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Experimental Investigation Of Breakup And Coalescence Characteristics Of A Hollow Cone Swirling Spray

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EXPERIMENTAL INVESTIGATION OF BREAKUP AND COALESCENCE CHARACTERISTICS OF A HOLLOW CONE SWIRLING SPRAY

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering in the department of Mechanical and Aerospace Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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ABSTRACT

Atomization can be achieved by discharging liquid at relative high velocities into a slow moving environment (hydraulic nozzles) or by discharging liquid at low velocities into a fast moving gas flow (air-blast nozzles). These two types of injector nozzles are featured in majority of the industry applications such as power generation, food or pharmaceutical powder formation, spray painting, petroleum refining, and thermal sprays. The most common atomizer used in combustion engines is the pressure-swirl nozzle (Simplex nozzle) to obtain a homogenous mixture at different equivalence ratios. The experimental studies performed with pressure-swirl nozzles have reported contradictory results over the last few years. Thus, the fundamentals of spray dynamics, such as spray formation, liquid breakup length, droplet breakup regimes, and coalescence still need to be understood for a pressure-swirl nozzle.

An experimental study of the breakup characteristics of various liquids and fuels with different thermal physical properties emanating from hollow cone hydraulic injector nozzles induced by pressure-swirling was investigated. The experiments were conducted using two nozzles with different orifice diameters 0.3mm and 0.5mm and injection pressures (0.3-4MPa) which correspond to \( \text{Re}_p = 7,000-31,000 \) depending on the liquids being tested. Three laser-based techniques, i.e., Shadowgraph, Particle Image Velocimetry (PIV) and Phase Doppler Particle Anemometry (PDPA) were utilized in this study. Although each technique had its limitation in different flow regimes, the results were cross-validated, and generally showed correct trends in axial and radial measurements of velocity and diameter for different nozzles, Weber and Reynolds numbers.
The spatial variation of diameter and velocity arises principally due to primary breakup of liquid films and subsequent secondary breakup of large droplets due to aerodynamic shear. Downstream of the nozzle, coalescence of droplets due to collision is also found to be significant. Different types of liquid film break up was considered and found to match well with the theory. The spray is subdivided into three zones: near the nozzle, a zone consisting of film and ligament regime, where primary breakup and some secondary breakup take place; a second zone where the secondary breakup process continues, but weakens, and the centrifugal dispersion becomes dominant, and a third zone away from the spray where coalescence is dominant. Each regime has been analyzed in detail to understand the effect of surface tension and viscosity. Surface tension and viscosity were engineered to mimic fuels, which were then compared with real fuels such as Ethanol, Jet-A and Kerosene. Results show similarity in the diameter in the beginning stages of breakup but in the coalescence regime, the values deviate from each other, indicating that the vapor pressure also plays a major role in this regime.
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CHAPTER ONE: INTRODUCTION

1.1 Liquid Breakup from Solid Stream Nozzles

The idea of a liquid jet stream breaking up into millions of smaller droplets has been around for over a hundred and fifty years. One of the pioneers of this work was Savart (1833) who supplied the first experimental results related to jet disintegration. At the time it was established that if the jet diameter is fixed the continuous liquid jet length would be proportional to the jet velocity; or similarly if the jet velocity is fixed, the length of the continuous liquid jet is proportional to the liquid jet diameter. One of the earliest works proposed on this subject was done by Rayleigh in 1878; he focused on the stability analysis for an infinitely long column of liquid which neglected viscous and aerodynamic effects. In this theory it was explained that the liquid jet would breakup into smaller droplets due the capillary-based instabilities. Later in 1931, Weber extended Rayleigh’s analysis by incorporating liquid viscosity and found that the breakup rate decreased while increasing the droplet size. With these significant theories discovered it prompted more researchers like Tyler (1933), Ohnesorge (1936), Sterling and Sleicher (1975) and Reitz and Bracco (1982) to further extend both Rayleigh and Weber’s analysis. In doing so, a general dispersion equation for an axisymmetric liquid jet which includes aerodynamic forces and viscosity was generated, as given below.
\[ \omega^2 + 2\nu k^2 \omega \left[ \frac{I'_i(\xi)}{I_o(\xi)} - \frac{2kl}{k^2 + l^2} \frac{I_i(\xi)}{I_o(\xi)} \frac{I'_o(la)}{I_o(la)} \right] \]

\[ = \frac{\sigma k}{\rho_l a^2} (1 - \xi^2) \left( \frac{l^2 - k^2}{l^2 + k^2} \right) \frac{I_i(\xi)}{I_o(\xi)} + \frac{\rho_s}{\rho_l} (U - \frac{i\omega}{k})^2 k^2 \left( \frac{l^2 - k^2}{l^2 + k^2} \right) \frac{I_i(\xi)}{I_o(\xi)} K_0(\xi) \]

where \( \xi = ka, \nu = \frac{\mu}{\rho_l}, l^2 = k^2 + \frac{\omega}{\nu} \)

Accordingly, it has been determined that the spray characteristics from injector nozzles are influenced by numerous different parameters, such as the injection nozzles internal flow physics, injection velocity, physical and the thermodynamic states of both liquid and gas phases [Reitz and Bracco (1986)].

With the knowledge of the different parameters affecting the spray characteristics, researchers began exploring different parametric studies to investigate the liquid jet interaction with the gas phase in both static and dynamic conditions and its ability to generate jet breakup/atomization. It is extremely important for one to know the basic theory of how the liquid jet forms into little droplets throughout the sprays trajectory. When a continuous liquid jet is injected from a nozzle a high kinetic energy gas medium is required whether it be coaxial flow or cross flow, the liquid jet becomes very unstable and will breakup into two main regimes. The first regime starts when the liquid propagates from the nozzle and interacts with the gas phase. In this regime, primary breakup regime, the interaction between the gas and liquid phase causes waves to develop along the peripheral of the liquid film. Once the wave becomes unstable it will shear off creating elongated ligaments due to the Kelvin-Helmholtz instabilities. These ligaments will then further breakdown into large droplets. The second regime which is called the secondary breakup regime
happens a little further along the bulk liquids trajectory. In this regime the larger droplets that were formed in the previous regime start to reduce in size due to the Rayleigh-Taylor instabilities. This regime will continue until the critical Weber number is reached. At this point the droplets will begin to coalesce and/or vaporize if external heat is present. The two regimes can be seen in the following figure.

Figure 1: Schematic of liquid jet breakup and vaporization in: A - coaxial-flow before combustion, B - cross-flow before combustion

One of the first significant investigations done on these parameters was by Chelko (1950). In this study, the behavior of the liquid jet being injected into a cross flow air stream with high velocities was considered. By doing this study a good understanding of how the liquid jet streams trajectory behave amongst the different cross flow velocities. At the time of this research the technology for detailed quantitative values of what is happening in the flow could not be accomplished, thus accurate models could not be generated. This research and others at the time became a catapult for the need of more advanced techniques for data collecting. In the decades to
come from various researchers more sophisticated techniques would be developed especially the introduction of various laser diagnostics technique. By using lasers and various optical devices one has the capability to accurately capture the droplet size, velocity, and droplet distribution along the liquid jet’s trajectory. Some of the laser diagnostic techniques which have been commonly used since the turn of the century are Particle Image Velocimetry (PIV) and Laser Doppler-Phase Doppler Anemometry (LD-PDA), each having their advantages and disadvantages depending on the system parameter. PIV is favorable when one is studying the flow field, whereas PDPA allows one to gain the droplet diameter and velocity averages at a given point along the flow. Some important studies which were done using such techniques were Rachner et al. (2002), Cavaliere et al. (2003), and Sedarsky et al. (2010). In Rachner et al. (2002) study of jet penetration, fuel displacement, and droplet size distribution for kerosene at high pressure was studied utilizing PDA and a time-resolved shadowgraph technique to gather their data. While Sedarsky et al. (2010) used high speed shadowgraph and PIV to study the breakup of the liquid jet at various conditions. One of the major advancements made in this area of research was done by Bellofiore (2006). A combination of all three techniques was utilized for this study. PIV and PDA measurement techniques were used to detect the droplet velocity fields and droplet size distribution along the premixing duct, while using the shadowgraph technique to analyze the jet spray trajectories. What makes this case so interesting is the fact that these measurement techniques were done when the system was operated at or near real LPP gas turbine operating conditions. Although these techniques have been proven to gather quantitative results with supreme accuracy they have their limitations like all instruments.
One of the hardest regions to understand and obtain accurate results is near the nozzle region because of the dense fog of droplets which surround the continuous liquid jet. Since the dense fog surrounds the nozzle exit making it nearly impossible to gather any sort of data with conventional techniques or laser diagnostic techniques. In response to this demand a couple of new experimental techniques were developed, X-ray and ballistic imaging. By utilizing these experimental techniques researchers got a deeper understanding of the spray structure near or at the nozzles exit. Some researchers that have had success using these techniques in studying the different system parameters was Powell et al. (2001) from Argonne National Laboratory using X-ray absorption techniques and Linne et al. (2005) using time-gated ballistic imaging to understand the liquid core of the spray. By using these techniques high resolution results of the spray structure at the nozzle such as droplets, voids, and ligament formation were obtainable.

Researchers have spent the last fifty plus years studying and optimizing the effects of system parameters abilities for either co-flow or cross flow air stream configurations to atomize the liquid jet. They have discovered numerous limitations for these parameters and promising results but one issue still lingers. That is to understand a way to establish uniform atomization without the need for a high momentum gas phase medium in a short distance or period of time.
1.2 Atomization Induced Nozzles

All the research studies discussed in the previous section pertain to a continuous liquid jet injected into a static or dynamic condition, which has been shown to contribute significantly on how the liquid jet atomizes into droplets. While this method of delivering liquid droplets has been heavily researched, there still lays one major problem as stated above. How to uniformly create a droplet distribution within the gas phase medium in a short distance and/or time frame? One of the few ideas that were implemented to solve such an issue was redesigning the internal characteristics of nozzles to induce atomization directly after being emanating from the nozzle into the surrounding gas phase. By achieving this, the liquid will be leaving the nozzle already atomized into droplets. A comparison of the two types of injector nozzles can be seen in Figure 2.

![Figure 2: Liquid jet nozzles verse liquid atomizer nozzle](image)

This would reduce the primary and possibly the secondary breakup regimes, meaning that far less time and distance is needed to achieve a uniform droplet distribution. Unfortunately, this
newer concept has more complications due to the different types of nozzles that induce atomization without the need for a high inertia gas phase.

The two most common injector nozzles utilized in the industry are hydraulic and air-blast atomizers, both of which have completely different approaches to atomization. The hydrodynamic instabilities of liquid sheets, leading to breakup, are predominant in air-blast atomizers but also occur in hydraulic nozzles as well [Park et al. (2009), Shi and Kleinstreuer (2007), and Cavaliere et al. (2003)]. The hydraulic nozzle primarily produces liquid atomization by forcing the liquid through a single narrow annulus under a pressure gradient; the pressure head is converted into kinetic energy [El-Sayed et al. (2011) and Lefebvre (1989)]. On the other hand, an air-blast nozzle has two orifices that use preset air-liquid momentum ratio to induce atomization which occurs by exposing the thin liquid conical sheet to a high velocity airstream on both sides of the sheet [Sivakumar and Kulkarni (2011), Lefebvre (1989)]. Several papers have dealt with air-blast atomizer to study both spray characteristics and breakup dynamics [Park et al (2009), Sivakumar and Kulkarni (2011), Lefebvre (1989)]. Unlike the air-blast atomizer, hydraulic nozzles are slightly more complex. A clear understanding of hydraulic nozzles is not available as many types of such nozzles are used in the industry. Some of the more common types are plain orifice, pressure-swirl (Simplex nozzle), square spray, dual orifice and fan sprays. These nozzles generate either full or hollow cone sprays. Recent studies consist of characterizing the spray from convergent diesel nozzles [Payri et al. (2008)], analyzing the breakup characteristics from splash plate nozzles [Ahmed et al (2009)], and liquid property effects (e.g. in biofuels) on single and multi-orifice nozzles [Park et al (2009)]. These experiments have looked into various operating conditions and physical properties to fully understand the atomization
dynamics, using either Shadowgraph type technique or PDPA. However, the numerical models have been unable to match the measurements in hydraulic nozzles and at times have been contradictory especially in pressure-swirl nozzles [Shi and Kleinstreuer (2007)]. One of the key reasons for such inconsistency can be attributed to the type of measurement technique being utilized and lack of experimental results. Not all measurement techniques are best suited for all aspects and flow regimes of the spray cone.

