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I, Vincent Notaro, hereby submit this original work as part of the requirements for the degree of Master of Science in Aerospace Engineering.

It is entitled:

Mixing Analysis of Like Doublet Injectors in High Pressure Environments for Gelled Propellant Simulants

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Mixing Analysis of Like Doublet Injectors in High Pressure Environments for Gelled Propellant Simulants

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by

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Abstract

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Thesis Committee: Jong Guen Lee, San-Mou Jeng, and Milind A. Jog.

Impinging doublet injectors offer rocket designers an effective way to atomize and mix opposing jets of fuel and oxidizer. The adaptability of the injector designs and ease of manufacturing make them attractive choices for designers. The adaptability of injector designs introduces many variables to the system like orifice diameter, nozzle orifice pairings, and working fluid to name a few. This expanse of variables requires characterization of phenomenon produced and measurement of performance. The characterization of phenomenon can be used to help explain performance. The atomization and spray characteristics of impinging jets are well understood. The studies in this field cover a multitude of design variables. While mixing quantification is well understood for liquid working fluids and similar orifice pairings, data are still lacking on non-Newtonian working fluids, specifically gelled simulants, and dissimilar orifice pairings. In addition, like mixing data exists for sprays in elevated ambient pressure conditions. Gelling of propellants provides advantages of easier handling and less vapor issues as compared to liquid propellants. Dissimilar orifice pairs offer the opportunity to achieve desired mixture ratios without largely varying operating conditions.

A review of mixing studies for liquid working fluids is conducted. The studies focus on defining mixing efficiencies changes based on the injector design variables. In addition, some mixing mechanisms are established and discussed phenomenologically. A review of atomization studies is also conducted. These studies help shed light on mixing characteristics as well as help progress diagnostics in the mixing study field. These studies also focus injector design variables but cover more variables in greater depth than the mixing studies.

A combination of a pressure chamber, two flow systems for the two different working fluids, and two pairings of nozzles is used to characterize mixing over different injection velocities and ambient conditions. In addition, the two working fluids and two different nozzle pairings allow comparisons to be made between the different cases. The injection velocity conditions range from 8 m/s to 20 m/s in ambient pressure conditions from atmospheric to 500 psi. Mixing efficiency is calculated using spray mass distributions acquired by PLIF technique. The data processing procedure is defined and is applicable to similar data acquisition systems.

The mixing data acquired show that for similar orifice diameter impingement, the ambient pressure increase above atmospheric enhances mixing for both gelled and non-gelled fluid due to reduced break-up lengths. However, the mixing efficiency stops increasing and remains constant above a certain ambient pressure. Gelled simulant generally results in poorer mixing efficiencies than the non-gelled simulant, suggesting momentum carried and pre-impingement jet conditions are the determining factors in mixing. For dissimilar orifice diameter impingement, mixing is generally constant over all the ambient pressures including atmospheric. This may be due to the far downstream distance collection location. For optimized operating conditions, the dissimilar orifice-diameter impingement case can produce better mixing than the similar orifice diameter impingement case.

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1 Introduction

When two opposing, free, liquid jets impinge co-axially, they create a circular liquid sheet in the plane perpendicular to their momentum vectors. If the jets are forced to impinge with their momentum vectors in the same plane but not co-axially aligned, a liquid sheet will be formed also in the plane perpendicular to their momentum vectors. However, the free impinging jets create a radial, almost elliptical, sheet that eventually breaks up. The break of the sheet is due to instabilities from aerodynamic forces like air density and hydrodynamic forces from the momentum exchange of the jets. The break up destabilizes the sheet and causes ligaments to separate from the bottom periodically. These ligaments continue to decrease in size and finally expel droplets. A representative image of the impinging jets and the liquid sheet can be found in figure 1. The configuration in the figure is known as a doublet impinging jets. There are other configurations involving three, four, and five impinging jets with corresponding names of triplet, quadruplet, and quintuplet, respectively.

Doublet impinging jets provide a way to mix and atomize one or two types of fluids. When the impinging jets are the same fluid, it is known as “like” impingement. When different fluids impinge, it is known as “unlike” impingement. These jets can easily be created with nozzles which act to conform the flow to their inner geometries. Nozzles are easy to manufacture and provide infinite internal and external geometric designs allowing designs to produce whatever impinging jet they require. When the orifice diameter of the nozzles that are impinging are the same, it is known as “similar” orifice diameter impingement. When the orifice diameters are not equivalent, it is known as “dissimilar” orifice diameter impingement. Typically, regardless of like or unlike and similar or dissimilar impingement, nozzles are set to impinge with intersecting centers of momentum. This symmetry is known as “aligned” impingement. “Unaligned” impingement may be achieved but is not generally used.

Figure 1. Doublet injector and sheet with typical terminology

For the reasons stated, impinging jets have been used in rocket injector systems. A system of doublet nozzles can be used as an injection interface for combustion systems. The individual reference to a “nozzle” and a “injector” will be synonymous from now on. The single injection point of fuel and of oxidizer simplifies the design and analysis. One pair of nozzles can be investigated and its results applied to the array of similar pairs. An array of doublet injectors would provide a efficient way to introduce mixed and atomized fuel and oxidizer to the combustion chamber. The nozzle geometry and flow rate can be tailored to meet mixture ratio requirements. In addition, a fuel and oxidizer combination that would ignite on contact would remove the need for an external ignition device in the combustion system. A small set of propellants, known as hypergolics, exist and have been used. Doublet nozzles are prominent components in hypergolic systems due to easy manufacturing and assembly, effective mixing and atomization, and simplifications offered to the system. However, common hypergolic propellants (typically a hydrazine derivative and nitrogen tetroxide) are highly toxic and carry strict handling requirements. To minimize the draw backs of hypergolics, a gelling agent can be added to the propellants. This gelling helps reduces vapor issues and handling issues without preventing variable flow rate capability. Gelling merges the handling and storage capabilities of solid propellants with the variable thrust and performance of liquid propellants.

1.1 Objective

The purpose of this research is to characterize mixing efficiencies for a variety of injection flow conditions. The injectors are designed to mimic common hypergolic dimensions found in past research. The flow conditions are varied by ambient pressure changes and gelling of the working fluid. The flow conditions in regards to ambient pressure have not yet been fully characterized. Mixing efficiency data for gelled simulants are still lacking. The similarity of the injectors and of the gelled simulant makes the research directly applicable to hypergolic systems whereas the flow conditions allow advancements in characterization research in the doublet injector field. The injector system used reflects these desires and allows accurate and reproducible measurements of spray conditions. Planar laser-induced fluorescence technique is applied as the superior analysis method for these kinds of measurements. The technique allows non-intrusive and quick data collection for dense spray regions.

The research completed is done to better understand the effects of elevated ambient pressure on mixing efficiency for like, doublet impinging jets. In addition, similar and dissimilar orifice diameter impingement and non-gelled (water) and gelled working fluids are used to create an array of variables to test. The

objectives of the mixing efficiency studies are:

1. Obtain similar orifice diameter impingement mixing efficiencies for non-gelled and gelled simulant in atmospheric ambient conditions.
2. Apply lessons learned from atmospheric ambient conditions to collect impingement data for non-gelled and gelled simulant in elevated ambient pressures for similar orifice diameter impingement.
3. Characterize pressure effects on non-gelled and gelled simulant at elevated ambient pressures and compare these effects.
4. Change injector configuration and acquire dissimilar orifice diameter impingement data at atmospheric and elevated ambient pressure conditions.
5. Characterize pressure effects on non-gelled simulant impingement at elevated ambient pressures and compare similar and dissimilar orifice diameter impingement across ambient pressure range.

Mixing efficiencies allow estimation of hot fire combustion performance and offer understanding into mixing phenomenon. Cold flow test are less expensive, safer, and more easily controlled than hot fire tests. Dissimilar orifice diameter impingement may offer an effective way to introduce desired fuel and oxidizer mixture ratios without compromising mixing efficiency. Gel simulants can rheologically match hypergolic propellants and allow direct cold flow/hot fire comparisons.

2 Background

Previous experimental studies on impinging jets focus mainly on two major topics. The first topic is the direct characterization of mixing. The second topic is the atomization and spray characteristics of the sheets formed by the jets. Both topics have a variety of different flow and ambient conditions and injector dimensions and configurations. The mixing characterization give results directly relating to the performance of an injection pair whereas the atomization and spray characterization help generate simulations and numerical correlations for modeling systems. The impact of one group on the other is not easily established but atomization characteristics may help explain mixing performance traits. The mixing studies will first be discussed followed by the atomization and spray studies. The atomization and spray studies will be applied to mixing phenomenon where applicable.

2.1 Mixing Studies

Experimental mixing studies start with the works of Rupe. In Rupe's first study[1], he establishes the definition of the mixing efficiency for non-reacting working fluids. This definition is developed for use with patternators. A patternator is a device used to collect spray based on spatial resolution. The collection occurs in an array of collection cells. The cells are spaced on a grid sequence which dictates the spatial resolution. When applied to doublet injectors, a way to distinguish one liquid from the other in the test cells should be established whether by using immiscible fluids or dyeing one fluid and not the other. The mixing efficiency works on the summation of deviations of collection cell's input ratio from the input mixture ratio. The deviations are weighted by collected mass. Deviations reduce the mixing efficiency. Smaller deviations correspond to achieving desired input ratio. Using his mixing ratio definition, Rupe[1] analyzes several variables effect on mixing. The momentum ratio, one jet's momentum over the others, of 1.0 gives the highest mixing efficiencies. Impingement angle and mixing efficiency have a linear correlation with better mixing occurring at lower impingement angles. For smaller area ratios, one jet's orifice diameter area over the others, mixing is better as momentum ratios decrease below 1.0. Increasing area scale, one test's jet area over another test's jet area, increases mixing factor. Pre-impingement distance is shown to not influence mixing.

Rupe's second study[2] is a follow-up to his first study. Unsatisfied that the correlations in his first study are not applicable to injector design optimization, he adds another correlation to allow injector optimization. His original claim was that the point of optimum mixing should occur when the area ratio and momentum ratio are both unity. However, he provides figure 2 as a contradictory case. Notice that the maximum mixing efficiency does not occur

Figure 2. Mixing factor and area ratio as a function of a normalized momentum ratio[2]

at a unity area ratio nor a unity momentum ratio. He finds with experimental results that optimum mixing for a pair of nozzles occurs when the ratios of the velocity heads and stream diameters is one. This ratio, known as the Rupe factor, can be applied over a range of impingement angles and area scales.

