number generator and distributed over a Gaussian distribution. The calculated result is the sum of all the individual errors added to the true values of the variables. This process is equivalent to running one simulation. This process is repeated depending on the number of iterations deemed acceptable.

Table C.1 summarizes all the mean values, and the systematic uncertainty estimates used for calculating the uncertainty in the liquid and gas momentum flux. Mean values of the measured variables, upstream pressure to the cavitating orifice, $P_{1,L}$, injection pressure of nitrogen, $P_{1,G}$, and the pressure drop across the liquid phase of the injector, $\Delta P_L$, are calculated using recorded LabView data at steady state for all test points on the lower boundary across all configurations.
Table C.1: Mean Values and Systematic Uncertainty Estimates for all Parameters used in Calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean Values</th>
<th>Systematic Uncertainty Estimates</th>
</tr>
</thead>
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<tr>
<td><strong>Liquid and Gas Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_{d,liq}</td>
<td>0.591</td>
<td>0.01</td>
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<tr>
<td>d_{o}</td>
<td>0.055 in</td>
<td>0.001</td>
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<tr>
<td>\rho_{L}</td>
<td>62.428 lb/ft³</td>
<td>1% of mean value</td>
</tr>
<tr>
<td>P_{v}</td>
<td>0.46 psia</td>
<td>0</td>
</tr>
<tr>
<td>d_{n}</td>
<td>0.197 in</td>
<td>0.001</td>
</tr>
<tr>
<td>\mu_{L}</td>
<td>0.0000185880 lbfs/ft²</td>
<td>5% of mean value</td>
</tr>
<tr>
<td>C_{d, gas}</td>
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<td>0.01</td>
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<tr>
<td>d_{tang.holes}</td>
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<tr>
<td>\rho_{g}</td>
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<td>1% of mean value</td>
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<tr>
<td>\gamma</td>
<td>1.4</td>
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<tr>
<td>R</td>
<td>55.165 ft-lbf/lb-R</td>
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<tr>
<td>T</td>
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<td>d_{ann,in}</td>
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<td>0.001</td>
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**Measured Variables**

**Example:** SP8, 1 mm recess

**Random Uncertainty Estimates**

| P_{1,L}       | 414.55 psia | 1 |
| P_{1,G}       | 340.32 psia (SP8) | 1 |
| \Delta P_{L}  | 69.01 psid (SP 8) | 1 |
The uncertainties calculated for the measured liquid and gas momentum flux values at the lower stability boundary for all configurations are summarized in Tables C.2-C.4. Probability densities for liquid and gas momentum flux are shown in Figures C.2 and C.3.

**Table C.2: Uncertainties Values for Liquid and gas Momentum Flux at the Lower Stability Boundary for the Non-Recessed Configuration.**

<table>
<thead>
<tr>
<th>SP</th>
<th>$U_{QG}$ %</th>
<th>$U_{QL}$ %</th>
<th>$U_{QG} = t^*\text{std. dev (kPa)}$</th>
<th>$U_{QL} = t^*\text{std. dev (kPa)}$</th>
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<td>14.51</td>
<td>7.04</td>
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<td>6</td>
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<td>6.97</td>
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<td>8</td>
<td>14.54</td>
<td>6.98</td>
<td>43.71</td>
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**Table C.3: Uncertainties Values for Liquid and gas Momentum Flux at the Lower Stability Boundary for the 1 mm Recess Configuration.**

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<th>$U_{QG}$ %</th>
<th>$U_{QL}$ %</th>
<th>$U_{QG} = t^*\text{std. dev (kPa)}$</th>
<th>$U_{QL} = t^*\text{std. dev (kPa)}$</th>
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<td>14.48</td>
<td>6.93</td>
<td>80.72</td>
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Table C.4: Uncertainties Values for Liquid and gas Momentum Flux at the Lower Stability Boundary for the 2 mm Recess Configuration.