1.3 Experimental Objects

In this thesis, the author experimentally studied the breakup characteristics and coalescence behavior for hydraulic based injector nozzles. The novelty of this work is in connecting the current theoretical models of breakup to actual experimental measurements for hollow cone sprays. The main objectives of this research is to first experimentally investigate the validation zones using optical techniques such as Shadowgraph, PIV, and PDPA, which are commonly used in characterizing spray nozzles. It will look into the effectiveness of each technique in the different breakup zones due to severe complexity of atomization. This study will also identify how each techniques validation zone is affected by the different hydraulic nozzles operating at different pressure in the axial and radial directions. Secondly, this research investigates the effects of Reynolds number and Weber number on the liquid breakup regimes including droplet coalescence in two cylindrical hollow cone pressure-swirl hydraulic atomizing nozzles. This study will identify the spray characteristics and droplet diameter and velocity profiles for each nozzle at different Reynolds number (injection pressure), liquid surface tension, liquid viscosity,
and liquid fuels in the axial and radial direction. This thesis will utilize the theory of liquid film breakup and show how the long and short wavelength instabilities are important for low and high Weber number ranges respectively. The dependence of liquid breakup characteristics has been validated with experimental data for the first time in the context of a pressure-swirl nozzle. Coalescence probability and swirl induced dispersion have also been studied in conjunction with breakup to provide a holistic view of droplet dynamics in these types of pressure atomizers.
CHAPTER TWO: EXPERIMENTAL SETUP AND INSTRUMENTATION
CROSS VALIDATION

2.1 Experimental Setup

The schematic diagram of the experimental setup utilized in this study is shown in Figure 3. The system consists of an autoclave (injection pressures up to 7.5MPa), test nozzles, and a three axis transverse system which precisely controls the placement of the nozzle (25.4µm increments) with respect to the diagnostic systems. Three different non-invasive optical techniques were utilized throughout various parts of this experimental study: Shadowgraph, Particle Image Velocimetry (PIV) and Phase Doppler Particle Anemometry (PDPA). Due to proprietary reasons, the schematic of the hydraulic nozzles cannot be given, thus a generic schematic is given in figure 4 followed by a summary of the two hydraulic nozzles in Table 1.

Figure 3: General Experimental Setup
Table 1: Nozzle Properties

<table>
<thead>
<tr>
<th>Nozzle Number</th>
<th>Parker Hannifin Part number</th>
<th>Flow Number (lbm/hr)/(psi)^{0.5}</th>
<th>Orifice Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>6030013E01</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>N2</td>
<td>6030013E04</td>
<td>1.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The Flow Number is characterized as the ratio of the mass flow rate (lbm/hour) and the square root of the differential pressure (psi). Reynolds number can be written in terms of a velocity scale based on the pressure differential [Kohnen et al. (2010)], Eqn (2.1)

\[ Re_p = \frac{\rho D}{\mu} U_{scale} \]  

(2.1)
where $U_{scale}$ can be written as followed in equation 2.2

$$U_{scale} = \sqrt{\frac{2\Delta P}{\rho}}$$

where $D$ is nozzle diameter, $\mu$ is liquid viscosity, $\rho$ is liquid density and $\Delta P$ is the differential pressure between injection pressure and ambient. From these equations the Reynolds number can be determined based on the injection pressures. Figure 5 shows how the Reynolds number varies based on the injection pressure.

![Graph showing Reynolds number variation with injection pressure for both nozzles](image)

**Figure 5: Reynolds number variation with injection pressure for both nozzles**

The data reported in this research was recorded on a vertical plane which passed through the center of the nozzle. Before capturing the data for PIV and shadowgraph, the calibration and proper focusing of the CCD camera was done using a grid that was placed under the nozzle and attached vertically to the traverse system. For simultaneous diameter and velocity measurements
through PDPA, the two laser beams were allowed to intersect directly below and in the center of the nozzle exit by moving the nozzle with the traverse system. In order to capture data at different axial or radial distances with respect to the tip, the nozzle was moved using the traverse system without disturbing the optical setup. The autoclave was pressurized with both liquid and air ranging from 0.3-4 MPa (Re<sub>p</sub> = 7,000 – 31,000) and was allowed to equilibrate for 10 minutes. The water was then injected into atmospheric conditions (25°C and 1.01kPa) through two different hydraulic nozzles. The droplet diameter and velocity was measured at several axial and radial locations throughout the spray using the different techniques mentioned previously.

In this chapter the three major techniques will be described in detailed and how the experiments were controlled to limit the uncertainty of the data that will be captured throughout the rest of this thesis. All three techniques will then be compared to one another for cross-validation purpose to determine which technique is optimal for which zone of the spray to ensure accuracy in data collecting.

2.1.1 PDPA Setup

The PDPA setup uses a 632 nm He-Ne laser along with a photo-multiplier tube positioned at a receiving angle of 70°. The choice of the angle of collection is based on the Brewster effect on the surface of the liquid droplet for 1<sup>st</sup> order refraction angle (Figure 3c). PDPA is traditionally a point measurement technique while PIV and Shadowgraph are field measurements and not usually comparable. Since the PDPA laser beams are of the order of 1 mm in diameter, the area in which the measurements are made is of the same order as the other two methods, thus
allowing direct comparison. This also ensured accurate results throughout the axial direction of the spray and the determination of the instrument capabilities at different zones of the spray. To ensure a statistically significant distribution, a running average was done to determine how many droplets should be recorded to obtain an acceptable mean. Figure 6 showcases the running average for both the diameter and velocity (Figure 6a and 6b respectively). It is determined that a minimum of 2000 droplet samples need to be taken in order to capture the true mean. For all PDPA measurement locations a sample size of 10,000 spherically validated data points was gathered, which is consistent with Kim et al. [2002]. This data has been compared with the shadowgraph data obtained at the same location for cross-validation. A set of sample histograms acquired through PDPA for $\Delta P = 1\text{MPa}$ ($\text{Re}_p=15,000$) is illustrated in Figure 7.

![Figure 6: Running Average of PDPA data for nozzle N1 at $\Delta P = 1\text{MPa}$ ($\text{Re}_p=15,000$) and $Z = 2.6 \text{ mm}$ – a) Diameter running average, b) Velocity running average](image-url)
2.1.2 Shadowgraph Setup

Both the Shadowgraph and PIV systems shared a 532nm (maximum energy 70 mJ per pulse) dual pulsed Nd-YAG laser (2 mm beam diameter) with an interline CCD camera (pixel resolution of 1376x1040) synchronized to the laser pulse. For shadowgraph, the 2 mm circular beam from an Nd:YAG laser is converted into a diffused mode using a combination of a 90° turning mirror and a circular diffuser (20°). The diffused light source is subsequently used to back illuminate the spray for effective imaging. The CCD camera coupled to a Navitar zoom lens assembly was used to image the spray (Figure 3a). The imaging setup allowed a spatial interrogation window of 0.9 mm x 0.9 mm with a depth of field of approximately 200µm. The overall spatial resolution achieved through this camera-lens setup was around 1µm/pixel.

Shadowgraph was used not only for visual inspection of the different breakup regimes and the nozzle spray characteristics, but also to measure the velocity and droplet diameter. The
diameter and velocity were calculated utilizing a post-processing algorithm with edge detection methods in Matlab. A background subtraction was incorporated to eliminate background noise that arose from the non-uniformity of the diffuser. To calculate the droplet diameter and velocity at a given point in the flow field, 200 pairs of images in a 0.9 mm x 0.9 mm window around that point were analyzed. Figure 8 shows that 200 images is an adequate number needed to capture the mean.

Each image generally contains more than 10 droplets making it a set of more than 2000 droplets when an ensemble over 200 images is considered. PDPA results are also found to be unaltered when ensemble over 2000 or more number of droplets. Thus, 200 sets of images for shadowgraph are sufficient and serve as minimum sample size for obtaining meaningful statistics. The acceptable droplets were determined using threshold values implemented within the in-house algorithm developed in Matlab. The grey scale image was converted to a black and white image by generating the image matrix in binary form. To determine the acceptance criteria,
the droplet shadow intensity was controlled by the edge detection function “canny” within Matlab with appropriate lower and upper bound limits that would determine how dark the pixel needed to be for it to be counted as 1 on the image matrix. By altering these values, the out-of-focus droplets, which distinguished droplets from one plane to another, were eliminated. The second criterion was the minimum droplet diameter. This was to ensure that all droplets were larger than the spatial resolution (10 pixel ~ 3 µm diameter droplet) which the camera could accurately distinguish. Anything smaller would resemble a speckle and could not be identified as a droplet. The last criterion was the droplet sphericity. The algorithm would find the center point of the droplet and determine the aspect ratio value. Acceptable aspect ratio range was determined to be 0.9 – 1.1. Figure 9 shows a schematic of the image processing routine. The velocity measurements were made by tracking the center of the droplet from the two image pairs. Subsequent to complete analysis, the post processing algorithms were used to generate histograms for diameter and velocity.
2.1.3 PIV Setup

In a similar setup as Shadowgraph, PIV was executed by replacing the diffuser with an appropriate plano-concave lens which converted the circular beam into a ~2 mm thick laser sheet with a sheet height of ~15 mm. The laser was positioned such that the vertical light sheet passed through the center of the spray. The CCD camera was repositioned from parallel to perpendicular viewing of the light source (Figure 3b). The pulse duration of the laser was of the order of 10 ns. The time interval between two pulses (Δt) was varied to determine its effect on the velocity field. After a few iterations, it was determined that 2 µs was optimum for the flow field near the nozzle.
exit (5-25mm) and around 3 µs further downstream of the spray (~25-63mm) for both Shadowgraph and the PIV technique.

The PIV technique was utilized to determine the velocity measurements of the droplets for cross-validation purposes rather than the gas phase, [Scarano et al. (1999), Raffel et al. (2007), Soria (1994, 1998)]. Although the PIV measurements were made in a 15 mm zone based on the laser sheet height, the post processing and vector generation were kept restricted to a window of 1mm x 1mm around the point of interest (insert Figure 3b), but full field measurements were also made. The statistical average of the velocity vectors was chosen as representative average velocity of this point in the flow field. It is important to note that the PIV generally uses seed particles to map the flow field and the size should be small so that they follow the flow field. In the current application, the droplets are considerably large compared to the seed particles. However, the purpose of PIV in this thesis was to measure the velocity of the droplet (discrete phase only), the high inertia of droplets was not considered to be a major issue. The gas phase velocity was not measured.

In PIV, the highest peak of the correlation map represents the most probable displacement value, while the second strongest peak corresponds to the noise peak. In order to screen out the unreliable vectors, the minimum accepted value for the displacement to noise peak ratio was fixed at 1.5, below which the displacement peak was discarded. It is known that the random error of the statistical method involved in PIV measurements increases with the ratio of maximum displacement of the particles to the size of the interrogation window. For example, for a 32 x 32 window size, a displacement of more than 2 pixels limits the random error to 1%, [Scarano et al
However, increase in the displacement of particles also results in the loss of the correlation peak [Raffel et al (1998)]. Figure 10 illustrates the effects of the integration window on the average velocity with the corresponding correlation peak.

![Figure 10: PIV integration window effects on velocity average with respective correlation peak for nozzle N1 at ΔP = 1MPa (Reₚ = 15,000) and Z = 25 mm](image)

Although the vectors are very similar in direction in magnitude the correlation peak indicates a difference. For the 32x32 first pass integration window it can clearly be seen that it has a higher peak to peak ratio. To optimize, the acceptable displacement of particles was limited to 15 pixels. To determine the adequate number of image pairs needed to ensure proper statistical description, several cases were analyzed. Using the cross-correlation technique with a 32 x 32 first pass
integration window and a subsequent second pass with 16 x 16 integration window with 50\%
overlap (Figure 11), it was found that 100 image pairs was sufficient for an appropriate
statistical average.

Figure 11: PIV velocity average for different number of images for nozzle N1 at \( \Delta P = 1 \text{MPa} \) (Re\(_p\) = 15,000) and \( Z = 25 \text{ mm} \)

Since PIV uses a statistical method based on auto or cross-correlations to determine the most
probable velocity vector [Soria (1998)], the acceptability of the calculated vector map from each
image pair is estimated by the correlation map or Q factor (the ratio of the strongest and second
strongest peaks), and not by the number of droplets present. Each image pair in PIV results in a
vector field (number of vectors depends on the size of the interrogation window). For an
unsteady flow field, an ensemble over multiple numbers of such vector fields is required to arrive at a mean velocity. However, the number of image pairs required strongly depends on the flow situation. Strong turbulence would need ensemble over more than 500 image pairs to arrive at converged statistics (mean statistics), [Uzol and Camci (2001)]. Although the field is somewhat unsteady in nature in the current experiment, we observed ensemble over 100 image pairs was sufficient to obtain converged flow statistics. Also it must be noted that the statistical method involved in PIV being very different from shadowgraph or PDPA, it does not require large sample sets. Using 100 images for the ensemble averaging, we reduced the other uncertainties arising from grid generation which reduces with increase in the number of image pairs. The uncertainty stemming from inherent grid generation and peak validation became insignificant with the increase in the number of image pairs.