2.1.1 Momentum ratio versus Rupe number

The Rupe factor is converted into the Rupe number by adding one to the Rupe factor and taking the inverse of that value. The work of Won et al.[3] covers mixing efficiencies of unlike triplet and unlike doublet configurations. The discussion to follow will only focus on the unlike doublet components. They study the effects of diameter orifice ratio and momentum ratio on mixing efficiencies. However, their definition of the momentum ratio is the inverse of the momentum ratio used by Rupe[1, 2]. Rupe uses the fuel values for the numerator whereas Won et al. use the oxidizer values for the numerator. See the nomenclature section for exact definitions. Won et al. choose oxidizer over fuel ratio to elongate the axes of their plots. The authors provide a plot (see figure 3) of the same mixing efficiencies but with different independent variables:

momentum ratio and Rupe number. On the plot, when compared by momentum ratio, the differences of the curves are more apparent. This difference comes about because the Rupe number should be used for optimization of a single pair of injectors whereas the momentum ratio should be used to compare different pairs of injectors. Won et al. continue to offer the case for using momentum ratio over Rupe number by stating that at higher jet Reynolds numbers, hydrodynamic waves generated by the momentum exchange, disintegrate the sheet and provide direct mechanical mixing. The Rupe number is limited to dynamically similar, symmetrical, and stable free-streams which may not occur in realistic operating conditions.

2.1.2 Mixing Mechanisms

Using mixture ratio, Ashgriz et al.[4] provide a explanation of the mixing mechanism occurring in impinging jets. They show that mixing occurs in two regimes: pre-atomization and post-atomization. The pre-atomization regime encompasses from the exit of the orifices to the break-up of the sheet. It has three atomization modes: reflective, well mixed, and transmissive. Reflective atomization results in the liquid jets bounc-

a) MR

b) Rupe number

Figure 3. Effect of diameter ratio on the mixing efficiency of unlike doublet element.[3]

ing off one another and coming back towards their respective injectors.

Transmissive atomization results in the crossing of the free streams with the majority of the fluids flowing to the opposite side of their injectors. Well mixed atomization is a balance between the reflective and transmissive modes. The post-atomization regime's mixing mechanism is turbulent dispersion.

The authors provide a schematic (see figure 4) of the defined regimes. They find that an increase in

jet velocity, jet diameter, and impingement angle reduce the time needed to redirect momentum. In addition, they say that most practical impinging jets operate in transmissive atomization and they show that the extent of mixing decreases with an increase in jet velocity, jet diameter, and impingement angle in that regime.

2.1.3 Nozzle Geometry

The great variety of possible nozzle variables makes infinite possible combinations of doublets. The external nozzle variables include pre-impingement length and impingement angle. The internal nozzle variables include, orifice diameter, orifice shape, orifice length-to-diameter ratio, orifice entrance conditions (round, sharp, or bevel edged), and orifice length roughness. Figure 5 has a diagram of the internal nozzle geometry variables. The external variables define impingement whereas the internal variables generate the shape and size of the free liquid jet. Most studies vary external nozzle variables greatly but a couple of efforts have been made to isolate internal nozzle variables' effects.

Riebling[5] tackles the internal geometry variable of orifice length-to-diameter and its effect on mixing. Using unlike impingement of equal diameter orifices and constant impingement angle, pre-impingement distance, and mixture ratio, he concludes that mixing is unaffected by changes in orifice length-to-diameter values between 7 and 100. This shows that large values of orifice length-to-diameter do not guarantee good mixing. He also notices that mixing is unaffected by changes in Reynolds number when Reynolds number is greater than 14,600. His mixing efficiencies do not match Rupe[2] but this due to the difference in

Figure 4. Schematic of atomization modes: a) reflective, b) well mixed, and c) transmissive atomization; turbulent dispersion downstream of atomization point enhances mixing.[4]

Figure 5. Bevel-edged nozzle

downstream collection length. Riebling's values are lower because he collected spray closer to the impingement point. Mixing efficiency increases with collection distance mostly likely because of air entrainment for non-reacting sprays.

The previously mentioned studies use circular orifices and aligned impingement i.e., intersecting jet momentum vectors. Hoehn et al.[6] expand mixing characterization on the internal variables of orifice diameter and orifice shape. In addition, they experiment with unaligned impingement or "misimpingement" as referred to in the report. They test different size circular and rectangular orifices in aligned and unaligned impingement. The authors find that non-circular orifices can produce slightly higher mixing efficiencies when the streams are hydraulically similar. Misimpingement, i.e. unaligned impingement, reduces mixing efficiency due to reduced contact area of the jets. The fluids mix when in contact and less mixing will occur if less area is intersected. Hoehn et al. study is performed to verify data taken by McHale et al.[7] which they due achieve finding equivalent results within tolerances for equivalent cases.

Some discussion about internal nozzle geometry should lead to cavitation concerns. In particular, the sharp-edged entrance of a injector can create cavitation that can significantly affect the flow characteristics of the exiting liquid jet. Hoehn et al.[6], in the second part of their report, address cavitation's effect on mixing, noting that the present of cavitation adversely affects mixing efficiency. However, they say that cold flow tests experiencing cavitation may not be relevant to predicting hot firing performance because of the unique flow characteristics generated by the cavitation. Nurick[8], using circular and rectangular orifices, focuses solely on cavitation and its effect on unlike mixing. He finds that cavitation reduces mixing efficiency in circular orifices. Noncavitated conditions for circular orifices produce constant mixing efficiencies. Rectangular orifices have constant mixing efficiencies regardless of cavitating or non-cavitating conditions.

2.1.4 Using PLIF Technique

Studies up to this point have all used patternators to capture and analyze spray distributions. The patternator must be within the flow path to capture the spray. There is less obtrusive technique called planar laser-induced fluorescence that utilizes the fluorescence characteristic of a molecule to capture spray distribution images. The fluorescence is induced by absorption of laser light and the molecules used are typically dyes dissolved in the working fluid. The intensity of the fluorescence is related to the amount of dye that is illuminated which is related to the volume of the fluid present within the analysis region. However, the

camera or sensor must capture images at an angle. This angle creates a perspective distortion on the data. Correcting for this distortion can give accurate spray mass distributions without disturbing the spray.

One study[9] directly addresses the use of PLIF to analyze doublet injectors. This study will start as a launch point for the following studies which all analyze doublet injector mixing with PLIF. The work of Jung et al.[9] discusses topics of signal linearity, quantification of mass distribution data, comparisons to PDPA and patternators, and laser extinction. A linear relationship between signal strength and laser power allows direct correlation between signal and quantified data without need for a correction if the laser power is kept in the correct intensity regime. Quantification of mass distribution data is achieved if one compensates for sensor exposure time, dye concentration levels, and laser intensity at the imaging location with a linear laser intensity to signal strength ratio. The authors compare mass flux measurements from PLIF, patternators, and PDPA. They find that PLIF accurately mimics equivalent patternator measurements but PDPA's accuracy suffers due to the high concentrations of non-spherical drops. Laser extinction is avoided if the distance traveled by the laser through the spray mass is kept short. They check this issue by passing the laser through both directions of the spray and looking for non-symmetric gray level distributions. Figure 6 illustrates this idea of passing the laser through both directions. Notice how both curves are symmetrical and relatively equivalent across the x-axis. Jung et al.[9] derived this idea by adapting the work of Talley et al.[10] on hollow cone sprays. Talley et al. found that signal strength decreases as the laser passed through the cone spray. However, the extinction in both the forward and backward directions was symmetrical. The symmetry allowed them to recreate the actual signal profile generated by a hollow cone spray by merging the signal taken from both directions with the extinction.

The acquisition of spray mass distributions is an essential part to analyzing mixing efficiencies using PLIF. More work by Jung and others[11] establish some findings that will help in spray mass distribution comparison. Using continuous laser PLIF with a variety of impingement angles, pre-impingement distances, and downstream imaging locations they find that most mass of the spray is concentrated at the center of the distribution. This center concentration holds for laminar and turbulent sheets. The concen-

Figure 6. Actual gray levels of fluorescence signal for the forward and backward sheet beams[9]

tration is formed because the largest droplets are expelled from ligaments which have maximum thickness at their center. The center concentration gives a reference point to compare images of the same spray conditions. Typically, just the fuel working fluid is dyed and imaged and then just the oxidizer working fluid is dyed and imaged. These large droplets may reduce combustion performance which prompts the authors to investigate ways to avoid this issue. They find that increasing impingement angle is more effective than increasing injection velocity at distributing droplet size evenly. However, increasing impingement angle increases backflow which, in reacting conditions, could damage the injection system. The increase in pre-impingement length may mitigate backflow issues due to the jet diameter divergence which would also increase spray mass distribution.

Using PLIF and spray mass distributions, Yuan and Huang[12] along with others[13] have shown that mixing efficiency trends can be predicted by tracking penetration percentage trends. The penetration percentage is the mass imbalance from one side of the spray to the other where the dividing line is the center of the spray mass. It tracks when one jet is over-penetrating and by how much. In general, penetration percentages of 50% (mass is symmetrical about the spray center) gives the best mixing efficiencies. Figure 7 and figure 8 compile the data

Figure 7. Yuan and Huang[12] data are for 0.3 mm orifice diameter injectors at 15 mm downstream

from the first work[12] and the second work[13], respectively. The mixing efficiencies and penetration percentages are plotted on separate axes with the penetration percentage axis reversed to align the trends. Penetration percentage and mixing efficiency are inversely proportional. Figure 8's subplots correspond to elevated ambient pressure and show that even with the introduction of elevated ambient pressure, the trend generally remains. The data presented in these two figures are limited to short downstream distance lengths. This limitation may exclude mixing effects of turbulent dispersion. This limitation would reduce the captured mixing efficiency. In addition, the short pre-impingement lengths and relatively low maximum ambient pressure may skew data when relations between droplet collision probability and mixing efficiency are made[12]. Short pre-impingement lengths do not achieve liquid jet break-up which means droplets have not necessarily been formed meaning the interaction between the jets has not been strictly droplet drive. The

Figure 8. Yuan et al.[13] data are for 0.4 mm orifice diameter injectors at 10 mm downstream

low maximum ambient pressure coupled with the short downstream measurement distance means that the full effects of the pressure on the atomization and mixing process has not manifested.

Some mixing studies have been performed on non-gelled, hypergolic simulants. Although these works do not necessarily characterize mixing phenomenon, they act as correlations between mixing phenomenon and possible operating systems. The work of McDonnell et al.[14] finds that the scaling parameter between cold flow and hot fire tests is the Reynolds number. They test temperature dependent simulants to compare spray mass distributions at different mixture ratios. The authors struggle to correlate corresponding images of fuel and oxidizer spray distributions. Yuan et al.[15] prove more successful in analyzing the spray mass distributions and aligning them to give expected mixture ratios. They predict exhaust velocity using their calculated mass flow rate ratio of oxidizer and fuel and modified mixing efficiency. Using this predicted exhaust velocity and comparing it with hot fire observations, Yuan et al.[16] design a hypergolic liquid rocket engine using impinging-type injectors. They use cold flow and hot fire test data to find the optimum operating conditions for a pair of injectors and replicate that injector pairing and flow conditions into a engine manifold. The rocket engine performed as expected and helps validate the comparison between cold flow mixture ratio distribution and hot fire exhaustion velocity and temperature measurements.

2.2 Atomization Studies

Atomization characteristics may not be directly relate-able to mixing characteristics but they can help shed light on liquid sheet behavior that could influence it. These studies focus mainly on the shape, size, and unique characteristics of the liquid sheet. In addition, most mixing studies are coupled with atomization or visualizations studies on liquid sheets. The inclusion of the following material helps add to the knowledge of

impinging jet systems and some conclusions can be used to help explain mixing phenomenon. The lack of mixing data for non-Newtonian fluids requires looking into atomization of non-Newtonian fluids for insight.