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<tr>
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<th>$U_{QG}$ %</th>
<th>$U_{QL}$ %</th>
<th>$U_{QG} = t \times \text{std.dev (kPa)}$</th>
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Figure C.2: Liquid Momentum Flux Probability Density
Figure C.3: Gas Momentum Flux Probability Density
Appendix D: Sound Frequency Data for $Recess = 1 \text{ mm}$ for Self-Pulsation Cases

Figure D.1: Sound Frequency Graphs for 1 mm recess at $\rho_{UL}L^2 = 12.67 \text{ kPa}$
Figure D.2: Sound Frequency Graphs for 1 mm recess at $\rho_Lu_t^2 = 15.48$ kPa
Figure D.3: Sound Frequency Graphs for 1 mm recess at $\rho_u L^2 = 23.43$ kPa

- $\rho_u L^2 = 62.15$ kPa
- $\rho_u L^2 = 84.32$ kPa
- $\rho_u L^2 = 110.97$ kPa
- $\rho_u L^2 = 138.79$ kPa
- $\rho_u L^2 = 197.90$ kPa
- $\rho_u L^2 = 254.04$ kPa
Figure D.4: Sound Frequency Graphs for 1 mm recess at $\rho L u_1^2 = 32$ kPa

- $\rho L u_1^2 = 163.04$ kPa
- $\rho L u_1^2 = 203.79$ kPa
- $\rho L u_1^2 = 239.35$ kPa
- $\rho L u_1^2 = 277.76$ kPa
- $\rho L u_1^2 = 322.76$ kPa
- $\rho L u_1^2 = 383.24$ kPa
Figure D.5: Sound Frequency Graphs for 1 mm recess at $\rho G u_G^2 = 41.53$ kPa
Figure D.6: Sound Frequency Graphs for 1 mm recess at $\rho_L u_L^2 = 51.77$ kPa
Figure D7: Sound Frequency Graphs for 1 mm recess at $\rho_{L_1 L_2}^2 = 61.43$ kPa

Figure D.8: Sound Frequency Graphs for 1 mm recess at $\rho_{L_1 L_2}^2 = 71.83$ kPa
Appendix E: Sound Frequency Data for \textit{Recess} = 2 \text{ mm} for Self-Pulsation Cases

Figure E.1: Sound Frequency Graphs for 2 mm recess at $\rho_{L}u_{L}^{2} = 12.67$ kPa
Figure E.2: Sound Frequency Graphs for 2 mm recess at $\rho_{u_1}^2 = 15.48$ kPa
Figure E.3: Sound Frequency Graphs for 2 mm recess at $\rho_L U_L^2 = 23.43$ kPa
Figure E.4: Sound Frequency Graphs for 2 mm recess at $\rho_L u_1^2 = 32$ kPa
Figure E.5: Sound Frequency Graphs for 2 mm recess at $p_{LuL^2} = 41.53$ kPa
Figure E.6: Sound Frequency Graphs for 2 mm recess at $p_{rL/\text{L}^2} = 51.77$ kPa
Figure E.7: Sound Frequency Graphs for 2 mm recess at $\rho_L u_L^2 = 61.43$ kPa
Figure E.8: Sound Frequency Graphs for 2 mm recess at $\rho_Lu_L^2 = 71.83$ kPa

Amplitude vs. Frequency Graphs for Different Pressures:
Appendix F: Flow Conditions and Frequencies at the Lower Stability Boundary

Table F.1: Data Recorded at Lower Boundary for the *Non-Recessed Configuration*

<table>
<thead>
<tr>
<th>$\dot{m}_L$ (g/s)</th>
<th>$\rho_L u_L$ (kPa)</th>
<th>$\dot{m}_G$ (g/s)</th>
<th>$\rho_G u_G$ (kPa)</th>
<th>$\varphi$</th>
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<td>7.63</td>
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Table F.2: Data Recorded at Lower Boundary for *Recess = 1 mm*

<table>
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<th>$\dot{m}_L$ (g/s)</th>
<th>$\rho_L u_L$ (kPa)</th>
<th>$\dot{m}_G$ (g/s)</th>
<th>$\rho_G u_G$ (kPa)</th>
<th>$\varphi$</th>
<th>Frequency (Hz)</th>
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Table F.3: Data Recorded at Lower Boundary for *Recess = 2 mm*