2.2 Instrumentation Uncertainties

For each measurement technique, great care was taking to ensure accurate results for a comparative study. Since the droplets are small in size, and move at relatively high velocity, it is essential to have a small measurement volume. For PDPA, this was controlled by having a short fringe distance [Araneo et al (2006)]. For the current experimental setup, the fringe spacing was \~1.4 \mu m. The PDPA system had an accuracy of \~4\% for diameter measurements and \~1\% for velocity measurements with the spherically validated results corresponding to an aspect ratio range from 0.9 to 1.1. For the shadowgraph technique, the upper and lower bound intensity threshold values were modified to calculate the uncertainty for both the diameter and velocity.
The diameter was found to have a little more uncertainty (2 μm) since the image processing for diameter measurements are more intensity threshold dependent. The velocity measurements were made by tracking the center of the droplet which is not significantly dependent on the intensity which correlated to an uncertainty of 0.5 m/s. One of the most significant uncertainties in PIV depends on particle size. Santiago et al (1998) demonstrated that if the individual particles occupy 3-4 pixels in the interrogation window, the maximum uncertainty in the displacement can be limited to one-tenth of the particle diameter. In the current experiments, droplets were used as particles. The diameter of the droplet varied from 25-40 μm. With macro lens, ~11μm/pixel resolution was achieved, which translated to each pixel area of about ~121 μm². For the resolution used, the droplets or the particles occupied ~2-5 pixels and it is reasonable to assume that the uncertainty of the displacement was limited to one-tenth of the particle diameter which is between 2.5-4 μm. In the current experiment, the pulse separation time (Δt) was varied from 2 to 3 μsec, which resulted in a maximum uncertainty in velocity measurement from 0.8 – 2 m/s. A summary of the optical measurement uncertainties are shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Optical Measurement Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIV</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>Diameter (μm)</td>
</tr>
</tbody>
</table>
2.3 Cross-Validation and Limitation of Techniques

In order to validate and compare the measurements obtained by the three different techniques (Shadowgraph, PIV, PDPA), the droplet diameter and velocity were measured at different locations along the centerline (Figure 12a) for the smaller nozzle (N1) with orifice diameter of 0.3mm at $\Delta P = 1\text{MPa} \ (Re_p = 15,000)$. Figure 12 shows the velocity and diameter measurements using these three techniques at different locations along the centerline. Although the results obtained from different techniques compared well for the velocity and diameter measurements, not all methods are possible at all locations as can be seen from Figure 13. Radial measurements were also obtained for determining the limitations of the different techniques.

Figure 12: Instrument comparison at $\Delta P = 1\text{MPa} \ (Re_p = 15,000)$ and nozzle N1 - a) Spray measurement zone, b) Velocity comparison, c) Diameter comparison
2.3.1: PIV Results

In the primary breakup and at the beginning stages of secondary breakup regimes, the droplet size is large. High population of large droplets results in extremely dense spray, which significantly increases the noise level in the Mie Scattering signal (used for PIV). Therefore, PIV measurements were not possible in this region. In order to obtain proper peak correlation between the image pairs with acceptable uncertainties, measurements were made only further downstream mainly in the zone where secondary breakup and droplet coalescence are dominant. At $\Delta P = 1\text{MPa} \ (Re_p = 15,000)$, secondary breakup occurs around 25.4 mm away from the nozzle exit where the droplet diameter is nearly half the size of the droplets in the primary breakup.
regime. Although PIV measurements are possible as close as 12.7 mm from the nozzle, the uncertainty is quite high with no strong correlation peaks as seen in Figure 14. Figure 12b shows that the velocity measurements made using all instruments are in good agreement beyond 25.4mm.

![Figure 14: PIV velocity vectors for nozzle N1 at ΔP = 1MPa (Re_p = 15,000) and Z = 12.7 mm with respective correlation peak.](image)

Note that the secondary breakup zone is a function of injection pressure which causes the valid area of accurate PIV measurements to shift. Although the secondary breakup occurs closer to the nozzle at higher injection pressures, accurate PIV measurements is only possible beyond 35mm from the nozzle exit where coalescence begins. The shaded areas in Figure 13 indicate valid zones of measurements using each instrument. This shift occurs due to the high liquid flow rate which increases the density of droplets further downstream. Similar results are seen for the larger nozzle N2 in the axial direction. In addition, the droplet diameter reduces with an increase
in injection pressure. At low injection pressures, the cone angle is smaller resulting in a denser flow close to the nozzle, which further reduces the possibility of PIV measurements close to the nozzle. For medium injection pressures (ΔP = 1-2.4MPa), the spray angle is moderate allowing the droplets to expand further outwards reducing droplet concentration, allowing accurate PIV measurements to be possible. Figures 13 and 14 are to illustrate the PIV results. Figure 13 shows the velocity field of the whole spray zone for valid measurements by putting all the measurement locations together.

Figure 15: Full field PIV velocity vector field for nozzle N1 at ΔP = 1MPa (Reₚ = 15,000)
In the figure the core vectors are dominate in the axial direction with a slight radial component due to the swirl effects of the nozzle and become less dominate in the peripheral. These can be clearly seen from the zoomed in vector fields in different parts of spray in Figure 16. At high injection pressures greater than 2.4 MPa ($Re_p > 28,000$), the swirling effect near the nozzle significantly reduces the chances of obtaining PIV measurements, thus shifting the zone of valid PIV measurements further downstream.

![Velocity vector fields](image)

Figure 16: Zoomed in images of velocity vector fields at different locations of the spray for nozzle N1 at $\Delta P = 1\text{MPa}$ ($Re_p = 15,000$)

The flow from the pressure-swirl hollow cone injector nozzle has a certain thickness that broadens as the distance increases. This causes the width of the zone for higher density of droplets to increase axially. As previously discussed, for low injection pressures $\Delta P \sim 0.5\text{MPa}$
(Re_p = 9,500), the spray density decreases towards the periphery near the nozzle exit. Thus, for small cone angles, the PIV results in the core are not possible with acceptable peak to peak correlation. While the droplet density reduces in the radial direction, accurate PIV results still cannot be obtained due to large droplet diameters. They occupy too many pixels for accurate cross-correlation between the two images. It was found that for radial measurements PIV was accurate in the pressure zone \( \Delta P = 0.8 - 2 \text{MPa} \) (Re_p = 12,000 - 26,000), for accurate results. Pressure values outside of this range would cause inaccuracies in the value either from the larger droplets that would occupy too many pixels for proper cross-correlation or the density of the droplets is too large. Similar results are seen for the larger nozzle N2 in the axial direction but in the radial direction larger uncertainties are seen due to the droplets being 1.5 times the size of the droplets for the smaller nozzle N1.

2.3.2: PDPA Results

As a single point measurement, PDPA rendered successful data at locations closer to the nozzle where PIV data was not possible. However, PDPA had similar difficulties in delivering results for velocity and diameter measurements within 10 mm from the nozzle for majority of the injection pressures. For low to moderate injection pressure \( \Delta P = 0.5 - 2 \text{MPa} \) (Re_p = 9,500-21,000), the velocity and diameter measurements was made with instrument validation ranging from 20-65% spherical validation and 75-95% signal to noise validation depending on the axial location (Figure 12b) and injection pressure. Similar validation ranges were seen for nozzle N2 with the only difference being that the ranges shifts. This is due to larger spray and swirl angles
which causes a true hollow cone in the core. The only limitation found at these injection pressures and hydraulic nozzles is the film length and primary breakup regime which is a function of injection pressure. Measurements were made close to the nozzle exit, where liquid films, ligaments, and non-spherical droplets are dominant. This corresponds to the beginning stages of secondary breakup. This region which varied as a function of injection pressure caused the spherical validation percentage to be low, thus a longer sample time was needed to achieve 10,000 validated samples. As the injection pressure increases, the film length becomes smaller enabling PDPA measurements at a higher validation level closer to the nozzle. At $\Delta P = 1\text{MPa}$ ($Re_p = 15,000$), PDPA measurements are possible at a distance of $\sim 1.3 - 10\text{ mm}$ from the nozzle, with a satisfactory (70-75%) signal to noise validation percentage and (20-45%) spherical validation percentage. However, the presence of stretching droplets and ligaments increases the average diameter measured by the PDPA system causing the diameter measurements to be larger than Shadowgraph. Droplets in the aspect ratio range of 0.9 to 1.1 were accepted as part of spherical validation. Since PDPA makes measurements in the vertical direction the diameter measurements are highly dependent on the aspect ratio. In the case of Shadowgraph discussed in the next section, droplet diameter measurements are not dependent on the aspect ratio.

It is also observed that outside the ligament and primary breakup regime, the PDPA validation percentage for both criteria increased (85-95% signal to noise validation and 60-85% spherical validation) due to the presence of spherical droplets generated by later stages of secondary breakup. Further downstream, validation rate again decreases due to coalescence. This is evident in Figure 12c where the difference between the Shadowgraph and PDPA is the largest. As observed for PIV measurements, with increase in injection pressure, the zone where
PDPA measurement can be made at higher validation levels shifts closer to the nozzle due to shorter film length, Figure 13. However, at $\Delta P = 3\text{MPa} \ (\text{Re}_p = 31,000)$ the velocity and diameter start to show bimodal distribution at the points closer to the nozzle for both N1 and N2, which indicates the presence of strong recirculation where the diameter measurements increases near the nozzle at $\Delta P = 3\text{MPa} \ (\text{Re}_p = 31,000)$, thus shifting the zone of high validation measurements downward axially.

In all these measurements using PDPA, the limiting factor continues to be the film length and primary breakup [Araneo et al. (2006), Kohnen et al (2010)] in the radial direction. When the droplets emanate out of the liquid film and primary breakup zones, reliable measurements can be made. Far away from the axis in the radial direction, the droplets begin to coalesce at a faster rate causing PDPA to have a higher probability of capturing two droplets merging into one, skewing the data slightly on the higher side similar to locations close to the nozzle. This was noticed in all tested locations, nozzles, and injection pressures.

2.3.3: Shadowgraph Results

Unlike PIV and PDPA which utilize scattering or detecting frequency shifts through Doppler burst for measurements, the Shadowgraph technique depends on an observational approach for measurements. Thus, the Shadowgraph technique has fewer limitations arising from complex spray dynamics behavior which restricted the use of PIV and PDPA in a concentrated zone. The only limitation present for Shadowgraph is due to the effects of film length and the ability to accurately capture the droplet shape (Figure 12a). Owing to a high spatial resolution and small
depth of field achieved through a zoom lens, both velocity and diameter measurements are possible throughout the centerline for all injection pressures and nozzles studied. The lens with high optical zoom and small depth of field allows droplets in the zone of interest to be easily distinguished, facilitating better edge detection methods as explained in the previous section. Three sets of shadowgraph images are provided in Figure 17 at injection pressures of 0.5 MPa ($\text{Re}_p = 9,500$), 1 MPa ($\text{Re}_p = 15,000$) and 1.5 MPa ($\text{Re}_p = 18,000$) both at the secondary breakup regime ($Z = 1.3 \text{ mm and 2.6 mm}$) and at 25mm where for some conditions, the images clearly show coalescence beginning to take place for nozzle N1. Details of coalescence physics can be found in the later chapter. By selecting an optimum threshold gradient for the edge detection method, the uncertainty for the diameter measurements and velocity could be restricted to $2\mu$m and 0.5m/s respectively as previously stated.

![Figure 17: Shadowgraph images at different injection pressures and axial locations for nozzles N1](image)

Shadowgraph measurements for both the velocity and diameter compare well with the other measurement techniques (Figure 12b & 12c). The difference in the velocity points near the nozzle can be attributed to the presence of droplets with an aspect ratio less than unity in the
beginning stages of secondary breakup regime. These droplets which are more ellipsoidal in the vertical direction will have a slightly longer duration within the PDPA measurement volume thus causing the velocity to be lower than droplets with aspect ratios greater than unity. On the other hand, Shadowgraph only looks at the center of each droplet and tracks this location from two consecutive images. This may have reduced the average velocity measured by PDPA. Far downstream of the nozzle, good agreement of velocity measurements by the three techniques is seen. Shadowgraph diameter measurements fall within the uncertainty range of all techniques, and therefore, it compares well with PDPA measurements. Although there is a small deviation from the three techniques, they all show very similar trends in the axial direction. This indicates that the Shadowgraph is a measurement technique which can be used at any spray regime with acceptable uncertainties as illustrated in Figure 14. The only region of interest is near the periphery where the angles at which the droplets approach the measurement zone is widely different. This increases the risk of inaccurately capturing the correct shadow which would alter the diameter and velocity calculations. These measurements are accurate when threshold values (at $\Delta P = 1\text{MPa}$ [$\text{Re}_p = 15,000$], it was found that 0.3 and 0.45 was ideal for lower and upper thresholds) are chosen carefully to calculate the diameter and velocity values.