An early work that laid some groundwork for atomization studies is done by Heidmann et al.[17] Using a variety of different test fluids, they group liquid sheets, based on similar structures, into four categories: closed-rim, periodic-drop, open-rim, and fully-developed. The grouping can be related to different system variables, like orifice diameter, jet velocity, and ambient pressure, which can help others predict the structure of the liquid sheet. Sheet width increases as injection jet velocity increases in closed-rim, open-rim, and periodic-drop patterns. This increase means that droplets will distribute along the plane of the liquid sheet further from the center of the spray increasing spray mass distribution. Also, break-up length increases as velocity increases in closed-rim and periodic-drop regimes. The authors note that waves are generated on the liquid sheet and follow frequencies based on flow conditions. They show that the waves increase with jet velocity increase and decrease with impingement angle increase. However, jet diameter and pre-impingement length have small effects on the wave frequencies.

Dombrowski and Hooper[18] acknowledge the previous wave characteristics and establish two different forces that act on the sheet to generate them. They distinguish waves into two categories, aerodynamic and hydrodynamic. The former is caused by interaction of liquid with the surrounding medium and relates to sheet variables like surface tension and viscosity. The latter is caused by the impact of the liquid jets which relates to variables like jet exit velocity and impingement angle. Both waves contribute to the eventual break-up of the sheet. The authors show the sheet break-up length is affected by the velocity profile and impingement angle but is independent of Reynolds number. The velocity profile is the shape of the jet, formed by the internal geometry of the nozzle, and dictates the initial contact conditions of the free jets. Laminar flow conditions produce parabolic velocity profiles and turbulent flow conditions provide a flatter front.

2.2.1 Regime Naming

The early works provide a launch point for others to continue investigation. Li and Ashgriz[19] focus on the topic of sheet break-up regimes and try to correlate them with sheet break-up length and width. They define two regimes and some sub-regimes within Dombrowski and Hooper's[18] aerodynamic wave regime and quantify them by Reynolds number. First is the capillary instability regime for closed-rim sheets (as defined by Heidmann et al.[17]) which is further broken up into three regimes of pre-sheet formation, smooth

sheet, and ruffled sheet. Second is the Kelvin-Helmholtz instability regime for fully developed sheets (as defined by Heidmann et al.[17]) which is further broken up into two regimes of open-rim sheet and turbulent sheet.

Lai and Wang[21] continue naming spray structures but expand the variety of working fluids and types of impingement to encompass more phenomenon. They impinge six working fluids of constant surface tension in like and unlike impingement to expand on naming sheet regimes for higher viscosity liquids which produce more complicated flow patterns. Constant surface tension may not have necessarily been required because surface tension changes do not produce evident effects on liquid sheets.[17] Bailardi et al.[20] follow the trend of using a variety of different working fluids. They use 18 fluids to classify like impingement break-up characteristics into groups based on Reynolds and Weber numbers. The seven break-up modes they establish are closed rim, open rim, rimless separation, smooth sheet ligament, ruffled sheet ligament, fully developed break-up, and aerodynamic instability break-up. These modes are similar to previously established modes and may contain slight modifications to descriptions. A regime diagram, seen in figure 9, encompassing all the test fluids is created and helps predict break-up mode based on Reynolds, Weber and Ohnesorge number. The prediction of break-up length along with operating conditions may help engine designers determine necessary combustor lengths.

Figure 9. Regime diagram based on Reynolds and Weber number from Bailardi et al.[20]

2.2.2 Wave Frequencies

Using velocity profile as the basis of their work, Ryan et al.[22] investigate turbulent and laminar impinging jets. They use the injector geometries of Heidmann et al.[17] for turbulent jets and the injector geometries of Dombrowski and Hooper[18] for laminar jets to allow direct correlation with previously established findings. Ryan et al.[22] find that break-up increases with increased velocity and decreases with increasing impingement angle for turbulent jets. For laminar jets, break-up increases then peaks then decreases with increasing velocity and increases with increasing impingement angle. They expand more on the wave phenomenon found on liquid sheets. Figure 10 shows the three wave-like structures investigated

by the authors. Their findings show that surface wave size increases with increasing orifice diameter but surface wave separation remained relatively insensitive to jet velocity changes. Separation between detached ligaments is larger than edge ligaments at comparable conditions and edge ligament separation is larger than surface wave separation. The edge ligament trends followed the surface wave trends.

Interest in waves and ligament break-up is related to the eventual droplet sizes after atomization. The droplet size factors into combustion characteristics. More work on waves and ligaments is performed by Jung and others[23]. However, their definition of waves and ligaments are slightly different than Ryan and others[22]. Figure 11 illustrates the variables investigated by Jung et al.[23] The authors use sharp and rounded entrance nozzles to produce flow in order to see how internal nozzle geometry affects their variables. They note sharp edge entrances and smaller orifice length-to-diameter ratios produce more cavitation than round edge entrances. The induced cavitation plays into jet turbulence strength. Sharp edge entrances and shorter orifice length-to-diameter ratios produce shorter sheet and ligament break-up lengths because of increased turbulence strength. Sheet and ligament wavelengths follow their respective break-up length trends. Increasing impingement angle decreases sheet break-up length and wavelength because impact force increases but has no effect on ligament wavelength because the sheet velocity is independent of impingement angle.

Figure 10. Spray image showing surface waves, edge ligaments, and detached ligaments from Ryan et al.[22]

Figure 11. Spray image showing sheet and ligament break-up length and wavelength from Jung et al.[23]

2.2.3 Droplet Studies

The formation and break-up of liquid sheet waves and ligaments dictates the eventual droplet distribution and sizing. Lee et al.[24] use droplet distributions to highlight some trends of like and unlike impingement. They find that for symmetric jets (like impingement, equal momentum) mixture ratios generated along the plane of the sheet are generally uniform and that the uniformity improves the further downstream the sam-

ples are collected. Droplet dispersion from the sheet, in the plane of the sheet, is broader with increasing impingement angle. For asymmetric jets (unlike impingement, different velocities, or diameters), impingement angle has minimal effect on mixing and large velocity imbalances cause the sheet to become unstable. For both symmetric and asymmetric jets, flow rate distribution perpendicular to the sheet is Gaussian.

Droplet sizing can help shed light on atomization characteristics of different viscosity fluids. Lai and Wang[21] show that drop sizes decrease for all increasing jet velocities for both like and unlike impingement of different viscosity fluids. In addition, drop sizes are roughly the orifice diameter at very low jet velocities. However, like impingement has smaller drop sizes at lower jet velocities and larger drop sizes at higher jet velocities as compared to unlike impingement. The greatest velocities produce equal drop sizes regardless of like or unlike impingement. Lai continues his work along with others[26] on drop size measurements and unlike impingement. The authors use drop size measurements along the plane of the sheet to show that lower jet velocities have larger drop size overall and greater peaks to the center-line of the jets. Increasing jet velocity reduces drop sizes and increases distribution of drops along the plane of the sheet. Deviation angle measurements are found to follow momentum conservation principles.

Figure 12. Example spray image showing time average of perturbed sheet and ejection angle definition from Bremond and Villermaux[25]

Understanding that the ligaments created from the sheet stem from the rim of the liquid sheet, Bremond and Villermaux[25] use similar and dissimilar orifice diameter, like impingement to find that drop sizing is proportional to local sheet rim diameter. They then focus on periodic drop phenomenon and find that for water impingement, ejection angle (θ_e in figure 12) decreases as either impingement angle or injection velocity increases. The mean drop size of the expelled drops decreases with increasing jet velocity and increases with increasing impingement angle.

2.2.4 High Pressure

Previous mentioned atomization studies are all performed in atmospheric ambient pressure conditions. However, these injector systems are typically used in environments that have ambient pressures elevated above atmospheric. A couple of works on the atomization and break-up of liquid sheets in elevated ambient pressures will be discussed starting with the work of Strakey and Talley.[27] These authors measure mean

droplet size and distribution and break-up length for high jet velocities and high ambient pressures. They find that increasing ambient gas density, i.e. increasing ambient pressure, decreases break-up lengths due to the increase in impact wave instability and an increase in aerodynamic stresses. The break-up becomes independent of injector operating conditions at very high injection velocity and gas density. In addition, at high ambient pressure, mean droplet size decreases with increasing pressure but the width of the droplet distribution increases. They cannot offer an explanation as to why droplet distribution increases.

Jung et al.[28], similar to Ryan et al.[22], use the idea of laminar and turbulent to distinguish break-up regimes in higher ambient pressure conditions. However, instead of jet velocity profiles being classified as laminar or turbulent, they classify liquid sheets as laminar or turbulent depending on structures within each sheet. Jung et al.[28] find that aerodynamic forces significantly affect the break-up of laminar sheets when the aerodynamic force is greater than the surface tension force. Laminar sheets expand as injection velocity is increased when the aerodynamic force does not dominant break-up. Turbulent sheets were broken into three regimes. The expansion regime has break-up length increase with increasing injection velocity and no effects of aerodynamic forces are noticed. The wave break-up regime has break-up length decrease with increasing injection velocity and ambient gas density. The catastrophic regime has break-up lengths that are indistinguishable and unmeasurable. Yasuda et al.[29] focus on the interaction of immiscible liquids impinging in elevated ambient pressures. They find that the sheets formed by the liquids is dual filmed, comprising of a layer of one liquid and a layer of another liquid. The increase in ambient pressure conditions reduces sheet size, promotes break-up, and intensifies liquid atomization.

2.2.5 Gel

Previously mentioned atomization studies have all used Newtonian fluids. In addition, none of the mixing studies mentioned used non-Newtonian fluids. Non-Newtonian doublet impingement requires examination due to the more complicated spray structures and additional variables involved in the impingement process. Similar to Newtonian fluid studies of this nature, an attempt is made to create a regime diagram encompassing both Newtonian and non-Newtonian fluids. The work of von Kampen et al.[30] uses shear-thinning gelled fluids to accomplish this task. They also illustrate the ray-shaped patterns exhibited by gelled fluids which are not normally seen in Newtonian fluids.

Fakhri et al.[31] use sharp and angled injectors to test nozzle geometry effects on non-gelled and gelled liquids. The non-reacting, gelled simulant is rheologically matched to common hypergolic propellants.

They find that gelled simulants have less free jet perturbations than non-gelled simulants because of the gels greater viscosity and that orifice length-to-diameter ratio has a larger effect on flow conditions than orifice entrance (sharp or angled) conditions. The less perturbed gel jets cause gel sheet break-up lengths to be greater than non-gelled liquids break-up lengths. Larger orifice length-to-diameter ratios, which create less perturbed jets, create larger break-up lengths. In addition, higher velocities, shorter orifice length-to-diameter ratios, and gelled simulants generate smaller droplet sizes.