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<th>Frequency (Hz)</th>
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Appendix G: Self-Pulsations Region Dominant Frequencies for $Recess = 1 \text{ mm}$

Table G.1: Flow Conditions and Frequencies for $Recess = 1 \text{ mm}$ for SP1 – SP2

<table>
<thead>
<tr>
<th></th>
<th>$\dot{m}_D$ (g/s)</th>
<th>$p_D u_D$ (kPa)</th>
<th>$\dot{m}_C$ (g/s)</th>
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<th>Dominant Frequency (Hz)</th>
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Table G.2: Flow Conditions and Frequencies for \textit{Recess = 1 mm} for SP3 – SP4

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Appendix H: Self-Pulsations Dominant Frequencies for $\textit{Recess} = 2 \text{ mm}$

Table H.1: Flow Conditions and Frequencies for $\textit{Recess} = 2 \text{ mm}$ for SP1 – SP2

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Table H.2: Flow Conditions and Frequencies for *Recess = 2 mm* for SP3 – SP4

|       | SP3          |               |               |               |               |               |               |               |
|-------|--------------|---------------|---------------|---------------|---------------|---------------|---------------|
|       | \( \dot{\mathbf{m}}_L \) (g/s) | \( \rho_L \dot{u}_L \) (kPa) | \( \dot{\mathbf{m}}_C \) (g/s) | \( \rho_C \dot{u}_C \) (kPa) | Dominant Frequency (Hz) |
| 43.08 | 23.43        | 2.27          | 27.93         | 1251          |               |               |               |
| 2.92  | 46.13        |               |               |               | 2578          |               |               |
| 3.61  | 70.62        |               |               |               | 1308          |               |               |
| 4.26  | 98.22        |               |               |               | 1371          |               |               |
| 4.89  | 129.17       |               |               |               | 1406          |               |               |
| 5.47  | 161.71       |               |               |               | 1432          |               |               |
| 6.23  | 209.77       |               |               |               | 1498          |               |               |
| 7.01  | 265.77       |               |               |               | 16114         |               |               |
| 7.70  | 320.89       |               |               |               | 1617          |               |               |

|       | SP4          |               |               |               |               |               |               |               |
|-------|--------------|---------------|---------------|---------------|---------------|---------------|---------------|
|       | \( \dot{\mathbf{m}}_L \) (g/s) | \( \rho_L \dot{u}_L \) (kPa) | \( \dot{\mathbf{m}}_C \) (g/s) | \( \rho_C \dot{u}_C \) (kPa) | Dominant Frequency (Hz) |
| 49.20 | 32.00        | 2.58          | 36.15         | 1371          |               |               |               |
| 2.90  | 45.43        |               |               |               | 1419          |               |               |
| 3.32  | 59.72        |               |               |               | 1440          |               |               |
| 4.15  | 93.13        |               |               |               | 1453          |               |               |
| 4.75  | 122.18       |               |               |               | 1489          |               |               |
| 5.38  | 156.47       |               |               |               | 1524          |               |               |
| 5.87  | 186.38       |               |               |               | 1567          |               |               |
| 6.49  | 228.23       |               |               |               | 1677          |               |               |
| 7.19  | 279.50       |               |               |               | 1678          |               |               |
| 7.77  | 326.50       |               |               |               | 1671          |               |               |
| 8.28  | 371.13       |               |               |               | 1660          |               |               |
Table H.3: Flow Conditions and Frequencies for *Recess = 2 mm* for SP5 – SP6

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Table H.4: Flow Conditions and Frequencies for \textit{Recess} = 2 \text{ mm} \text{ for SP7 – SP8}

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<th></th>
<th>( m_B ) (g/s)</th>
<th>( p_{L,B} ) (kPa)</th>
<th>( m_C ) (g/s)</th>
<th>( p_{C,L,C} ) (kPa)</th>
<th>Dominant Frequency (Hz)</th>
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REFERENCES