2.3.4: Instrument Limitations

As previously stated Figure 13a represents the actual flow emanating from the nozzle with different zones where a certain instrumentation technique could be used with the highest accuracy. In Figure 13b, the actual measurement types in each zone for different pressures are
indicated. The flow map only represents axial locations because radial measurements are possible with all measurement techniques taking the precautionary measures as described previously. For all zones and injection pressures, Shadowgraph is capable of making accurate measurements for each breakup zone with the film length and primary breakup being the only limitation. However for PDPA, the values obtained at axial locations very close to the nozzle can be skewed by the initial stages of secondary breakup zones due to the irregular shape of the droplets. As shown in Figure 13, as the pressure increases, the valid measurement zone with high spherical validation increases because the atomization regimes shift towards the nozzle. However, at a critical injection pressure, the high spherical measurement zone shifts downwards again due to the recirculation zone that was generated at these high injection pressures. PIV had the smallest valid measurement zone due to spray density and the droplet diameter.

In order to normalize the regime map, first the film length is measured using the Shadowgraph technique. Each image frame was inspected and the pixel length was measured. An average from 20 images is reported here with the standard deviation marked as the error bars. Figure 18a shows the film where the film length is indicated by the red line. The film length is the vertical distance from the nozzle tip where the liquid sheet begins to disintegrate into ligaments. Figure 18b shows the film length as a function of injection pressure which will be explained in more detail in a later chapter. The film length for the smaller nozzle N1 compares well with the literature [El Sayed et al (2011)]. El_Sayed et al. (2011) showed similar decay in film length with pressure utilizing a flat fan hydraulic nozzle. In the current work, the film length reaches an asymptotic value around $\Delta P \sim 1$MPa $(Re_p = 15,000)$ when the spray angle becomes constant, which will be shown in a later chapter. This indicates that the film length is also
directly dependent of the spray cone angle. The non-dimensional validation regime is shown as normalized axial length vs. Reynolds number in Figure 19.

Figure 18: Pressure effects on film length - a) High speed image of nozzle N1, b) Plot of the effects of pressure on the film length for nozzle N1

Figure 19: Acceptable measurement non-dimensional flow regime map (low val: low spherical validation)
2.4 Summary

The main objective of this section was to determine the acceptable sampling rate for each technique used and experimentally study the limitations of three laser-based non-intrusive measurement techniques, Shadowgraph, PIV (Particle Image Velocimetry), and PDPA (Phase Doppler Particle Anemometry) that will be utilized in this thesis, for two hydraulic injector nozzles with orifice diameter 0.3mm and 0.5mm induced by pressure-swirl. It was found that for a correct arithmetic average PIV would need ~100 image pairs, Shadowgraph ~200 image pairs, and PDPA ~2000 droplets but 10,000 was chosen for redundancy. To determine the limitations for the three techniques water was injected into the testing zone at injection pressures ranging from 0.3-4MPa, corresponding to Reynolds numbers of 7,000-26,000.

The cross-validation of the three techniques compared well with each other, but limitations were found. It was observed that both PDPA and Shadowgraph proved to capture accurate data within this range of study once beyond the film length. The only limitation which was observed between the two techniques was having low spherical validation. This only means that it took the measurement techniques longer to gather enough samples for a mean value to be statistical accurate. Although these measurements can be made in mostly all the specific regimes in the spray, caution should be taken in the beginning stages of secondary breakup regime due to the dependence on droplet aspect ratio for PDPA as it was seen to have slightly higher diameter measurements than Shadowgraph. Similar effects were seen with the larger nozzle N2 with the shaded regions shifting downwards due to the larger film zone. On the other hand, PIV was only valid in the later stages of secondary breakup and coalescence, where the droplet size and density
was less. For radial measurements, measurements with PIV, PDPA and Shadowgraph at all zones could be made with cautionary measures taken for each technique. Away from the axis near the periphery of the cone, obtaining accurate peak to peak cross-correlation with PIV was limited due to a higher probability of large diameter droplets and/or a high density of spray which tended to increase the uncertainty of the measurement technique.
CHAPTER THREE: EXPERIMENTAL RESULTS FOR DETERMINING SPRAY PROFILE FOR SIMPLEX NOZZLES:

3.1 Introduction

Atomization of a liquid film or ligament from an injector nozzle is critical for various industry applications such as power generation, food and pharmaceutical powder formation, spray painting, petroleum refining and thermal sprays. The two most common injector nozzles utilized in the industry are hydraulic and air-blast atomizers, both of which have completely different approaches to atomization. The hydrodynamic instabilities of liquid sheets, leading to breakup, are predominant in air-blast atomizers but also occur in hydraulic nozzles as well [Park et al (2009), Shi and Kleinstreuer (2007), Cavaliere (2003)]. The hydraulic nozzle primarily produces liquid atomization by forcing the liquid through a single narrow annulus under a pressure gradient; the pressure head is converted into kinetic energy [El-Sayed et al. (2011), Lefebvre (1989)]. On the other hand, an air-blast nozzle has two orifices that use preset air-liquid momentum ratio to induce atomization which occurs by exposing the thin liquid conical sheet to a high velocity airstream on both sides of the sheet [Lefebvre (1989)].

Most aero-engines and IC engines use liquid fuel and different atomization techniques to obtain a homogenous mixture at different equivalence ratios. However, depending on the design of the pre-vaporizers and combustors, different nozzles are used in the engines. This mixture quality not only determines the combustion performance and efficiency of the power generation unit, but also controls emissions. Unlike the air-blast atomizer, hydraulic nozzles are slightly more complex. A clear understanding of hydraulic nozzles is not available as many types of such
nozzles are used in the industry. Some of the more common types are plain orifice, pressure-swirl (Simplex nozzle), square spray, dual orifice and fan sprays. These nozzles generate either full or hollow cone sprays. The most common atomizer used in these combustion engines is the pressure-swirl nozzle (Simplex nozzle). Moreover, among different designs of pressure-swirl nozzles, hollow cone nozzles are preferred in combustion applications due to their uniform liquid distribution in the radial direction. This uniform liquid distribution helps to enhance and homogenize air-fuel mixture which improves the combustion performance and reduces emission of the engines. Recent studies consist of characterizing the spray from convergent diesel nozzles [Payri et al. (2008)], analyzing the breakup characteristics from splash plate nozzles [Ahmed et al. (2009)], and liquid property effects (e.g. in biofuels) on single and multi-orifice nozzles [Park et al. (2009)]. These experiments have looked into various operating conditions and physical properties to fully understand the atomization dynamics, using either Shadowgraph type technique or PDPA. The experimental studies performed with pressure-swirl nozzles have reported contradictory results over the last few years compared to the numerical models [Shi and Kleinstreuer (2007)]. Thus, the fundamentals of spray dynamics, such as spray formation, liquid breakup length, and droplet breakup regimes still need to be understood properly for a pressure-swirl nozzle. It is critical to understand and adequately predict these characteristics based on the operating conditions such as atomizing pressure, flow rate, and liquid properties such as viscosity, surface tension and density, and physical properties of the atomizers such as cone angle and nozzle geometry. For predictions to be accurate, experimental results need to be generated in order to validate the available physical models.
3.2 Experimental Setup

The schematic diagram of the experimental setup utilized in this chapter is shown in Figure 20. Similar to the previous chapter the liquid delivery system is the same as described above. The system utilizes an autoclave (injection pressures up to 7.5MPa), two test nozzles, and a three axis transverse system which precisely controlled the placement of the nozzle (25.4 µm increments) with respect to the diagnostic systems. This work utilizes only PDPA and high speed imagery techniques to quantify the velocity and diameter distributions throughout the spray, spray angle, and the instability characteristics. The PDPA setup uses a 632 nm He-Ne laser along with a photo-multiplier tube positioned at a receiving angle of 70°. The choice of the angle of collection is based on the Brewster effect on the surface of the liquid droplet for 1st order refraction angle. This technique was used in order to obtain the diameter and velocity distribution throughout the sprays trajectory. In order to obtain the high speed images necessary for proper analysis a Phantom V12.1 High Speed camera was utilized at 28,000 fps at a 320x248 resolution. To obtain the images properly a high powered single LED light source was used and positioned in the background, 180° from the camera. This ensured a sharp contrast between the liquid and the background for image post processing. To ensure proper analysis a calibration and background frame was captured for all test runs. By utilizing this technique the spray formation such as the cone angle and the instability analysis could be performed with reasonable accuracy.
This chapter will explore the various systematic parameters of two simplex nozzles and its effects on the spray formation of water. The results will be centered on the beginning stages of liquid emanating from the nozzle looking at how Reynolds number (injection pressure) and Weber number effect the spray cone angle, film length, the Kelvin-Helmholtz instabilities, and the droplet distribution throughout the cone. The injection pressures will range from 0.3 - 7MPa ($Re_p = 6,000 – 40,000$), depending on the type of analysis being conducted and will be specified in the following sections.
3.3 Results and Discussion

3.3.1: Hollow Cone Spray Dynamics: Measurements and Observations for Water

3.3.1.1: Nozzle Characterization

To determine the liquid spray profile that would be generated throughout the nozzle the spray cone angle was determined for both simplex nozzles. The spray cone angle was captured using the high speed images captured with a V12.1 Phantom camera. To obtain a correct statistical average a sample size of 100 images were considered. Once the images were captured the in-house algorithm developed in Matlab was used to determine the spray cone angle. The grey scale image was converted to a black and white image by generating the image matrix in binary form. To determine the acceptance criteria, the shadow intensity of the spray was controlled by the edge detection function “canny” within Matlab with the appropriate lower and upper bound threshold limits that would determine how dark the pixel needed to be for it to be counted as 1 on the image matrix. The process of transitioning the image to black and white is seen in Figure 21. Once the images were converted the edges were determined by the “regionprop” function in Matlab to form a trapezoid. From this trapezoid the cone angle could be extended upwards and using geometry the spray cone angle could be determined through a set of calculations built into the code.
These values were also compared with the calculated values from geometric considerations. By moving the PDPA measurement volume radially, the outside of the spray was located. This was done at two axial locations. Figure 22 shows a schematic of how the spray cone angle is calculated using geometric considerations (Fig 22a), and the data rate of PDPA (Fig 22b) which is used to calculate the spray angle.
Figure 22: Calculating spray angle using geometric considerations from PDPA data - a) Schematic of how values were obtained, b) PDPA data rate indicating edge of spray.

The edge of the spray is determined by the peak in the data rate near the nozzle due to the hollow cone swirl effect of the nozzle and at by the minimum value at far field locations. Figure 23 shows how the difference between the calculated spray angles compared with the two different techniques. The slight difference between the two techniques may be attributed to the swirl type nozzle which will cause the droplets to have high centrifugal acceleration, allowing the angle to be slightly larger when using the images from the high speed camera since the threshold values could be altered to eliminate this effect. However, the average value that was found using edge detection of the 100 images was still comparable to the calculated values from geometry and the detected edges using the data rate from PDPA.
Once the spray angle values were comparable the injection pressures was varied from 0.3 – 7MPa (Re_p = 6,000 – 71,000) for both nozzles. As shown in Figure 24 for nozzle N1, the spray angle monotonically increases from 30° at ΔP = 0.5 MPa (Re_p = 9,500) before reaching a constant value of 78° around ΔP ~1.4 MPa (~Re_p = 18,000). In nozzle N2, due to higher flow number which increases the Reynolds numbers (Figure 5) at the same pressures, cone angles are found to be high even for low injection pressures and reach an asymptote at ~100°. Both of the nozzles spray cone angle being to become constant around 2MPa.
Another important factor in characterizing the injector nozzles is the discharge coefficient that is associated to the two nozzles. Each of the injector nozzles is characterized to the industry as Flow Number (FN) 0.4 and 1.7. Although these numbers appear as constant non-dimensional numbers they have units (lbf/hr)/(psi)^0.5 as shown in Table 1 in the previous chapter. Thus to calculate the discharge coefficient for the nozzles equation 3.1 was utilized.

\[
C_d = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{theory}}}
\]  

(3.1)

\(\dot{m}_{\text{actual}}\) and \(\dot{m}_{\text{theory}}\) are the mass flow rates calculated by experimentation and mass flow rates calculated by theory which is based off of the flow number equation, Eqn. 3.2

\[
FN = \frac{\dot{m}}{\sqrt{\Delta P}}
\]  

(3.2)
where \( \dot{m} \) is the mass flow rate (lbm/hr) and \( \Delta P \) is the injection pressure (psi). To experimentally determine the discharge coefficient the nozzles were placed inside a beaker for a short period of time which allowed for the volumetric flow rate to be determined. From the volumetric flow rate the mass flow rate was calculated by multiplying the value by the water density. Figure 25 shows how the two nozzles compare at different injection pressures. It can be seen that both nozzles remain constant throughout all injection pressures (Reynolds numbers) tested with nozzle N1 having a discharge coefficient of \( C_d \sim 0.6 \) while nozzle N2 was \( C_d \sim 0.9 \).