Other authors[32, 33] have noted similar trends but have used different non-Newtonian fluids to create regime diagrams and to characterize atomization in atmospheric ambient conditions. The work of Ramasubramanian et al.[34] covers both of these topics but adds elevated ambient pressure effects to their analysis. The authors relate atmospheric ambient pressure data and elevated ambient pressure data by scaling the jet Reynolds and Weber numbers by the gas density of the ambient conditions. They find that an increase of the viscosity of Newtonian fluids requires higher gas density scaled Weber numbers to achieve break-up. In addition, break-up lengths decrease as ambient pressure increases for Newtonian and non-Newtonian fluids. The surface wavelength and ligament wavelength, similar to Jung et al.[23], decrease in size as gas density scaled Reynolds number is increased. The regime diagram proposed includes data from other studies[35, 36, 31, 37].

3 Experimental Elements

3.1 Test Location

All tests are performed in the Combustion Diagnostics Laboratory of the University of Cincinnati. The lab is located in the Engineering Research Center, room 487, on West Campus. Work in this lab focuses on non-reacting and non-combusting flow fields.

3.2 Pressure Chamber and Pressurization Manifold

All tests, whether atmospheric or elevated ambient pressure, are performed in a custom built pressure chamber. The chamber was made by PresSure Products Company. A dimensional schematic can be found in the appendix A. The main body of the chamber is rolled carbon steel and is rated for a maximum working pressure of 750 psi at a maximum temperature of 200°F. It has one physical access point from the top. The top is covered by a lid that is secured with 12 nuts and bolts. The bolts are not set into the main chamber.

The lid is removed with a hydraulic crane because of its weight and elevation about shoulder height. On the bottom, one can find a pressure relief valve and a drain, both of which are closed with ball valves (Apollo 76-104-27A). The whole chamber sits on a rolling cart for movement purposes and for access to the drain.

Five Model B Weld Sight Glass windows offer optical access to the pressure chamber. Four windows are 3 in. diameter and one window is 4 in. diameter. The four 3 in. windows all lie on the same horizontal plane with two windows aligned at 180°. The third and fourth windows are for visualization during testing. The 4 in. diameter window is set at a 45° angle to the horizontal. Looking into this window from the exterior of the chamber offers a view of the top of the chamber. The 4 in. diameter window is set lower than the 3 in. windows and is aligned with the two 3 in. diameter windows that are aligned at 180°. All five windows are equipped with spray rings. Spray rings are a series of small injectors facing the interior of the window. Pressurized nitrogen (distributed from Wright Brothers, Inc.) is injected against the window and a small nitrogen cushion is created to prevent droplets from depositing on the window and to remove any moisture build-up if it occurs. A 1/4 in. NPT threaded hole provides access for the injected nitrogen to the spray ring. The only spray ring used during experimentation was the one paired with 45° window. The droplets that would deposit on windows are expelled much below the three 3 in. windows' height. The spray ring prevented droplet build up that would cloud data acquisition without interfering with measurements itself.

The chamber is pressurized with food grade nitrogen (same gas that is used with the spray rings) distributed from T-bottles connected to a manifold. The T-bottles are connected to the manifold with 1/4 in. braided hosing rated up to 3050 psi. The manifold allows multiple T-bottles to be connected to a single high pressure regulator. Only one nitrogen tank is used to pressurize the chamber at a time. The pressure regulator and chamber are connected with high pressure nylon tubing (Freelin-Wade) rated up to 920 psi. The nylon tubing is connected to three-way ball valve (Swagelok B-43XS4). This allows nitrogen from the manifold to easily be switched from pressurizing the chamber to activating the spray rings. The three-way ball valve is connected to the chamber with 1/4 in. stainless steel tubing. A pressure gauge is branched off the tubing for continually monitoring of chamber pressure. A 1/4 in. NPT threaded hole is drilled through the chamber lid as the main access point for nitrogen pressurization. The three-way ball valve is connected to the spray ring access point with the same 920 psi nylon tubing. A check valve (Swagelok B-4C-1) was added between the three-way valve and spray ring NPT bore.

3.3 Flow Systems

There are two main flow systems used for experimentation. The main difference being that the hydraulic cylinders drive the gel simulant rather than nitrogen back pressure that drives the non-gelled simulant (water). The hydraulic oil used to actuate the cylinders is driven by nitrogen back pressure similar to how the non-gelled simulant is actuated. A simplified schematic is provided for both flow systems. The major components missing from these diagrams are the optical components but they will be discussed in section 3.4.3. Figure 13 shows the non-gelled system and figure 14 shows the gelled simulant system. Fluid properties will be addressed in their respective flow system configurations sections.

Figure 13. Non-gelled simulant (water) like-impingement system flow set-up

3.3.1 Water Configuration

A custom made Bosch Rexroth aluminum structural frame cart holds five 5.5 L tanks that are during experimentation. Two of the five tanks are made of carbon steel and hold hydraulic oil. They will be addressed in the next section. The other three of five tanks carry the non-gelled working fluids and its dyed variants for experimentation. The tanks themselves are custom made (by GMP Welding & Fabricating) of stainless steel to carry 5.5 L of fluid with a working pressure of 1400 psi. They consist of a main stainless tube section capped at either end with stainless steel dome caps. The final assembly gives the shape of an elongated pill capsule. The bottom cap has a 1/4 in. NPT bore drilled in the center for a drain. The top cap

Figure 14. Gelled simulant like-impingement system flow set-up

has two 1/4 in. NPT threaded holes and a 3/4 in. stainless steel tube attached. The 3/4 in. tube acts as the filling point for the tank and is closed with a ball valve (If no part item is specified after a name, it should be assumed that it has already been specified and another of the exact same parts is being used.). One 1/4 in. hole is the pressurization input and the other 1/4 in. hole is the fluid output location.

The fitting configuration for each stainless steel tank is the same regardless of its working fluid. The three working fluids were water, water dyed at 3 mg/L (referred to as diluted dye), and water dyed at 6 mg/L (referred to as concentrated dye). See section 4.1 for an explanation of the different dye concentrations. The dye is Rhodamine 6G, pure (molecular weight: 479.01, molecular symbol: $C_{28}H_{31}ClN_2O_3$) from Acros Organics. It is measured on an Ohaus scale (model PA214). The water fluid properties are a density of 1000 kg/m^3 (1.94 slugs/ft^3), a viscosity of $1.002 \cdot 10^{-3} \text{ Pa}\cdot\text{s}$ ($2.09 \cdot 10^{-5} \text{ (lb}_f\cdot\text{s)/ft}^2$) and a surface tension of 0.072 N/m ($0.00493 \text{ lb}_f/\text{ft}$).

A graphical view of the fitting configuration can be found in figure 13 on the tanks with the labels “test fluid”. The flow output, in actuality, is from the top of the tank. The drain at the bottom of the tank exits with 1/4 in. stainless steel tubing and is stopped by a flow plug valve (Swagelok B-4P4T). The pressurization input through one of the 1/4 in. NPT holes on the top cap is connected to the first port of a union cross (Swagelok B-400-4). The second port is connected to a T-bottle nitrogen tank with 920 psi nylon tubing

with a flow plug valve in-between. The third port is connected with stainless steel tubing to a pressure relief valve (Swagelok SS-4R3A-BU) set to release at 900 psi. The fourth port is connected to a flow plug valve for depressurization. A pressure gauge is branched off the fourth port's stainless tubing connection.

The second 1/4 in. NPT hole in the top cap is the fluid output portion. A long stainless steel tube section is inserted through this hole so that it extends to near the bottom of the tank and protrudes out of the top. The long tube section bends at 90° and is monitored with a flow plug valve. Nylon tubing (Freelin-Wade) rated at 760 psi connects it the flow valve to a flow switching system. The 760 psi tubing is used over the 920 psi tubing because the 760 psi tubing does not trap the Rhodamine as easily as the 920 psi. Water flushing removed the dye adequately. The flow switching system comprises of two five-way ball valves (Swagelok B-43ZF2). The flow switching system design allows any combination of the three test fluids to be easily distributed to either injector. The set-up for the five-way valves are the same for both. They corresponded to each injector, either fuel or oxidizer. The first port is capped and allows for a flow shut off option. The second port is the output of the chosen test fluid. The other three ports had inputs from the water, the dilute dye, and the concentrated dye. Since three 5.5 L tanks carry each fluid, the tanks were split with a union tee (Swagelok B-400-3) and connected to both five-way valves. Stainless steel tubing connected each five-way valve output to a metering valve (SS-4MA-MH) which was used to control flow. The metering valve was connected to an inline filter (Swagelok with 1/4 in. connectors) with 60 micron filter basket. The filter then ran to a check valve.

Nylon tubing connects the check valve to a variable area flow meter (Brooks MT3809) with 1/2 in. NPT pipe fittings. The flow meter accuracy is $\pm 2\%$ full scale. The flow meters have a maximum capacity of 0.12 gallons per minute (gpm) or 454.25 cubic centimeters per minute (ccpm) and are specified for a fluid with specific gravity of 0.8. Since the working fluid differs from specified flow meter fluid, a variable area flow meter correction is applied. Equation 1 shows the equation for the correction factor[38].

$$F_{cor} = \frac{(SG_{float} - SG_{new}) \cdot SG_{scale}}{(SG_{float} - SG_{scale}) \cdot SG_{new}} \quad (1)$$

The correction factor is simply multiplied by the meters volumetric flow rate reading to give the actual flow rate of the new fluid. The values used in this equation are $SG_{float} = 8.02$ (for stainless steel), $SG_{new} = 1$ (for water), and $SG_{scale} = 0.8$ (for kerosene) giving a $F_{cor} = 0.88$. The digital displays (Precision Digital Model PD6000-6R0) attached to the flow meters accommodate this correction and their readings are used

to monitor flow rate. The flow meters are set far from the injectors to allow the flow to be undisturbed by fittings and fully developed. There are two 1/4 in. NPT holes threaded in lid of the chamber that allow fluid to be passed through them. The nozzles and apparatus that holds the nozzles will be addressed in section 3.3.3.

3.3.2 Gel Configuration

As seen in figure 14, the gelled simulant flow system uses the same elements and concepts as the non-gelled simulant flow system. The main difference is the addition of hydraulic cylinders (Miller Fluid Power HV3-50R2N-02.50-12.000-0100-N11-0) to drive the gelled simulant. The tanks containing the hydraulic oil (Mobil DTE 25 ISO VG46) have the exact same construction, capacity, and fitting configuration as the tanks containing the working fluids in the non-gelled flow system. However, the hydraulic oil tanks are made of carbon steel (again fabricated by GMP Welding & Fabricating) and only rated for a maximum working pressure of 900 psi. For the fluid output portion, flow is controlled with needle valves (Swagelok SS-4L-MH) and directly connected to hydraulic cylinders with braided hoses and stainless steel tubing. The hydraulic oil flow controls the piston motion which drives the gel simulant output. A three-way ball valve is located just after the hydraulic cylinder's gelled simulant output to allow flushing of the system with water after testing. After the three-way valve, flow from the hydraulic cylinders is passed through an inline filter with 440 micron filter basket and then through a check valve. Nylon tubing (rated at 760 psi) connects the check valve to the top of the chamber lid where flow will reach the injectors.

The hydraulic cylinders capacities are 0.965 L (0.034 ft³) with 12 in. strokes. Gelled simulant is loaded with the help of a custom PVC hopper and linear actuators. The PVC hopper is a large section of 4 in. diameter PVC pipe with the necessary reducers and a flow valve to fit on the hydraulic cylinder. The linear actuators (Firgelli Automations FA-400-L-12-18) withdraw the hydraulic cylinder piston slowly. The suction caused by this action draws the gelled simulant from the hopper into the cylinder. The actuators are bolted to an aluminum plate and c-shaped mounts, bolted to the same plate, hold the hydraulic cylinders in the horizontal plane. The hydraulic cylinders are not mounted on the aluminum plate so they can be removed for cleaning when necessary.

The hydraulic cylinder piston, when fully extended and the cylinder is full of gelled simulant, is detached from the linear actuator. A linear position transducer (UniMeasure LX-PA-25) is connected to each piston, one for fuel and one for oxidizer. The linear position transducer will track the movement of the

piston as hydraulic oil drives the flow. The movement of the piston along with knowledge of the piston dimensions allows the volumetric flow rate to be determined. A LabVIEW[39] program is used to convert both transducers' measurements to flow rates for the fuel and oxidizer. The LabVIEW front panel and block diagram are shown in appendix B.

The gelled simulant used in experimentation comprises of a 75% by volume ethanol (Decon Labs, Inc. Ethanol 200 Proof) and 25% by volume distilled water base. A carbomer polymer is added to the liquid mixture to act as a gelling agent. The specific carbomer is Carbopol 981A from the Lubrizol Corporation and comprises of 0.1% by weight of the final gel simulant. It is known to exhibit low yield stress and negligible thixotropy. A fumed silica filler is added for thickening purposes. The specific fumed silica used is CAB-O-SIL TS-720 from the Cabot Corporation and comprises of 5% by weight of the final gelled simulant. Gel was made in 16 L batches and mixed with a cordless drill with stirrer attachment. A cup and cone arrangement of the rheometer (TA Instruments AR200) is used to determine the change of viscosity with applied shear. Fresh batches of gel are prepared and rheologically tested to maintain conformity with standard gelled hypergolic propellants in terms of the relation of viscosity to shear rate. The rheometer offers torque control ($0.0003 \mu\text{N}\cdot\text{m}$ to $200 \text{ mN}\cdot\text{m}$) with a resolution of $0.1 \text{ nN}\cdot\text{m}$.

The gelled simulant making process starts with the liquid mixture of ethanol and water being mixed with the carbomer. This mixture is allowed to sit for at least 24 hours to allow the carbomer to work. Then the fumed silica is added in small amounts and mixed until the final gel is formed. Gel is stored in five gallon buckets with sealing lids to prevent ethanol evaporation. The gel separates within hours but is always mixed before being loaded into the hydraulic cylinders which restores its homogeneity. The physical properties of the gel are a density of 866.9 kg/m^3 (1.68 slugs/ft^3), a surface tension of 0.0255 N/m ($0.00175 \text{ lb}_f/\text{ft}$) and a viscosity versus shear rate curve, measured from the rheometer, is shown in figure 15. The gelled simulant is dyed at slightly different concentrations than the non-gelled simulant. The gelled simulant concentrations are based on ethanol volume. This allows one to avoid computing the volume reduction of ethanol and water mixtures. The dye concentrations (using Rhodamine 6G, pure) for the gelled simulant are 3 mg/L of ethanol

Figure 15. Gelled simulant viscosity versus shear rate

The gelled simulant making process starts with the liquid mixture of ethanol and water being mixed with the carbomer. This mixture is allowed to sit for at least 24 hours to allow the carbomer to work. Then the fumed silica is added in small amounts and mixed until the final gel is formed. Gel is stored in five gallon buckets with sealing lids to prevent ethanol evaporation. The gel separates within hours but is always mixed before being loaded into the hydraulic cylinders which restores its homogeneity. The physical properties of the gel are a density of 866.9 kg/m^3 (1.68 slugs/ft^3), a surface tension of 0.0255 N/m ($0.00175 \text{ lb}_f/\text{ft}$) and a viscosity versus shear rate curve, measured from the rheometer, is shown in figure 15. The gelled simulant is dyed at slightly different concentrations than the non-gelled simulant. The gelled simulant concentrations are based on ethanol volume. This allows one to avoid computing the volume reduction of ethanol and water mixtures. The dye concentrations (using Rhodamine 6G, pure) for the gelled simulant are 3 mg/L of ethanol

and 6 mg/L of ethanol for the same reasons as the non-gelled simulant. The naming convention regarding the dyed fluid, established in the non-gelled configuration, remains consistent.

3.3.3 Nozzles

Three separate nozzles are used to control the free streams. They are manufactured (by Blue Chip Tooling, Inc.) from stainless steel using electric discharge machining. All nozzles have an orifice length-to-diameter ratio of 5, a sharp edge entrance, and fit a mounting block that slides onto a hanging apparatus inside the chamber attached to the lid. Two nozzles are identical in dimensions. This pair of nozzles makes up the similar orifice impingement case. Their orifice diameters are 0.020 in. (0.508 mm). The third nozzle has an orifice diameter of 0.028 in. (0.711 mm). The diameters are verified to be within $\pm 2\%$ of the nominal dimensions using a microscope. One 0.020 in. diameter nozzle and one 0.028 in. diameter nozzle make up the dissimilar orifice impingement case. The diameters and orifice length-to-diameter are chosen to match typical dimensions found in rocket systems. A fully dimensioned drawing with tolerances of the both diameter nozzles including internal geometry can be found in appendix C. The nozzles follow the same construction with the orifice diameter and orifice length (found in the Section A-A cut-away in appendix C) changing to maintain the orifice length-to-diameter ratio of 5.

The previously mentioned mounting block's dimensions can be found in appendix D, figure 32. The mounting blocks slide onto a mounting plate (figure 33) with rods. The plate allows the jets center of momentum to be aligned and adjusted with screws to maintain aligned impingement. An assembly of the nozzles, mounting blocks, and mounting plate is illustrated in figure 34. The nozzle assembly hangs on an adapter plate which is attached to dowel rods that attach to the lid of the chamber. The adapter plate and dowel rod drawings are shown in figure 35 and figure 36 respectively. Spacers similar to the dowel rod construction can be added to change the height of the nozzle assembly. This allows data acquisition at different downstream locations in the spray, if desired. The nozzle geometry and mounting orientations are the same for both the non-gelled and gelled simulant flow systems.

3.4 Data Collection System

The data collection equipment and configuration are constant for both flow systems. Data are collected using PLIF technique. A laser fluoresces the dyed liquid or gelled simulant and the fluorescence is captured

with an intensified charged-couple device (ICCD) camera which records to a computer. The intensified charge-coupled device along with its corresponding computer program will be discussed first, followed by the laser specifics. Lastly, the optical components will be specified along with their layout.

3.4.1 Intensified Charged-couple Device Camera

The ICCD camera is a Princeton Instruments PI-MAX3: 1024i. The program that controlled the ICCD was LightField[40] also from Princeton Instruments. The ICCD camera imaged spray through the 45° window on the pressure chamber. The capture settings for the device were a gain intensity of 5 at 10 frames per second using the full 1024 by 1024 pixel sensor when cooled to -25°C. The cooling helps reduce sensor noise. There is one exposure per frame. The device is triggered based on the laser pulsation.

A Tamron SP 180MM F/3.5 Di 1:1 macro lens attaches to the ICCD to give the desired imaging size. The f-number was set manually on the lens to 3.5. Two filters are mounted before the macro lens. The first is a longwave-pass filter from Andover (part number: 590FG05-50). It attenuates fluorescence signal and laser signal below 590 nm. The second filter is a bandpass filter also from Andover (part number: 620FS10-50). It allows fluorescence signal at 620 nm with a bandwidth of 10 nm to pass through.

3.4.2 Laser

The laser used in experimentation is a Continuum Surelite Model SLIII-10. It is set to pulse at 10 Hz and provides the trigger for the ICCD camera. A second harmonic generate is added and produces 532 nm output. A laser sensor (Coherent EM USB J-50MB-YAG) and its corresponding program[41] measure a pulse energy of 6.5 mJ when the Q-switch delay is set to 385 on the laser. The pulse duration is 7 ns. The beam passes through a beam splitter (Continuum Surelite Model SSP-3) and is redirected to pressure chamber through optical components which are addressed in the next section. Rhodamine 6G is known to fluoresce well when absorbing 532 nm light and emit a decent signal at 620 nm. The excess laser signal and scattering are attenuated by the filters attached to the intensified charged-couple device.

3.4.3 Optical Components

The laser beam is converted to a laser sheet of dimensions 45 mm by 2 mm. This is achieved by redirecting the light from the beam splitter to the appropriate pressure chamber access window height. It

then passes through a negative cylindrical lens and finally is collimated with a plano-convex lens. The layout of optical components can be seen in figure 16. The redirection is achieved by mirrors. The negative cylindrical lens is from Edmunds (25 mm Dia x -50mm FL Cylinder Lens VIS 0° Coating). The plano-convex lens is also from Edmunds (50.0mm Dia. x 500.0mm FL, Uncoated, Plano-Convex Lens).

3.5 Test Conditions

All conditions tested are for like impingement. Injector nozzles are aligned based on center of momentum vectors for the free stream jets. The spray is imaged at 2 in. (50.8 cm) downstream of the impingement point with the pre-impingement length of 5 mm for all cases. The downstream position was greater than all the break-up lengths for all the flow conditions test. See the work of Ramasubramanian et al.[34] as they used similar flow systems,

Figure 16. Optical component layout and corresponding dimensions (not to scale)

nozzles, and working fluids. This allowed droplet fluorescence to be captured. Flow was constant and steady before images were taken. Cavitation in the nozzle is monitored visually and is avoided whenever possible.

There are two geometric cases of impingement. The first is the pairing of similar orifice diameter nozzles and the second is a pairing of the smaller and larger orifice diameter nozzles. The first pairing is known as the similar orifice diameter case and the second pairing is known as the dissimilar orifice diameter case.

3.5.1 Similar Orifice Diameter Impingement Case

For the similar orifice diameter case, two working fluids are used, non-gelled (water) and gelled simulant. When the non-gelled simulant is tested, chamber gauge pressures are atmospheric, 0.69 MPa (100 psi), 2.07 MPa (300 psi), and 3.45 MPa (500 psi) over four flow rates of 100 ccpm, 150 ccpm, 200 ccpm, and 250 ccpm. When experimenting with gelled simulants, the chamber gauge pressures are atmospheric, 1.72 MPa (250 psi), 2.62 MPa (380 psi), and 3.45 MPa (500 psi) at five flow rates of 100 ccpm, 125 ccpm, 150 ccpm, 175 ccpm, and 200 ccpm. For both working fluids, flow rates for both the oxidizer and fuel jet are equal.