Figure 25: Discharge Coefficient for nozzle N1 and N2
3.3.1.2: Axial Measurements

Even though the nozzles being studied are hollow cones, a significant number of drops are distributed throughout the core of the spray (due to the centrifugal force associated with the pressure swirl) that causes breakup and coalescence (to be discussed later). Thus axial measurements are still needed in order to understand the spray dynamics of these types of injector nozzles. First, results from PDPA are presented for 10,000 spherically validated samples.

Figure 26: Diameter measurements along the centerline using PDPA - a) Reynolds number effects for nozzle N1, b) Reynolds number effects for nozzle N2, c) Nozzle effects at $Re_p = 21,000$
The variation of Arithmetic Mean Diameter (AMD) along the centerline of the spray cone for different Reynolds numbers and injector nozzles is reported in Figure 26 respectively. For all Reynolds numbers (both nozzles), the droplet diameter decreases along the centerline initially and then increases away from the nozzle tip. Such a behavior of droplet diameter has also been reported by Kim et al. [2008]. However, the current measurements are reported for a larger range of axial distance from the nozzle exit than the ones previously reported. The trend suggests the presence of the first flow regime, namely droplet deformation and breakup, where the droplet diameter decreases, and the regime of coalescence, where droplet diameter increases with axial direction. This is also illustrated in Figure 27, where Shadowgraph images are acquired to illustrate the breakup regimes including the primary breakup regime (liquid sheet breakup).

Figure 27: Representative spray profile for nozzle N2 at $Re_p = 21,000$ indicating typical values of lengths for spray zones with dominant mechanism: Zone A: primary breakup; Zone B: Secondary breakup and centrifugal dispersion; Zone C: Coalescence.
The liquid discharges out of the spray nozzle in the form of films, which break up due to hydrodynamic instability in the form of ligaments (Figure 27). This regime is primarily characterized by formation of ligaments and larger droplets through primary breakup, which could not be explored due to PDPA system's limitation of achieving high spherical validation in the zone of liquid film. The larger droplets formed through primary breakup undergo cascading secondary atomization due to aerodynamic/shear instabilities generating smaller droplets (Figure 27). Thus, the droplet diameter in this zone decreases rapidly as we move away from the nozzle. In addition to secondary atomization, droplet coalescence also becomes important along the axis. During this process, smaller droplets collide, form larger droplets and lose their momentum due to drag. Thus, the droplet diameter starts increasing away from the nozzle. As the droplets become larger and slower, the probability of subsequent droplet-droplet collision increases, resulting in further coalescence. In addition to this, the centrifugal effect due to pressure swirls leads to carrying the heavier droplets towards the outer perimeter of the spray cone depleting larger droplets from the center. To understand these competing processes and to identify the transition points we explore the physics governing these mechanisms through various measurements in later sections.

The transition points from one regime to the other regime are observed to shift slightly towards the nozzle as Reynolds number increases (Figure 26a). With an increase in Reynolds number, the spray angle and mass flow rate increase while the penetration depth decreases. High Reynolds number leads to increase in drag force on the droplets which subsequently reduce the momentum causing a higher probability of coalescence, resulting in shorter primary and secondary breakup regimes.
At very high Reynolds numbers ($Re_p > 25,000$), one can observe deviation from this droplet diameter trend (Figure 26a) for nozzle N1. The spray induces a strong recirculation zone close to the nozzle exit. This results in a bimodal distribution of droplet velocities with peaks at ~10 m/s and ~45 m/s respectively (Figure 28).

Figure 28: Histogram plots at $Re_p = 26,000$ for nozzle N1 - a) 4 mm axial location, b) 10 mm axial location
The recirculation zone causes a higher probability of droplet coalescence at a relatively smaller distance from the nozzle (Figure 28a). This early coalescence is further corroborated by the increase in diameter as shown in Figure 26a. Beyond a certain distance from the nozzle tip, i.e., ~10mm, the recirculation becomes weak and the smaller droplet velocity peak disappears. Once the droplets leave the recirculation zone, they continue on the traditional breakup path resulting in a similar diameter trend as observed at lower pressures. This can be seen clearly in Figure 28b, where the droplet diameter exhibits a bimodal distribution with the second peak shifting to lower diameter values, indicating secondary breakup. It was also observed that the recirculation zone, where the droplet velocity is characterized by the bimodal distribution, becomes shorter as the Reynolds number is increased beyond $Re_p = 25,000$. In general, the droplet diameter is likely to display a similar profile when the cone angle reaches an asymptotic value at higher Reynolds number. However, the length of the recirculation zone near the nozzle exit alters with Reynolds number even beyond this point. For nearly the same Reynolds number, when the nozzle diameter was increased (Nozzle N2), the transition zone from secondary breakup to coalescence is seen to shift away from the nozzle exit compared to Nozzle N1 (Figure 26c). This indicates that this transition zone is also dependent on the nozzle geometry in addition to the Reynolds number. Though the trends are very different initially, both nozzles exhibit similar values of droplet diameter far downstream of the nozzle. The initial difference is associated with the droplet distribution at the nozzle exit where the larger nozzle N2 produces larger diameter droplets. This is due to the higher mass flux, which in turn, produces a thicker liquid film that subsequently results in larger ligaments which finally shear off to form larger droplets compared to Nozzle N1. However, further downstream, the droplet diameters for both
nozzles approach similar diameter values. This similarity is characterized from the swirl aspect of these nozzles. For the larger nozzle (N2) the spray cone angle is larger, thus the majority of the droplets are swept to the periphery during the initial stages of breakup creating a sparsely populated core. Therefore at downstream locations, the droplets exhibit a lower probability of coalescence particularly at the center. This can be seen in Figure 26b where the increasing diameter slope in the coalescence regime is much less for nozzle N2 compared to nozzle N1. Details of the theory and mechanisms of droplet breakup and coalescence can be found later in the thesis (Chapters 4 & 5).

Figure 29 shows the effects of Reynolds number and nozzle diameter on droplet velocity along the centerline. The results show that the droplet velocity decreases rapidly within the first 25.4 mm from the tip of the nozzle and then decreases at a slower rate until it reaches ~5 m/s for both nozzles and Reynolds numbers. These results are in good agreement with the literature [Shi and Kleinstreuer (2007)]. This can be observed for both nozzles and all Reynolds number. It is important to note that as the Reynolds number increases, the slope of the velocity within the first 25.4 mm becomes steeper due to the larger drag force (larger back pressure). The sharp drop seen for Reₚ = 26,000 is associated with the bimodal distribution which dramatically lowers the average velocity of the droplets. For larger nozzle (N2), at locations close to the nozzle, the velocity values are much smaller compared to the smaller nozzle (N1) due to higher initial momentum flux.
Figure 29: Velocity measurements along the centerline - a) Reynolds number effects for nozzle N1, b) Nozzles effects at $Re_p = 21,000$

3.3.1.3: Radial Measurements

As described in the experimental setup, for full characterization of the flow with the complex nature of hollow cone sprays, radial measurements were needed at various Reynolds numbers (injection pressures) and injector nozzles. Figure 30 (a)-(c) show the data rate, average diameter, and velocity as a function of radial location for nozzle (N1). Measurements were made at an axial location of 10mm from the nozzle and $Re_p = 9,500$ as shown in Figure 30(d).
It can be noticed that there exists a linear decay in data rate where the maximum occurs in the core and the minimum at the periphery. Data rate represents the population density of droplets. In a hollow cone spray, bulk of the droplets is supposed to remain in the outer regime of the spray cone. Thus, the trend is opposite to what is expected. At this particular Reynolds number, the spray cone angle is very small ($\theta = 25^\circ$). Low spray angle restricts the liquid film to spread in
radial direction. Moreover, the liquid film thickness being comparable to the radius of the nozzle, the film around the nozzle intersects across the diameter of the nozzle near the nozzle tip (or low axial distances). Thus, majority of the droplets will be entrapped in the core causing the date rate to be highest in the core and lowest at the edge. Due to this overlap, the diameter and velocity start out high in the core and reduces linearly radially outwards as observed in Figure 30. The swirling flow or the tangential component of the flow in a pressure-swirl nozzle helps to spread the droplets towards the outer periphery and larger droplets are more sensitive to this radial motion due to higher centrifugal force. As the swirling strength is weak for lower Reynolds numbers, the majority of the droplets are accumulated in the core. This also results in low probability of coalescence in the radial direction allowing the droplets to continue on the principal droplet breakup cycle. This can clearly be seen in Figure 31a where the diameter histogram clearly shows a shift in the peak location with change in radial location.

Figure 31: Radial histograms at Z = 10 mm, Reₚ = 9,500, nozzle N1, θ = 25° - a) Diameter, b) Velocity
In Figure 31b, we also observe the introduction of a second peak for the velocity histogram which also confirms breakup. Applying conservation of momentum during the droplet breakup process, it can be shown that the velocity of the daughter droplets is lower than the parent droplet thereby introducing the second peak in the velocity histogram (Figure 31b). The bimodal nature of the velocity histogram at the periphery of the spray is also reflected in the form of a lower mean ($V_{avg}$) and a higher standard deviation ($V_{std}$) as shown in Figure 30b.

Figure 32 shows the change in the data rate, velocity and diameter of the droplets for different radial locations at the axial location 63mm for nozzle (N1) and $Re_p = 9,500$. Although the liquid film at this particular location does not intersect, the droplet population still remains high at the center core of the spray. The droplets which were trapped at the core near the nozzle exit fails to reach the periphery even at higher axial distances due to weak swirl at low Reynolds number. Thus the data rate will still be high towards the center and low towards the periphery. However, far from the nozzle exit at 63mm, the diameter increases towards the periphery (Figure 32c) due to centrifugal effect and higher coalescence probability. As reported in the previous section droplets in the outer periphery experience a strong coalescence causing increase in diameter. This is also indicated by the decrease in standard deviation which shows a decreasing profile, implying collision of smaller droplets to form larger droplets resulting in a decrease in the half-width of the histogram. This is also evident in the velocity plot where the values decrease radially which is caused by newly formed droplets (due to collisions) which experience a higher drag force. Since the standard deviation for the velocity component is very similar throughout all radial locations, uniform droplet coalescence is to be expected.
Figure 32: Radial measurements at $Z = 63$ mm, $Re_p = 9,500$, nozzles N1, $\theta = 25^\circ$ - a) Data rate, b) Velocity profile, c) Diameter profile