3.5.2 Dissimilar Orifice Diameter Impingement Case

For dissimilar orifice impingement with non-gelled simulant (water) as the working fluid, four chamber pressures, atmospheric, 0.69 MPa (100 psi), 2.07 MPa (300 psi), and 3.45 MPa (500 psi), are tested for three momentum ratios. The momentum ratio is defined as follows:

$$MR = \frac{\rho_F v_F^2 d_F^2}{\rho_O v_O^2 d_O^2} \quad (2)$$

where the fuel nozzle is always the smaller diameter nozzle. Three momentum ratios are considered, 0.5, 1.0, and 2.0. They correspond to equal jet velocity, equal jet momentum, and equal jet volumetric rate. The flow rate of the simulant fuel is set and the simulant oxidizer flow rate is adjusted to achieve a specific momentum ratio. For $MR = 0.5$, two fuel flow rates are tested at 100 ccpm and 150 ccpm. There are only two flow rates because of hydraulic flip misalignment of impingement at higher flow rates. For both $MR = 1.0$ and $MR = 2.0$, four fuel flow rates of 100 ccpm, 150 ccpm, 200 ccpm, and 250 ccpm are examined.

Based on the momentum ratio in equation 2, all similar orifice diameter impingement cases have unity momentum ratios because of the symmetrical fluid, geometry, and flow condition.

4 Data: Collection to Results

All images are taken with the same ICCD and laser set-up using PLIF. The 1024 pixel by 1024 pixel sensor along with zoom of the macro lens results in each pixel covering roughly 0.05 mm of actual spray area along the horizontal axis (relative to images taken). The images are taken at a 45° angle and this angle prevents a standard resolution along the vertical axis from being defined. The corrected actual imaging area is noted in section 4.3.2.

4.1 Collection

For each flow condition (specific chamber pressure value, fuel flow rate, and corresponding oxidizer flow rate), two sets of 200 frames are collected. One set of 200 occurs when the fluid from both nozzles is dyed at the diluted concentration. This gives the overall spray pattern. The second set of 200 occurs when the fuel nozzle injects dyed fluid with concentrated solution and the oxidizer injects undyed fluid. This combination gives the fuel distribution that can be compared to the overall distribution. The concentrated

dye is used to increase the signal-to-noise ratio when the volume of dyed fluid in the spray is lessened.

4.2 Laser Extinction

The alignment of the 3 in. diameter optical access windows and the 4 in., 45° window forces the ICCD's horizontal line of sight to match the laser direction. Because the lid was circular with symmetrical bolts, it could be rotated to establish a spray sheet plane parallel (see figure 17a) with the laser direction or perpendicular with the laser sheet (see figure 17b). A parallel sheet would force the laser to pass through more fluid and dye resulting in beam scattering and signal reduction due to energy loss. The distance through perpendicular sheet is shorter and shown to help reduce extinction issues if they exist.[9]

Figure 17. Imaging orientations based on lid rotation position

The images taken in this study are taken when the spray sheet is parallel with the laser direction. This orientation does not show extinction issues and allows better imaging of the complete spray mass distribution based on size. Figure 18 illustrates that our experimental method avoids extinction issues. The fluorescence intensities of the most dense spray region are plotted and a Gaussian curve is fit. Extinction would be evident if the ends of the bell curve were uneven. However, the symmetry of the pixel intensities is maintained.

Figure 18. Similar orifice diameter, equal momentum, like, water impingement at a jet velocity of 20.56 m/s in 0.69 MPa ambient conditions

4.3 Corrections

4.3.1 Background

For each spray, 200 individual frames are captured with one exposure per frame. For each frame, a background is automatically subtracted by LightField. The background is an average of 200 frames when the laser and spray rings are active but neither jet is flowing. This background helped minimize noise from the ICCD and scattering of laser light from chamber pressure windows and particles in the pressure chamber.

4.3.2 Perspective

Each frame is taken at a 45° angle. This induces a perspective distortion. The true spray mass distribution is desired and a perspective correction is applied after the images are averaged. The correction uses a square gridded plate at the downstream imaging location along with projective mapping[42] and bicubic interpolation[43] from ImageJ[44]. ImageJ is an open source Java-based image processing software. Projective mapping uses four distorted polygon points and aligns them to a different set of four

chosen polygon points with the correct dimensions. Bicubic interpolation is a two-dimensional interpolating method using the surrounding 16 pixels of each pixel to calculate its new value. An example of the bicubic projective mapping on the gridded plate is shown in figure 19. The correction allows images to be analyzed in the correct spatial resolution with corresponding intensities. One can see that the actual imaging area is roughly 1.75 in. by 2.5 in.

4.3.3 Dye Concentration

Because two sets of images at different dye concentrations will analyze one spray distribution, the difference in concentration is corrected. The captured images represent the fluorescence signal of the spray.

Figure 19. Bicubic projective mapping correction on gridded plate

This signal intensity is expressed as follows:

$$f_{x,y} = KI_{x,y}n_{x,y} = KI_{x,y}CV_{x,y} \quad (3)$$

Because the local laser intensity and collection efficiency remain constant, the fluorescence intensity is directly related to the dye concentration and local volume of the spray. Normalizing the fluorescence signal by dye concentration allows the the fluorescence signals from the concentrated dyed case to be compared to the diluted dyed case. With two incompressible fluids, the volume is related directly to the mass. This correction occurs in the computer code used to calculate mixing efficiency discussed in section 4.5.

4.4 Processing

A graphical progression of the data processing can be found in figure 20. The montage of 200 images (“1”) is directly from LightField. These images are of the spray distribution when the fuel and oxidizer working fluids are both the diluted dye solution. The final image of this spray distribution is labeled “5b”. The image labeled “5a” represents the spray distribution when just the fuel jet working fluid is dyed at the concentrated dye amount and the oxidizer jet is undyed. It is created by repeating steps “2” through “4” on those images. The threshold applied to the averaged, perspective corrected image eliminates false signals. It is determined by the maximum value still present after the background subtraction was applied with no flow. The threshold only negates values lower than its setting without scaling or changing desired intensities. One can see that there is no substantial loss of data between “3” and “4”. Image “6” is generated by dividing “5a” by “5b”. The division occurs pixel by pixel and gives the overlapping spray area. Knowing a majority of the spray droplets are concentrated at the center of the spray mass distribution[?], the overlay uses the center of spray mass as the reference point. Corresponding spray centers deviate less than 30 pixels (1.5 mm) in the horizontal direction and 8 pixels (0.4 mm) in the vertical direction. The alignment of the center of spray mass distribution corrects errors associated with flow rate setting. Imbalanced flow rates introduce a small momentum imbalance that adds a sheet deviation angle.[26]

A couple of notes should be added about figure 20. The visual of the mixing (“6”) is qualitative rather than quantitative. The dye concentration is not corrected for and the direct division gives a mass distribution that is scaled by the dye concentration ratio. The more green and yellow right side of the sheet means a higher concentration of fuel is present and conversely, the blue left side means more oxidizer is present. The

Figure 20. Progression of PLIF data processing for mixing analysis for the same flow conditions as in figure 18

vertical line to the right of the spray center masses in all of the pictures is the split line on the ICCD sensor. The ICCD sensor has two sensor panels combined to make one; the line is where the sensors meet and is typically present in images.

The total and fuel spray distribution images for the dissimilar orifice diameter impingement case can be found in appendix E. The images there do not have the dye concentration correction applied. The intensities shown in each image are the averaged, perspective corrected, and thresholded values. The total and fuel spray distributions are aligned spatially, based on the center of mass, for each image.

4.5 Mixing Efficiency Definition

Since fluorescence intensities are related to mass distribution as seen in section 4.3.3. The mass distributions can be used in the common definition of the mixing efficiency defined by Rupe[1]. The mixing efficiencies initial definition is for patternators but if one considers the pixels of an image like a patternator,

the definition can readily be applied. The mixing efficiency is found in equation 4.

$$E_m = 100 \cdot \left(1 - \left(\sum_0^N \frac{\omega}{W} \cdot \frac{R - r_{x,y}}{R} + \sum_0^{\tilde{N}} \frac{\omega}{W} \cdot \frac{R - r_{x,y}}{R - 1} \right) \right) \quad (4)$$

The total spray distribution (both jets dyed with diluted concentration) gives the the local mass flow rate of spray (ω) and nominal mass flow rate of spray (W). The fuel spray distribution (fuel jet spraying concentrated dye solution and undyed oxidizer jet) gives the numerator of the local mixture ratio ($r_{x,y}$).

The first summation represents the mass ratio and fuel mixture ratio scaled deviation of locations where fuel is needed and the second summation is the mass ratio and oxidizer mixture ratio scaled deviation of locations where oxidizer is needed. The lesser the deviations, the closer to nominal mixture ratio, and the better the mixing is. Therefore, a mixing efficiency of 100 means complete mixing and a mixing efficiency of 0 means no mixing. The normalization and symmetry of the mixing efficiency definition allows either the oxidizer values to be in the numerator or the fuel values to be in the numerator for mixing ratios (see variables $r_{x,y}$ and R).

A MATLAB[45] code is used to apply the mixing efficiency definition. The code uses three pictures whose pixel intensities values are adapted into delimited text number matrices. The code can be found in appendix F. The code works with the picture values like any other matrix and computes the mixing efficiency. The qualitative mixing image, (image “6” in figure 20) is used only to keep track of the overlapping area of the two images.

4.6 Relative Velocity

In order to compare similar and dissimilar orifice impingement, the velocity differences of the dissimilar orifice impingement should be accounted for. For dissimilar impingement, one jet will usually have a velocity different than the other which makes using one jet velocity as an independent property difficult. However, Ashgriz and Poo[46] provide a definition of relative velocity based on droplet dynamics geometries that can incorporate both jet velocities. In addition, they offer ways to incorporate relative velocity to other fluid dynamic variables like Reynolds number and Weber number. The relative velocity is defined in equation 5.

$$v_{rel} = \left(v_F^2 + v_O^2 - 2v_F v_O \cos \alpha \right)^{\frac{1}{2}} \quad (5)$$

This definition is directly adaptable to dissimilar sized and different velocity elements which makes it ideal for dissimilar orifice diameter impingement. For similar orifice diameter impingement and unity momentum ratio, the single jet exit velocities are the relative velocities. The relative velocity allows similar and dissimilar orifice configurations to be compared readily and easily. Relative velocity will be used as the independent variable for mixing analysis.

5 Results and Discussion

Using mixing efficiency defined in equation 4, the effect of ambient pressure on the mixing efficiency will be discussed for different injector configurations and fluids. Results on the similar orifice diameter impingement of water and gelled fluid will be examined. Data on dissimilar orifice diameter impingement case will follow.

All cases for similar orifice diameter impingement have unity momentum ratios (Rupe number equals to 0.5) to give the best mixing results for like impingement of non-gelled and gelled fluids. The momentum ratios chosen for the dissimilar impingement represented equal jet-velocity cases, equal jet-momentum ratio cases, and equal jet-volumetric/mass flow rate cases. A table of results with corresponding test conditions can be found in the appendix G.

5.1 Similar Orifice Diameter Like Impingement Case

5.1.1 Ambient Pressure Effect for Non-gelled Fluid (Water) Case

The mixing efficiency data for non-gelled simulant are plotted in figure 21. At a jet velocity of 8.22 m/s, mixing efficiency increases gradually as the ambient pressure increases. The total mixing efficiency increase from atmospheric conditions to 3.45 MPa is 10.3%. However, at jet velocities of 16.45 m/s or above, after the increase in ambient pressure from atmospheric to 0.69 MPa, the mixing efficiency does not increase anymore. For most jet velocity cases, any pressure increase above atmospheric pressure results in better mixing. The continual increase of mixing extent at the lowest jet velocity can be attributed to a decreasing break-up length[34] and longest contact time. Decreasing break-up length means increased turbulent dispersion which contributes to better mixing.[4] The contact time dictates the duration at which droplets can mix microscopically. Mixing efficiency does not change as the ambient pressure changes at higher jet velocities because break-up length does not decrease as much as lower jet velocities[27, 34], meaning the pre-atomization

and post-atomization break-up regimes are roughly the same and contact time is fixed for a set velocity.

The shorter contact time for the highest jet velocity may explain why it's mixing extent is less than that of the jet velocity of 16.45 m/s. For the jet velocity of 12.33 m/s case, mixing decreases after the initial jump from atmospheric. This may be due to the fact that this jet velocity is within the laminar to turbulent transition regime. The fluctuations of the jet are amplified by the increasing pressure.[34] This amplification may reduce contact area and time due to the inconsistent impact in this regime which would reduce mixing extent.

Data from Ashgriz et al.[4] with comparable injector configurations and operating conditions show

that our mixing efficiencies fall in the same range and show the same trends for mixing at atmospheric conditions. No data point was acquired at the higher jet velocity at atmospheric conditions because hydraulic flip causes jet alignment issues.

5.1.2 Ambient Pressure Effect for Gelled Fluid Case

Mixing efficiency data for gelled simulant are illustrated in figure 22. Any pressure increase from atmospheric pressure improves mixing. After the initial improvement from 0.1 to 1.72 MPa, mixing efficiency remains almost constant for jet velocities at or below 12.33 m/s and improves gradually for jet velocities at or above 14.39 m/s. For the latter cases, the mixing efficiency continues to increase due to faster break-up at higher ambient pressures. In addition, the higher jet velocity cases have more available energy to carry into the impact which can help mixing. Mixing effi-

Figure 21. Similar orifice diameter, equal momentum, like, water impingement and data from Ashgriz et al.[4] (injector orifice diameter = 0.508 mm, collection downstream distance = 50.8 mm, injector orifice length-to-diameter ratio = 5.4). Velocity labels in the legend indicate single jet exit velocity. Error bars are one standard deviation.

Figure 22. Similar orifice diameter, equal momentum, like, gel impingement. Velocity labels in the legend indicate single jet exit velocity.

ciency remains constant regardless of jet velocity for chamber pressures of 0.1 and 1.72 MPa. The efficiency range increases only at higher chamber pressures. The increasing aerodynamic forces on the individual jets due to the increasing gas density may contribute to the increased range of mixing efficiencies at higher ambient pressures.

5.1.3 Mixing Efficiency and Break-up Length Correlation

The mixing efficiency is compared to the normalized sheet break-up lengths found in Ramasubramanian et al.[34] Comparing the respective plots for the non-gelled and gelled working fluid for similar orifice diameter impingement shows that mixing efficiency and break-up length may be inversely proportional. The axes of the sheet break-up lengths are reversed so that the trends will visually be the same. The increases of ambient pressure from atmospheric results in a decreasing break-up length and an increasing mixing efficiency across both fluids and all jet velocities. In figure 23a, the case of a jet velocity of 16.45 m/s highlights the fact that a stagnating break-up length and mixing efficiency occur relative to one another as ambient pressure increases. In figure 23b, note the relative equivalence of each at point at an ambient pressure (0.1, 1.72, and 3.45 MPa) for both the mixing efficiency values and the normalized sheet break-up lengths.

Figure 23. Mixing efficiency compared to normalized sheet break-up length. Notice that break-up length axis is inverted. Shorter break-up lengths may contribute to greater mixing efficiencies.

5.1.4 Comparison between Non-gelled and Gelled Simulant

Three exit jet velocity cases are compared between the gelled and non-gelled simulants as shown in figure 24. At the lowest jet velocity (8.22 m/s), the gelled simulant exhibits better mixing especially for the higher ambient pressure cases. In this case, the pre-impingement jet perturbations of the water are greater than that of the gelled fluid.[47] Increasing disturbances tend to decrease mixing extent.[4] At a jet velocity of 12.33 m/s, at lower ambient pressures, the non-gelled simulant has the better mixing efficiencies but at elevated ambient pressures, the

Figure 24. Similar orifice diameter, like, water versus gel comparison. For equivalent jet velocity, water momentum rate is 15.5% per jet greater than gel momentum rate.

mixing efficiency becomes less than that of the gelled simulant. At lower ambient pressures, although jet perturbations are greater for the non-gelled fluid, the momentum carried into the impact is greater due to its higher density. This momentum increase causes break up sooner and increases turbulent dispersion, resulting in slight increases of mixing efficiency. In addition, the gelled simulant produces more stable sheets, resulting in greater break-up lengths[47] which decrease turbulent dispersion mixing in the post-atomization regime. Post-atomization mixing is known to significantly affect the extent of mixing.[4] At the highest injection velocity case (16.45 m/s), the mixing efficiency of the non-gelled mixture is always greater than that of the gelled mixture. The momentum of the water for comparable jet velocities is 15.5% greater than that of the gelled mixture, hence the better mixing efficiency. The momentum difference is due to the density difference of the two fluids.

For a given equal jet velocity, the non-gelled fluid has greater momentum due to its higher density and generally more jet turbulence than that of the gelled mixture. At comparable lower jet velocities and even with lower momentum, the gelled mixture produces better mixing because of its more stable jet stream. However, as jet velocity increases, the increase of mixing due to momentum exchange becomes dominant and the gelled mixture's better mixing, even with more stable streams, is overtaken by the mixing increase due to momentum exchange of the more turbulent water jets.

5.2 Dissimilar Orifice Diameter Like Impingement Case

Three momentum ratios are tested, 0.5, 1.0, and 2.0 which correspond to equal exit jet velocities, equal jet momentum, and equal jet flow rates, respectively. The working fluid is the non-gelled simulant. The relative velocity (see equation 5) will be used to compare similar and dissimilar orifice diameter impingement cases.

5.2.1 Ambient Pressure Effect for Non-gelled Simulant

All the mixing efficiency data for dissimilar orifice diameter impingement are shown in figure 25. The efficiencies are grouped based on the momentum ratio ($\frac{\rho_F v_F^2 d_F^2}{\rho_O v_O^2 d_O^2}$) of the jets. In figure 25a, one can see the mixing efficiency is relatively independent of chamber pressure. Even at atmospheric conditions, the mixing efficiency is comparable to that for all elevated ambient pressure cases. The higher relative jet velocity results in greater mixing efficiency due to greater impact energy. Figure 25b shows the mixing efficiencies for the equal jet momentum condition. Similar to the equal jet velocity case, the mixing efficiency largely remains independent of elevated ambient pressure. However, at the lowest relative jet velocity ($v_{rel} = 7.34$ m/s), there exists a significant increase in mixing efficiency with the elevation of pressure from atmospheric pressure. For the equal jet volumetric flow rate conditions, the jet velocity imbalance is greatest. This imbalance produces the most misalignment at atmospheric conditions and may contribute to the very low mixing efficiencies found there. With misalignment of jets, the droplets expelled from the sheet at these conditions fall outside the laser sheet. Figure 25c illustrates that at any pressure above atmospheric, mixing is independent of pressure. The highest and lowest relative jet velocity cases show the greatest increase of mixing efficiency from atmospheric conditions. For dissimilar orifice diameter impingement cases, elevation of ambient pressure above atmospheric improves mixing only when the jet velocity is relatively low (7.12 m/s and 10.68 m/s).

5.2.2 Comparison between Similar and Dissimilar Orifice Diameter Impingement

The comparisons of mixing efficiencies between similar and dissimilar orifice diameter impingement cases are shown in figure 26. Each sub-figure represents data for different ambient pressure conditions. When separated by momentum ratio, it generally becomes clear that the best mixing occurs for dissimilar orifice diameter impingement at a momentum ratio of 0.5 and the least efficient mixing occurs for dissimilar

Figure 25. Dissimilar orifice diameter, like, water impingement. Fuel jet exit velocity is equivalent for all plot marker symbols (all circle marker symbols in all plots ‘o’ represent single fuel jet exit velocities equal to 12.33 m/s). Error bars are one standard deviation.

orifice impingement at momentum ratio of 2.0. At a momentum ratio of 0.5, the Rupe number is 0.59 and at a momentum ratio of 2.0, the Rupe number is 0.26. A Rupe number of 0.5 is the optimum mixing situation. The mixing efficiency of the unity momentum dissimilar and similar orifice diameter impingement cases usually fall between that of the mixing efficiencies for momentum ratios 0.5 and 2.0. The mixing efficiencies of the dissimilar orifice pairing are in the range of the similar orifice pairing due equivalent jet conditions for the smaller orifice jet and the relatively small differences of the larger jet. Because the orifices of the dissimilar case (0.508 mm and 0.711 mm) are not greatly different, the contact area is sufficient enough to produce mixing efficiencies of similar orifice diameter jets. Turbulence due to increased injection velocity of the smaller free stream jet works to increase contact area.

For the unity momentum ratio cases, as the ambient pressure increases, the similar orifice diameter impingement case results in better mixing efficiencies. The amplification of the turbulent jet fluctuations due to increased ambient pressure for the dissimilar orifice diameter impingement case reduce the mixing efficiency to a greater extent than the pressure’s effect on the similar orifice impingement case. The larger diameter orifice of the dissimilar case incurs more aerodynamic forces and consequent perturbations than the smaller diameter orifices for the similar case. It should be noted that dissimilar orifice diameter impingement case (at MR = 0.5) produces greater mixing efficiencies than similar orifice diameter impingement case of optimum mixing conditions. This trend is consistent with the like impingement and unlike impingement cases at atmospheric condition.[2] Our data show that this trend holds as the ambient pressure is increased to 3.45 MPa for like impingement. Also, it should be noted that the relatively large downstream distance from the impingement point may explain why the mixing efficiencies are generally high (greater than 70%)

for all cases tested. In addition to the larger downstream distance, the greater orifice diameter values may contribute to why these values are greater (Rupe's finding[1] on area scale) than the mixing efficiencies of Yuan et al.[13] at the lower jet velocities.

Figure 26. Like, water impingement at different ambient pressures. Dissimilar and similar labels in the legend represent the orifice diameter pair combination with its corresponding momentum ratio.

6 Conclusions

Using a pressure chamber and flow systems, two different nozzle pairings and two working fluids are investigated. The flow conditions are varied with a specific focus on ambient pressure conditions. A comparison of the nozzle pairings gives details into the specific mixing attributes of the sprays generated. The focus

on ambient pressure conditions progresses research in the ambient condition effects on mixing. Atomization characteristics are used to shed light on possible effects on mixing phenomenon and mixing efficiency quantification is achieved.