Figure 33 displays the spray characteristics for the same nozzle (N1) at higher Reynolds number ($Re_p = 21,000$). For this Reynolds number, the spray angle is much wider ($\theta = 74^\circ$), therefore, the liquid film will not intersect near the nozzle exit. This causes the data rate, which also characterizes droplet density at different locations, to follow what is traditionally expected from a hollow cone nozzle. The larger spray angle causes the data rate to be lower at the core and larger towards the periphery. Figure 33a shows that the data rate increases radially reaching a maximum value at a radial location of 6mm. Beyond this radial distance, the data rate starts decreasing as the measurement point approaches the outer extreme of the spray. The location of this outer extreme where the data rate reduces to 1% of the maximum data rate is close to the estimated value based on the spray angle. The average velocity is seen to increase mildly before it starts decreasing with radial locations. With high data rate (or droplet population towards the outer radius), droplets are more prone to coalescence resulting in higher average droplet diameter (Figure 33c). Besides coalescence, the centrifugal action also helps the heavier droplets to move towards outer periphery. Larger droplets move slowly to maintain the same momentum, resulting in reduction in average velocity ($V_{avg}$) as shown in Figure 33b.
The data rate at a further downstream axial location of 63mm (Figure 34a) shows a similar increase in data rate with radial distance. However, once it reaches a maximum value at radial location 6mm, it reduces rather slowly compared to the axial distance, $Z = 10\text{mm}$. This indicates that as the spray moves axially downstream the thickness of the zone, where the majority of the droplets occur also increases. Thus a comparatively larger zone in the radial direction contains moderate to high data rate or droplet population. Stronger swirl or tangential velocity brings the droplets towards the periphery inducing coalescence. Coalescence in the outer radius along with the centrifugal effect increases the average droplet diameter while the axial velocity becomes lower (Figure 34b and 34c). This increase in diameter also helps explain why the data rate is much lower at the later axial location than at the first axial location. Since coalescence is occurring in this region of the spray the droplet count should be reducing.
To determine how nozzle N2 geometry effects the spray profile two Reynolds numbers was chosen, Re_p = 18,000 and Re_p = 35,000 (injection pressures ΔP = 0.5MPa and ΔP = 2MPa respectively). Since the office diameter is nearly twice the size as nozzle N1 the linear decay in the data rate at low Reynolds number is never seen and follows the tradition path of a hollow cone nozzle, Figure 35a and Figure 36a. Looking at both Reynolds number cases you can clearly see the similar profiles for both cases. The data rate for both show a parabolic trend where the maximum value is found towards the periphery of spray and closer towards the nozzle at axial location Z = 10 mm. This clearly indicates that majority of spray is being dispersed outwards due the swirl intensity of the larger nozzle. Due to the larger mass flow rate from the higher Reynolds number the data is much higher. For both cases the profiles for the diameter and velocity trends are very similar. As expected the diameter is seen to be linearly increasing throughout the radial locations with the lower Reynolds number having larger diameters throughout for axial location Z = 63 mm. This is associated to the particular axial location where the driven mechanism is coalescence, which will be further discussed in the later sections. This is verified by the decrease
in the average diameter, Figure 35c & 36c. The interesting thing to observe is that at axial location Z = 10 mm the diameter is increasing linearly at the beginning but towards the periphery tends to level out or even decrease some for both Reynolds number while the velocity is increasing, Figure 35b, 36b, 35c, 36c. This increase in the droplet diameter for this particular location can be attributed to the centrifugal dispersion associated with the swirl nozzles. The larger droplets will tend to be dispersed radially while the smaller droplets will stay towards the core. This will allow the average velocity to increase while the average diameter increases as well because the increase of average diameter is not associated to coalescence which would traditionally slow the droplets down due to conservation momentum. At the outer most location of the spray where measurements were gather it is interesting to see how the diameter is beginning to decrease. This suggests that the swirl force has dissipated, thus allowing the droplets to begin the traditional atomization process of breakup. Since these test cases were in the moderate Reynolds number locations the overall results show similar behavior that was observed from nozzle N1.

Figure 35: Radial measurements at Rep = 18,000, nozzles N2, θ = 82° - a) Data rate, b) Diameter profile, c) Velocity profile
To compare the effects of nozzle geometry the radial data measurements for the two nozzles at \( \text{Re}_p = 21,000 \) are compared in Figures 37 and 38. The spray angles at this \( \text{Re}_p \) for N1 and N2 are 70° and 82°. With these similar angles and \( \text{Re}_p \), the nozzle effects can be isolated. Figures 37 and 38 show the data rate, diameter and the velocity profiles for both nozzles N1 and N2 at axial locations of 10 mm and 63 mm respectively. At \( Z = 10 \text{ mm} \), the radial measurements spanned from the center to 4 mm for low \( \text{Re}_p \) and 8 mm for high \( \text{Re}_p \). At axial location of 63 mm, the radial span was 13 mm and 40 mm respectively at low and high Reynolds number. These values were scaled by dividing the local radial location (R) with the total radial span (\( R_F \)). The data rates for both nozzles at both locations are remarkably similar. The shift in the peak at both locations may be attributed to the slight difference in the flow angle. The diameter and velocity radial profiles at \( Z = 10 \text{ mm} \) for nozzle (N1) show larger average velocity and smaller diameter (Figure 37b and 37c), compared to nozzle (N2). When the data rate or droplet population is low, a decrease in the probability of coalescence is indicated, corresponding to a sharper increase in droplet diameter along the radial direction. The overall increase in droplet diameter for nozzle
(N2) is also associated with the larger mass flux which produces larger ligaments being sheared off at the early stages of breakup. With the diameter being larger for nozzle (N2), velocity is less, as expected. At $Z = 63$ mm the droplet diameter from the larger nozzle is slightly higher at this location, indicating the inception of droplet coalescence prior to this axial location (Figure 38b). No significant difference in the droplet velocity is observed between the nozzles at $Z = 63$ mm. Thus, for the same Reynolds number, the discharge coefficient or flow number also plays an important role in the breakup process.

Figure 37: Radial measurements comparison of nozzle N1 and N2 at $Z = 10$ mm, Rep = 21,000 - a) Data rate, b) Diameter profile, c) Velocity profile

Figure 38: Radial measurements comparison of nozzle N1 and N2 at $Z = 63$ mm, Rep = 21,000 - a) Data rate, b) Diameter profile, c) Velocity profile

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3.3.2: Instability Analysis for Water

In this section the instabilities of breakup will be observed for both simplex nozzles. This will look into the film length, maximum wave amplitude at the most unstable wave before it shears off, and the wave length which determines the type of instability present. All of which are important parameters when characterizing the flow from the simplex nozzles.

3.3.2.1: Film Length and Wave Amplitude

The first important parameter to look into when characterizing nozzles is the film length. This determines the length of when the liquid will start to shear off to begin the breakup process. The second important parameter is the maximum wave amplitude at the most unstable wave which begins the shearing of the liquid from the film. To determine the film length and the maximum wave amplitude the Phantom high speed camera was utilized. The camera was set to record 28,000 fps to accurately track the propagation of waves. Images were taken at injection pressures from 0.3 - 2MPa (Reₚ = 6,000 – 35,000 depending on the nozzle being used). Once the images were captured they were uploaded into the image processing software with a calibration file which correlated a pixel to length scale. To obtain an accurate statistical average 100 images were considered for both measurements. Figure 39 shows the film length and the maximum wave amplitude where the film length is indicated by the red line, Figure 39a. Maximum wave amplitude denotes the radial distance from the centerline of the spray to the peak of the wave just before the shearing of the liquid film, Figure 39b. The film length is the vertical distance from the nozzle tip where liquid sheet begins to disintegrate into ligaments.
Looking at the results obtained for the two nozzles at the test cases it was found that the two parameters are correlated. Figure 40a and 40b show both the maximum wave amplitude and film length as a function of injection pressure. One can notice in Figure 40a that the trends for the maximum wave amplitude are opposite for two nozzles. This opposite trend shows that the instabilities that cause breakup in the nozzles are of different types. At low pressure, the instabilities in the liquid film for the small nozzle N1 converge into a sharp point with small amplitudes and long wavelengths that induce breakup. With an increase in pressure, the flow angle sharply increases resulting in outward flow expansion and the instabilities become shorter in wavelengths and larger in amplitude. Thus, the wave amplitude reduces with increase in pressure until it attains a constant value at around 1.2 MPa. On the other hand, the flow for the nozzle N2 expands outwards with shorter wavelengths and larger amplitudes. The cone angle does not increase significantly with the pressure for this nozzle. Nozzle N2 experiences this type
of instability breakup for the majority of cases. However, it can be noted that at a certain pressure for both nozzles, the maximum wave amplitude becomes constant which directly corresponds to when the spray angle becomes constant due to the aforementioned reason.

![Figure 40: Pressure effects on wave amplitude and film length – a) Plot of the effects of pressure on the maximum wave amplitude, b) Plot of the effects of pressure on the film length](image)

When the maximum wave amplitude is non-dimensionalized with the nozzle diameter the same trends are seen at low injection pressures but once the wave amplitudes become constant they merge into one location, Figure 41a. This difference at low injection pressures is due to the two types of wavelengths experienced for the different nozzles because of the dramatic difference in spray angle. The larger spray angle causes the wave amplitudes to be much bigger than the smaller cone angle. From Figure 40b, one can see that both nozzles follow the same trend for
change in the liquid film length with pressure. The film length for nozzle N1 is smaller than nozzle N2 which directly corresponds to the lower mass flow rate, which represents lower liquid momentum. This trend correlates well with the literature [El-Sayed et al. (2011)]. The film lengths reach an asymptotic value around 2MPa which directly correlates to when the spray angle becomes constant. This indicates that the film length is also directly dependent of the spray cone angle. With the same scaling approach that was done for the maximum wave amplitude the opposite is seen. At the low injection pressures both nozzles produce similar results but once the dimensional film length becomes constant a difference is seen between the two nozzles on the non-dimensional scale where nozzle N2 is larger, Figure 41b. This is due to the difference in the mass flux which is much higher for nozzle N2. This higher mass flux causes the liquid film to be thicker and move at a faster rate. This allows the wave propagation to move further way from the nozzle before reaching the critical value.

Figure 41: Pressure effects on non-dimensionalized wave amplitude and film length – a) Plot of the effects of pressure on the maximum wave amplitude, b) Plot of the effects of pressure on the film length
Figure 42 showcases the above results as a function of Reynolds number. Similarly to the previous figures the trends for the maximum wave amplitude show two different trends with nozzle N1 increasing until an asymptotic value and nozzle N2 decreasing to an asymptotic value. As for the film length the values are very similar with the trends being nearly identical with nozzle N2 having higher overall values. An important thing to notice is the clear offset between the two nozzles. When the data is plotted versus Reynolds number the offsets are seen both in the y-axis and x-axis even for the non-dimensional plots, Figure 42b & 42d. If these plots were truly non-dimensional then very little shift should be seen in the y-axis for the two nozzles they should match reasonable well, but since this is not the case utilizing the orifice diameter for the two nozzles is not sufficient when looking at the effects of Reynolds number on the two measured parameters. Thus, when plotting against the Reynolds number a different scaling factor is needed.
Figure 42: Reynolds number effects on wave amplitude and film length – a) Reynolds number vs. wave amplitude, b) Reynolds number vs. Non-dimensional wave amplitude, c) Reynolds number vs. film length, d) Reynolds number vs. Non-dimensional film length

To properly understand the true effects of Reynolds number a new non-dimensional value was obtained. To determine the new wave amplitude scaling factor the spray angle and film length was considered since these are the driving mechanisms in the wave amplitude. Using the equation 3.3 a new non-dimensional scale could be found for both nozzles.
\[ \bar{Y} = \frac{\text{wave Amplitude}}{\frac{\text{Film length}}{\tan(\theta/2)}} \]  

(3.3)

Where \( \theta \) and \( \bar{Y} \) is the cone angle and the new non-dimensional wave amplitude value respectively. By using this new scaling factor the values that are obtained for both nozzles match reasonably well as a function of Reynolds number. Figure 43a shows how the maximum wave amplitude increases steady as Reynolds number increase then reaching an asymptotic value around 21,000. At which point you see a slight decrease in the trend at the later Reynolds numbers but rise again like a sinusoidal wave. This is caused by the uncertainty in the data which was shown in the spray angle for this particular Nozzle. Due to the intense swirling of the nozzle the exact location of the spray becomes difficult to accurately determine at higher Reynolds numbers. Since the film length is mainly a function of the mass flow rate and orifice diameter these two parameters were considered. By incorporating the previous non-dimensional scaling factor which divide the film length by the orifice diameter and then dividing it by the discharge coefficient a new scaling factor was determined. This eliminated the mass flow rate difference between the two nozzles. Figure 43b shows that the film length has a logarithmic decay as a function of Reynolds number. It can be seen that by using this new scaling factor the values for both nozzles seem to matching reasonably well especially at the overlapping Reynolds number cases.
3.3.2.2: Wavelength

The next important parameter that was analyzed was the wavelength at the onset of shearing from the liquid film. This parameter is critical in determine what kind of instabilities are present during the onset of breakup which is fundamentally important as this process controls the droplet diameter downstream of the nozzle. For comparison, the experimentally calculated results are compared to the theory in the literature. Senecal et al (1999) modeled break up of two-dimensional liquid films. They showed that based on the Weber number (We), the linear instability in liquid films can be categorized into long wavelength and short wavelength with a critical Weber number ($W_{ec}$) of 27/16. The long wavelength instability occurs for $We<W_{ec}$ and the short wavelength occurs for $We>W_{ec}$. Here, the Weber number is defined as followed:

$$ We = \frac{\rho_e U_i^2 t}{\sigma} $$

(3.4)
where \( \rho_g \) is gas phase density, \( U_l \) is liquid film velocity, \( t \) is half of film thickness (\( t = h/2 \), \( h \): film thickness) and \( \sigma \) is the surface tension of the liquid. Although this analysis has been done for 2D liquid films in general, it was extended for a hollow cone liquid film, which can be simplified as a two-dimensional film. At the nozzle exit, the liquid film forms a rim-like structure, which can be unwrapped to form a two-dimensional sheet [Schmidt et al. (1999)], as seen in Figure 44.