Mixing efficiencies of impinging jets of gelled and non-gelled simulants for hypergolic propellants are experimentally determined using PLIF. The effect of ambient pressure on the mixing efficiency is presented for similar and dissimilar orifice diameter impinging jets. For similar orifice diameter impingement, the ambient pressure increase above atmospheric enhances mixing for both gelled and non-gelled fluid due to reduced break-up lengths. However, the mixing efficiencies stop increasing and remain constant above a certain ambient pressure. Gelled simulant generally results in poorer mixing than the non-gelled simulant, suggesting the momentum carried and pre-impingement jet conditions are the determining factor in mixing efficiency. For dissimilar orifice diameter impingement, mixing is generally constant over all ambient pressures including atmospheric.

The equal jet-velocity cases ($MR = 0.5$) produce better mixing than equal momentum-ratio cases ($MR = 1.0$) or equal jet-volumetric flow rate cases ($MR = 2.0$). The equal jet-volumetric flow rate cases ($MR = 2.0$) results in worst mixing, regardless of ambient pressure and jet velocity for the range of pressures and velocities tested. For some optimized operating conditions, the dissimilar orifice diameter impingement case can produce better mixing than the similar orifice diameter impingement case.

The reproducible sprays and consistent data analysis procedure allow a variety of system variables to be examined. The adaptability of the nozzle configurations and data collection system allow the opportunity for the advancement of spray mixing research. An analysis of the downstream distance effect on mixing coupled with increased ambient pressure may highlight the dominant mixing mechanism in the pre-atomization and post-atomization regimes for similar and dissimilar orifice diameter impingement using a non-gelled and gelled working fluid. The characterization of gelled simulant mixing efficiencies for dissimilar orifice diameter impingement would progress the understanding of the effects of gel break up (or lack there of) on mixing efficiencies and would help explain free liquid jets influence on pre-atomization mixing.

Nomenclature

$\tilde{N}$	= number of samples with $r_{x,y} > R$
C	= number concentration of dye molecules
$ccpm$	= cubic centimeters per minute (cm^3/min)
d	= orifice diameter
E_m	= mixing efficiency
F_R	= Rupe factor, $\frac{\rho_F v_F^2 d_F}{\rho_O v_O^2 d_O}$
F_{cor}	= correction factor
$f_{x,y}$	= local fluorescence intensity
gpm	= gallons per minute
$I_{x,y}$	= local laser intensity
$ICCD$	= intensified charged-couple devise
K	= optical collection efficiency
L_b	= sheet break-up length
m	= nominal (input) mass of stream
$m_{x,y}$	= local mass of stream
MR	= momentum ratio, $\frac{\rho_F v_F^2 d_F^2}{\rho_O v_O^2 d_O^2}$, as defined by Won et al.[3], $\frac{\rho_O v_O^2 d_O^2}{\rho_F v_F^2 d_F^2}$
N	= number of samples with $r_{x,y} < R$
N_R	= Rupe number, $\frac{1}{1+F_R}$
$n_{x,y}$	= local number of dye molecules
NPT	= National Pipe Thread Taper
$P.P.$	= penetration percentage
$PDPA$	= phase doppler particle analyzer
$PLIF$	= planar laser-induced fluorescence
R	= nominal mixture ratio, $\frac{m_F}{W}$
$r_{x,y}$	= local mixture ratio, $\frac{m_{x,y,F}}{\omega}$
SG	= specific gravity of fluid
v	= jet velocity

$V_{x,y}$ = local volume of spray
 W = total nominal mass flow rate of spray, $m_F + m_O$

Symbols

α = impingement angle
 ω = total local mass flow rate of spray, $m_{x,y,F} + m_{x,y,O}$
 ρ = fluid density
 θ_e = ejection angle

Subscripts

F = fuel
float = related to float material of flow meter
new = related to new fluid (fluid not specified by flow meter)
 O = oxidizer
rel = relative
scale = related to fluid indicated on flow meter scale
 x, y = local, in regards to PLIF images

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Appendices

A Pressure Chamber Dimensional Drawing

Figure 27. PresSure Products custom pressure vessel rated for 750 psi working pressure

B LabVIEW Front Panel and Block Diagram

Figure 28. LabVIEW Front Panel used for gel simulant flow rate monitoring

Figure 29. LabVIEW Block Diagram corresponding to Front Panel in figure 28

C Nozzle Geometry

Figure 30. 0.028 in. orifice diameter nozzle design drawing

Figure 31. 0.020 in. orifice diameter nozzle design drawing

D Nozzle Mounting Blocks, Mounting Plate, and Hanging Apparatus

Figure 32. Individual nozzle mounting block

Figure 34. Nozzle assembly showing configuration of nozzles, mounting blocks, and mounting plates

Figure 35. Nozzle adapter plate used to attach to chamber lib

Figure 36. Dowel rods connecting adapter plate in figure 35 to chamber lid

E Spray Mass Distribution Matrices for Dissimilar Orifice Diameter Impingement

Figure 37. $MR = 0.5$: Total mass distribution images are above the purple line and fuel mass distribution images are below the purple line. Injector and laser orientations are the same throughout appendix E and correspond to figure 17a.

Figure 38. MR = 1.0: Total mass distribution images

Figure 39. MR = 1.0: Fuel mass distribution images

Figure 40. MR = 2.0: Total mass distribution images

Figure 41. MR = 2.0: Fuel mass distribution images

F Mixing Efficiency MATLAB Code

```

filepath = ['C:\Users\Vince\Desktop\Mixing\Similar Orifice Diameter'...
'\Water\100 psi\250 ccpm'];
items = dir(filepath);
itemsname = {items.name};
itemsisdir = {items.isdir};
for i = 1:length(itemsname)
    if cell2mat(itemsisdir(i)) == 0
        assignin('base',itemsname{i}(1:end-4),dlmread(strcat...
(filepath,'\',itemsname{i})));
    end
end
% three variables will be defined based on file names (DD, DNDf, mixf)
% DD - total spray mass distribution
% DNDf - just fuel spray mass distribution
% mixf - qualitative visual of mixing

countz = 0; sumf = 0; sumfs = 0; % reset variables
W = sum(DD(:))/3; % correct for dye concentration
F = 0.5 % similar orifice impingement mixture ratio
for i = 1:numel(mixf) % iterates through all pixels
    w = DD(i)/3;
    f = DNDf(i)/6/w;
    if mixf(i) == 0
        countz = countz + 1;
    elseif f < F
        sumf = sumf + w/W*(F - f)/F;
    elseif f >= F
        sumfs = sumfs + w/W*(F - f)/(F - 1);
    end
end
Em = (1-(sumf+sumfs))*100

```

Figure 42. Browser and file list used in above MATLAB code

G Test Data Summaries

Similar orifice diameters (0.508 mm) and MR = 1.0								
Working fluid - Water				Working fluid - Gel				
Chamber Pressure (<i>psi</i>)	Jet Flow Rate (<i>cm³/min</i>)	Jet Velocity (<i>m/s</i>)	Mixing Efficiency	Chamber Pressure (<i>psi</i>)	Jet Flow Rate (<i>cm³/min</i>)	Jet Velocity (<i>m/s</i>)	Mixing Efficiency	
0	100	8.22	76.1	0	100	8.22	74.3	
	150	12.33	81.7		125	10.28	73.1	
	200	16.45	79.5		150	12.33	73.3	
100	100	8.22	77.0		175	14.39	73.8	
	150	12.33	86.3		200	16.45	74.0	
	200	16.45	88.4	250	100	8.22	86.0	
	250	20.56	84.2		125	10.28	84.9	
300	100	8.22	80.0		150	12.33	85.4	
	150	12.33	81.6		175	14.39	80.6	
	200	16.45	89.8		200	16.45	85.1	
	250	20.56	86.1	380	100	8.22	82.6	
500	100	8.22	83.9		125	10.28	83.5	
	150	12.33	78.6		150	12.33	80.8	
	200	16.45	89.3		175	14.39	83.9	
	250	20.56	86.0		200	16.45	88.7	
				500	100	8.22	84.6	
					125	10.28	85.4	
					150	12.33	87.9	
					175	14.39	90.7	
					200	16.45	87.6	

Table 1: Data of like impingement at 50.8 mm downstream of impingement point with injectors of L/D = 5 at $\alpha = 60^\circ$ with 5 mm pre-impingement distance

Dissimilar orifices (fuel diameter = 0.508 mm and oxidizer diameter = 0.711 mm)					
Working fluid - water					
<i>MR = 0.5</i>					
Chamber Pressure (<i>psi</i>)	Fuel Jet Flow Rate (<i>cm³/min</i>)	Oxidizer Jet Flow Rate (<i>cm³/min</i>)	Fuel Jet Velocity (<i>m/s</i>)	Oxidizer Jet Velocity (<i>m/s</i>)	Mixing Efficiency
0	100	198	8.22	8.31	78.4
	150	297	12.33	12.46	85.5
100	100	198	8.22	8.31	87.8
	150	297	12.33	12.46	89.4
300	100	198	8.22	8.31	76.2
	150	297	12.33	12.46	82.8
500	100	198	8.22	8.31	82.8
	150	297	12.33	12.46	92.5
<i>MR = 1.0</i>					
Chamber Pressure (<i>psi</i>)	Fuel Jet Flow Rate (<i>cm³/min</i>)	Oxidizer Jet Flow Rate (<i>cm³/min</i>)	Fuel Jet Velocity (<i>m/s</i>)	Oxidizer Jet Velocity (<i>m/s</i>)	Mixing Efficiency
0	100	140	8.22	5.88	65.7
	150	210	12.33	8.81	86.6
	200	280	16.45	11.75	84.0
	250	350	20.56	14.69	81.2
100	100	140	8.22	5.88	77.9
	150	210	12.33	8.81	73.9
	200	280	16.45	11.75	80.0
	250	350	20.56	14.69	87.2
300	100	140	8.22	5.88	70.8
	150	210	12.33	8.81	80.0
	200	280	16.45	11.75	84.7
	250	350	20.56	14.69	82.6
500	100	140	8.22	5.88	83.4
	150	210	12.33	8.81	76.4
	200	280	16.45	11.75	74.8
	250	350	20.56	14.69	85.8
<i>MR = 2.0</i>					
Chamber Pressure (<i>psi</i>)	Fuel Jet Flow Rate (<i>cm³/min</i>)	Oxidizer Jet Flow Rate (<i>cm³/min</i>)	Fuel Jet Velocity (<i>m/s</i>)	Oxidizer Jet Velocity (<i>m/s</i>)	Mixing Efficiency
0	100	99	8.22	4.15	31.1
	150	148	12.33	6.23	73.6
	200	198	16.45	8.31	69.4
	250	247	20.56	10.39	45.5
100	100	99	8.22	4.15	79.9
	150	148	12.33	6.23	78.3
	200	198	16.45	8.31	80.8
	250	247	20.56	10.39	85.0
300	100	99	8.22	4.15	73.3
	150	148	12.33	6.23	70.1
	200	198	16.45	8.31	68.3
	250	247	20.56	10.39	74.1
500	100	99	8.22	4.15	83.4
	150	148	12.33	6.23	62.6
	200	198	16.45	8.31	73.4
	250	247	20.56	10.39	76.2

Table 2: Data of like impingement at 50.8 mm downstream of impingement point with injectors of $L/D = 5$ at $\alpha = 60^\circ$ with 5 mm pre-impingement distance