![Figure 44: Schematic of how the hollow cone liquid film can be simplified as a 2-D film](image)

In the current experiment, the velocity of the liquid film is given by equation (3.5).

\[
U_l = k \ast U_{\text{scale}}
\]

(3.5)

where \( U_{\text{scale}} \) is the velocity scale defined earlier and \( k \) is a multiplying factor. Actual definition of \( 'k' \), a scale for estimating the liquid film velocity, was given by Lefebvre (1989), which depends on nozzle design and injection pressure. However, later Senecal et al. (1999) and Schmidt et al.
(1999) found that Lefebvre’s correlation led to unphysical values, such as velocity coefficient being greater than 1. They further argued that one could consider the swirl ports to be nozzles, and equation 3.6

\[ U_{Scale} = k \sqrt{\frac{2\Delta P}{\rho}} \]  

represented an expression for the coefficient of discharge for the swirl-ports with the assumption that the majority of the pressure drop occurred across the injector ports. The discharge coefficient \((C_d)\) for single phase nozzles with sharp inlet corners and an L/D of 4 is typically 0.78 or less as reported by Lichtarowicz et al. (1965) and under cavitation it can be as low as 0.61. Hence, 0.78 should be a practical upper bound for \(k\). Considering 10% loss in discharge coefficient due to other momentum losses across the injector, Senecal et al (1999) arrived at the value 0.7 as the upper limit, the same value used in this study. Furthermore, there are some physical considerations which limit the value of \(k\). It can never be more than 1 (value less than unity) following energy conservation, it must allow sufficient mass flow with non-negative air-core thickness. To satisfy all these conditions, Senecal et al (1999) and Schmidt et al (1999) applied the following condition:

\[ k = \max[0.7, \frac{4\dot{m}}{\pi d^2 \rho \cos(\theta)} \sqrt{\frac{\rho}{2\Delta P}}] \]  

(3.7)

where \(\dot{m}\) is mass flow rate and \(\theta\) is half cone angle. In our experiments, we found this value to be always 0.7. As the length of this film zone is of the order of a few millimeters, one can assume that the bulk velocity of the liquid film remains constant and takes on a value of the
velocity scale, $U_1$. From the mass flow rate of the nozzle, one can estimate the liquid film thickness at the nozzle tip from the following equation [Sivakumar and Kulkarni (2011)]:

$$h = 3.66\left(\frac{m\mu l}{\Delta P \rho l}\right)^{0.25}$$

(3.8)

where, $\rho_l$ is liquid density, $\mu_l$ is liquid viscosity, $h(=2t)$ is film thickness, $\Delta P$ is injection pressure and $D$ is nozzle orifice diameter. According to the film breakup theory, the instability grows very rapidly in a sinusoidal manner. The wave number of this instability can be expressed as,

$$K_s = \left\{ \begin{array}{ll}
\frac{We}{2} & \text{(for Long wavelength)} \\
\frac{2We}{3} & \text{(for Short wavelength)}
\end{array} \right. $$

(3.9)

Using the relation between wavelength and wave number ($K_s=2\pi/\lambda$) one can write:

$$\frac{\lambda}{h} = \left\{ \begin{array}{ll}
\frac{2\pi}{We} & \text{(for Long wavelength)} \\
\frac{3\pi}{2We} & \text{(for Short wavelength)}
\end{array} \right. $$

(3.10)

To determine the most unstable wavelength experimentally, the high speed camera was used at 30,000 fps. As shown in Figure 45, pixel lengths were measured for each frame to obtain the wavelength for different Reynolds numbers (injection pressures) for each nozzle. The most unstable wavelength ($\lambda$) denotes the distance from the peak of one wave to another wave just before the breakup of the liquid film (Figure 45). Typically, wavelengths were obtained by averaging 100 images as shown in Figure 45, where the standard deviations are used as the
uncertainty. From Figure 45b, one can notice that the trends for the maximum wavelength are not significantly different for the two nozzles.

Figure 45: Change in most unstable wavelength with Reynolds number - a) Representative picture of the spray profile for nozzle N2 at Rep = 18,000. b) Wavelength profile

At low Reynolds numbers, the instabilities in the liquid film small nozzle N1 converge into a sharp point with small amplitudes and long wavelengths that trigger breakup, Figure 46a. With increase in Reynolds number, the flow angle sharply increases, resulting in outward flow expansion and the instabilities become shorter in wavelengths and larger in amplitude, Figure 46b. Thus, the maximum wavelength reduces with increase in Reynolds number. On the other hand, the flow for nozzle N2 expands outwards for the entire range of Reynolds numbers tested but still a shift between long wavelengths and small amplitudes to short wavelengths and larger amplitudes can be seen, Figure 46. The cone angle does not increase significantly with the Reynolds number for this nozzle. Nozzle N2 experiences this short wavelength type of instability
breakup for the majority of Reynolds number tested. Even though the operating pressure range is almost the same for both the nozzles, the maximum wavelength does not match. This is associated with the relation between the film thickness and Weber number as seen in Equation 3.10.

![Transition from long to short wavelength](image)

**Figure 46: Pictures from nozzle N2 representing the shift from long to short wavelength instability**

If we calculate or estimate the film thickness (h) of the nozzles at different pressures using Equation 3.8 and use it to non-dimensionalize the most unstable wavelength, it follows the theoretical plot closely as shown in Figure 47. Considering the critical Weber number, We_c=27/16, the figure demarcates two zones (based on Weber numbers) where long and short wavelength breakups dominate. The figure also shows the theoretical λ/h for long and short wavelengths (Equation 3.10) as shown with red and blue lines respectively. The experimental
data seem to follow the theoretical profile closely. Variations can be attributed to the measurement uncertainty and small oscillations in operating pressure during the experiments.

![Figure 47: Comparison of most unstable wavelengths from breakup models with experimental results](image)

3.4 Summary

The flow characteristics of two hydraulic injector nozzles were studied experimentally as a function of Reynolds number (injection pressures) both axial and radially. Liquid was injected into the testing zone at 0.3MPa to 7MPa (Reₚ = 6,000 – 65,000) depending on the parameter being consider. The experimental study consisted of using PDPA and high speed imaging to understand the flow characteristics of the two simplex nozzles.
This chapter was broken down into two subsections hollow cone spray dynamics and instability analysis of water. In the first section it was found that both the spray cone angle and the discharge coefficient are highly dependent on the nozzle geometry. The spray cone angle varied from 25° to 78° and from 82° to 105° for nozzles N1 and N2 respectively. Both nozzles reached an asymptotic value around 2MPa. These values compared reasonably to the calculated values obtained from PDPA. Nozzle N2 also had a much higher discharge coefficient 0.9 compared to 0.6 for nozzle N1. It was observed that the velocity and average diameter profiles are highly dependent on the Reynolds number and the nozzle. In the axial direction, the average diameter decreased clearly illustrating different breakup regimes. Reynolds number shifts the transition from one regime to another closer to the nozzle tip with a diameter decrement along the centerline. Nozzle N2 generated larger diameters. The velocity has a constant decreasing slope for the first 25.4 mm of the spray trajectory at which point the slopes decreased and becomes uniform towards the end. For lower Reynolds number and lower discharge coefficient in the radial direction, the data rate, velocity, and average diameter decreased linearly due to the film lengths intersecting at axial location 10 mm. This behavior caused a shift in diameter profile due to increased probability of coalescence. Likewise, for higher Reynolds numbers and lower discharge coefficient, the spray resembled a more traditional hollow cone where the peak data rate occurs in the middle of the spray. At these conditions, it was also shown that the velocity transformed from a parabolic profile to a logarithmic decay at different axial locations due to coalescence. This was also reflected in the average droplet diameter which increased for most cases.
In the second section a detailed instability analysis was conducted for both nozzles. It was observed that the two nozzles experienced two different types of wavelength profiles which are dependent on Reynolds number. Two types of wave breakup were observed, short and long wavelengths and matched well with the theory in the literature. Nozzle N1 experienced long wavelength breakup for the majority of the cases while nozzle N2 experienced short wavelength breakup for the majority of the cases. This was also shown when looking at the max wave amplitude at the breakup point where opposite trends were observed at low injection pressures. It was found that the film length was both a function of injection pressure and nozzle characteristics. Both nozzles producing similar logarithmic decaying trends for the film length with nozzle N2 having higher overall values compared to nozzle N1.
CHAPTER FOUR: INVESTIGATION ON BREAKUP CHARACTERISTICS OF SIMPLEX NOZZLES

4.1 Introduction

In spray nozzles, liquid comes out in the form of a liquid sheet or film. This film goes through different aerodynamic instabilities to disintegrate into ligaments and eventually droplets. In a pressure-swirl nozzle, with increase in pressure, the spray profile changes and it is observed that before the spray becomes fully developed, the liquid must pass through four stages of spray development; dribble stage, distorted pencil stage, onion stage, and Tulip stage [Lefebvre (1989)] where the last three stages are usually dominated by long wavelength film breakup. Once the spray becomes fully developed, short wavelength film breakup becomes dominant. This was shown analytically [Senecal et al. (1999) and Schmidt et al. (1999)] using a linear instability analysis which allowed the prediction of film length based on Weber number which correlated to a certain type of wavelength breakup, as seen in the previous section. Once the Kelvin-Helmholtz instabilities and wave propagation attain the maximum growth, the liquid sheet will shear off to produce liquid ligaments beginning the onset of the breakup process.

The atomization process can be described as the mechanism to increase surface to mass ratio in the liquid phase in order to enhance the vaporization rate and drag force [Mansour and Chigier (1991)]. The breakup process itself consists of two steps: primary and secondary breakups. The primary atomization process is generally controlled by initial disturbances in the liquid-gas interface and the mechanism that allows these disturbances to grow. Thus, during primary atomization, the liquid film emanating from the nozzle undergoes hydrodynamic instabilities and
relatively large drag forces that cause the formation of ligaments or other irregular liquid elements, followed by the formation of droplets. A secondary breakup regime follows, which is caused by the aerodynamic instabilities resulting in larger droplets deforming and breaking up into smaller daughter droplets [Shi and Kleinstreuer (2007), Faeth et al. (1995), Park et al. (2009)]. The dynamics of these breakup processes of the liquid film, which is schematically shown in Figure 48, occurs within a very small region next to the nozzle exit. This is fundamentally important as these processes control the droplet diameter downstream of the nozzle. In order to understand the breakup process for hydraulic nozzles and to establish models for droplet distributions for liquid jet nozzles, researchers have used various optical techniques such as PDPA and LDV to investigate the effects of various system parameters, i.e. viscosity, density, and surface tension on the distribution of droplet diameters and velocities [Park et al. (2009), Kim et al. (2008), Payri et al. (2008), Tratnig et al. (2009)].

![Figure 48: Different stages of liquid breakup and droplet formation](image_url)
Aliseda et al (2008) developed a model for a coaxial atomizer generally used in pharmaceutical industry to predict the diameter distribution for non-Newtonian liquids. Butler Ellis et al (1999) and Bolszo et al (2010) reported the effect of oil-water emulsion on atomization characteristics for pressure swirl nozzles. They identified conditions at which the emulsion becomes unstable and the droplets contain only a single liquid phase. For Newtonian liquids, it has been reported that system parameters, such as viscosity, density and nozzle diameter affects the spreading (cone) angle and breakup [Ahmed et al. (2009)]. Theoretical analysis on deformation and distortion due to several instabilities has been summarized by Reitz and Bracco (1982), Lin and Reitz (1998), Sirignano and Mehring (2000), Lasheras et al (1998), Lasheras and Hopfinger (2000), Senecal et al (1999), Domouchel and group (2001, 2005, 2008). Senecal et al. (1999) and Schmidt et al (1999) reported two distinct regimes of film atomization for cylindrical jet hydraulic nozzles; long and short wave induced film breakup similar to the findings by Sivakumar and Kulkarni (2011) who reported five regimes for air-blast nozzles. Senecal et al. (1999) also found that different types of film breakups are dependent on Weber number. Using high speed imaging, Wahono et al. (2008) qualitatively visualized the spray structure to understand the types of instabilities and ligament formations that are exhibited in hydraulic jet nozzles. No significant model development or validation was done with these experiments that correlated the effects of injection pressure on droplet profiles and breakup regimes in a pressure-swirl induced hydraulic nozzle.
4.2 Experimental Setup

The schematic diagram of the experimental setup utilized in this chapter is shown in Figure 49. As describe in the previous chapters the system uses an autoclave (injection pressures up to 7.5MPa), test nozzles, and a three axis transverse system which precisely controlled the placement of the nozzle (25.4 µm increments) with respect to the diagnostic systems. This work utilizes only PDPA and Shadowgraph techniques to quantify the velocity, droplet shapes and diameter distributions. The Shadowgraph technique used a 532nm (maximum energy 70 mJ per pulse) dual pulsed Nd-YAG laser (2 mm beam diameter) with a synchronized CCD camera (pixel resolution of 1376 x 1040). A 90° turning mirror and a circular diffuser (20°) were used to convert the 2 mm beam into a diffused mode to provide adequate backlighting for the spray. The camera along with a Navitar zoom lens was placed in front of the spray. The setup with the zoom lens allowed a viewing window of 0.9 mm x 0.9 mm with a depth of field of approximately 200 µm. For shadowgraph, the spatial resolution achieved through this camera-lens setup was around 1µm/pixel. The PDPA system consisted of a 632 nm He-Ne laser with three adjoining photomultiplier tube receiver set at the appropriate receiving angle of 70° based on the Brewster effect on the surface of the water droplet for first order refraction angle (Figure 49).
This chapter will explore the primary and secondary breakup regimes of the two simplex nozzles and validate the observation results obtained in the previous chapter of the breakup regimes. The results will be centered on the beginning stages of breakup from the nozzle looking at how Reynolds number (injection pressure) and Weber number affect the primary and secondary breakup zones throughout the cone. The injection pressures will range from 0.5 - 2 MPa ($Re_p = 9,500 – 21,000$), depending on the type of analysis being conducted and will be specified in the following sections.
4.3 Results and Discussion

All the results presented for axial and radial measurements for several Reynolds numbers indicate that droplet dynamics is affected by the simultaneous presence of primary and secondary breakup. The potency of these mechanisms varies in different zones of the spray, where the breakup is function of the Weber number, Reynolds number and nozzle geometry. In order to assimilate and reconcile the observations reported in the previous chapter under a consistent framework, each of the breakup mechanisms is analyzed in detail.

4.3.1: Breakup Dynamics – Primary and Secondary Atomization

In a hollow cone pressure swirl nozzle, droplet generation takes place through a series of primary and secondary breakup processes [Lefebvre (1989); Senecal (1999)] as explained previously. The pressure differential across the nozzle and the swirl inside the nozzle injects a liquid film through the orifice. The relative velocity between this liquid film and the ambient gas phase (air in current experiment) induces an instability which grows as the liquid film moves away from the nozzle, and eventually breaks up in the form of ligaments. These unstable ligaments, in general, go through further atomization, and generate droplets. These droplets, in most cases, exhibit secondary atomization generating smaller daughter droplets due to aerodynamic breakup as discussed briefly in the previous sections.

Once the liquid film disintegrates, it forms ligaments. Theoretically, it is assumed that for short wavelength, one ligament forms per wavelength of the liquid film, and that for long
wavelength, two ligaments form per wavelength. From simple mass balance, one can find the
diameter of these ligaments for both types of instabilities:

\[
\begin{align*}
  d_L &= \sqrt{8 \frac{t}{K_s}} \quad \text{(for long wavelength)} \\
  d_L &= \sqrt{16 \frac{t}{K_s}} \quad \text{(for short wavelength)}
\end{align*}
\]

(4.1)

Where \( t \) is half film thickness and \( K_s \) is the most unstable wave number. Using Equation 3.10
along with the relations, \( h=2t \) and \( K_s=2\pi/\lambda \), Equation 4.1 can be rewritten as,

\[
\begin{align*}
  d_L &= \sqrt{4 \frac{h^2}{We}} \quad \text{(for long wavelength)} \\
  d_L &= \sqrt{6 \frac{h^2}{We}} \quad \text{(for short wavelength)}
\end{align*}
\]

(4.2)

The non-dimensional ligament diameters of both the nozzles are shown in Figure 50a as a
function of Weber number. Note that as the non-dimensional ligament diameter \( (d_L/h) \) is only a
function of \( We \), both nozzles follow a single characteristic curve. However, if the dimensional
ligament diameters \( (d_L) \) are plotted against \( We \), the two nozzles follow two distinct profiles as
shown in Figure 50b. The film thicknesses \( (h) \) for the same Weber number are different for two
nozzles resulting in two distinct curves for \( d_L \).
These cylindrical ligaments are not stable in nature. The surface tension force along with viscous dissipation introduces shape oscillation, and the ligament eventually breaks up into small droplets. Rayleigh (1879) introduced the theory of this type of instability and Dombrowski and Johns (1963) showed that most instability in ligaments leads to the results observed by Weber (1931) using capillary instability analysis. A simple model for this instability considers breakup of a cylindrical liquid column (ligament) and the resultant droplet diameter can be estimated by [Weber, (1931)]:

$$d_D = 1.88d_L(1 + 3Oh)^{1.6}$$  \hfill (4.3)

The Ohnesorgre number, Oh is defined as:

$$Oh = \frac{\mu_l}{(\rho_l\sigma d_L)^{0.5}}$$  \hfill (4.4)
where $\mu_l$, $\sigma_l$, $\rho_l$ are liquid viscosity, surface tension and density while $d_L$ is the diameter of the ligament. Figure 50b shows the droplet diameter $d_D$ for different Weber numbers for both nozzles. From Equation 4.3 it is noted that $d_D/d_L$ is always greater than 1, also seen in Figure 50b.

The initial decrease in the average droplet diameter along the $Z$ axis (Figure 26) can be now be explained by secondary breakup of droplets and dispersion of the droplets through centrifugal effect in the spray cone due to pressure swirl. The primary breakup of the liquid sheet explained in the previous paragraphs is strong only at axial distances close to nozzle. The secondary breakup, on the other hand, mainly occurs due to strong aerodynamic force arising from the relative velocity between the droplets and ambient air. This secondary breakup primarily depends on the diameter based Weber number ($We_D$) and Ohnesorge number ($Oh_D$).

$$We_D = \frac{\rho_l u_l^2 d_D}{\sigma}$$  \hspace{1cm} (4.5) \hspace{1cm} \text{(4.5)}$$

$$Oh_D = \frac{\mu_l}{(\rho_l \sigma d_D)^{0.5}}$$  \hspace{1cm} (4.6) \hspace{1cm} \text{(4.6)}$$

The secondary atomization can consist of several types of breakup [Guildenbecher et al. (2009), O’Rourke and Amsden (1987)] as shown in Table 3.
Table 3: Types of secondary breakup

<table>
<thead>
<tr>
<th>Types of Breakup</th>
<th>Range of $\text{We_D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrational deformation of the droplet and breakup</td>
<td>($\text{We_D} &lt; 11$ for $\text{Oh_D} &lt; 0.1$)</td>
</tr>
<tr>
<td>Bag breakup which causes the large droplet first to deform into a thin disk normal to the flow direction and then balloons out leading to disintegration</td>
<td>($11 &lt; \text{We_D} &lt; 35$ for $\text{Oh_D} &lt; 0.1$)</td>
</tr>
<tr>
<td>Multimode breakup which is a combination of both bag type and sheet thinning breakups</td>
<td>($35 &lt; \text{We_D} &lt; 80$ for $\text{Oh_D} &lt; 0.1$)</td>
</tr>
<tr>
<td>Sheet thinning breakup which causes the droplet to deflect at the periphery of the droplet disk instead of the center like bag breakup</td>
<td>($80 &lt; \text{We_D} &lt; 350$ for $\text{Oh_D} &lt; 0.1$)</td>
</tr>
<tr>
<td>Catastrophic breakup which is similar to stripping breakup but more explosive in nature</td>
<td>($\text{We_D} &gt; 350$ for $\text{Oh_D} &lt; 0.1$)</td>
</tr>
</tbody>
</table>

The secondary breakup process is cascading in nature and will continue until the Weber number of the final stable daughter droplets falls below a critical value. At this point, the breakup process terminates and the process of droplet coalescence starts dominating. In the current experiments, $\text{We_D}$ is found to be mostly less than 11 when $\text{Oh_D}$ is on the order of $10^{-3}$. This suggests the droplets generated from ligaments should first go through vibrational shape oscillation and eventual breakup. Although with increase in Weber number, the breakup is more likely to occur, there is no criterion for quantifying this probability. This type of breakup can be observed in Figure 51 where shadowgraph images of breakup are clearly seen at different Reynolds numbers. It is observed that for this particular location $Z = 1.3\text{mm}$ vibrational type breakup is present thus all other locations present this type of breakup until coalescence begins to dominate since the velocity scale will only decrease at axial locations further away from the nozzle. All testing conditions did not achieve the next type of breakup (bag) but from the images...
in Figure 51 a clear transition can be seen as the vibrational mode is slowly shifting to a more explosive type of breakup.

Figure 51: Shadowgraph images showing the progression of vibrational type breakup

Hsiang and Faeth (1992) showed that for $\text{Oh}_D<0.1$ the non-dimensional breakup time is written as

$$\frac{t_b}{t^*} = C$$ \hspace{1cm} (4.7)

where $C$ is a constant and approximated as 5.0 based on several experiments with multitude of liquids. Here, the time scale is calculated by,

$$t^* = \frac{d_0 \sqrt{\left(\rho_l/\rho_g\right)}}{U_0}$$ \hspace{1cm} (4.8)

where $d_0$ is the initial droplet diameter before breakup, $\rho_l$ and $\rho_g$ are density of the liquid and gas phase and $U_0$ is the droplet velocity. It may be concluded that larger breakup time, $t_b$, signifies
lower probability of breakup. If we calculate the probability density functions (PDF) for the \( \text{We}_D \) and \( \tau_b \) for the droplets at different axial locations along the center line of the spray (Figure 52 and 53), we can gain some useful information that helps us understand the droplet diameter profile.

Figure 52: PDF of \( \text{We}_D \) at different axial locations along the center line of the spray (Nozzle N1) at different Reynolds number - a) \( \text{Re}_p = 10,500 \), b) \( \text{Re}_p = 21,000 \), c) \( \text{Re}_p = 26,000 \)
Figure 53: PDF for the breakup time, $t_b$ for the droplets at different axial locations along the center line of the spray (Nozzle N1) at different Reynolds numbers - a) $Re_p = 10,500$, b) $Re_p = 21,000$, c) $Re_p = 26,000$

The PDFs of $We_D$ (Figure 52) at different Reynolds number ($Re_p$) for nozzle N1 reveal that most of the droplets have $We_D < 0.1$, however, there is a small percentage of droplets at lower $Z$ locations with $We_D \sim 1$ representing a population which are more prone to breakup. We also notice that the probability of droplets with lower Weber number increases at higher $Z$ locations, depicting lower probability of breakup (Figure 52). Comparing the breakup time, $t_b$, at any Reynolds number, PDF is seen to shift towards higher values with increase in $Z$ (Figure 53) showing retardation in breakup process at higher axial distances. The maximum $We_D$ shows a steady declining trend (Figure 54a) with the $Z$ location, indicating that the breakup intensity will become weaker with the distance from the nozzle. The maximum Weber number of 4 close to
the nozzle exit indicates that secondary breakup is potent in locations immediately downstream of the primary breakup zone. Nozzles N1 and N2 show similar decay rates in terms of maximum Weber number (Figure 54b). Nozzle N1 shows a slightly higher maximum Weber number very close to the nozzle exit compared to N2 nozzle.

If we consider the atomization of the droplets generated by primary breakup, we can estimate the droplet diameters from successive breakups. The secondary breakup process has been experimentally and numerically studied in detail. As mentioned earlier in our experiments the dominant mode of secondary breakup is vibrational deformation/breakup due to aerodynamic forces and thus, droplets generated from ligaments should first go through vibrational shape oscillation and eventual breakup. Among different models of this breakup, Taylor Analogy Breakup Model (TAB) which is briefly shown below and in the appendix is the most accepted one [O’Rourke and Amsden (1987)]. A simple spring-damped mass analysis show that the vibrational mode of breakup would result in daughter droplet sizes.
The daughter droplet size can be estimated using energy conservation between the parent and the daughter droplets. This analysis assumes distortion and oscillation in the parent droplet while the daughter droplets exhibit no such characteristics [O’Rourke and Amsden (1987)]:

\[ d_{32} = \frac{d_D}{1 + \frac{8K\gamma^2}{20} + \frac{\rho(d_D/2)^3(d_c/dc)^2}{\sigma} \left(\frac{6K-5}{120}\right)} \] (4.9)

where \( K \) is a factor (of order 10/3) that describes the ratio between energy due to distortion and energy contained in the fundamental mode of the parent droplet [O’Rourke and Amsden (1987)], \( \gamma \) is non-dimensional deformation of the droplet radius and \( d_{32} \) is the Sauter mean diameter of the daughter droplet distribution [O’Rourke and Amsden (1987)]. In the TAB model, the droplet deformation is measured by \( x \), which is the change in horizontal radius of the droplet from its undisturbed radius. \( \gamma = x/(r.C_r) \), where \( r.C_r \) represents the critical value of the \( x \), beyond which droplet deformation will result in breakup. Normally \( C_r = 0.5 \) under the assumption that maximum distortion allowed is equal to the droplet radius. A value of \( \gamma = 1 \) signifies that the droplet deformation is equal to the critical threshold needed for breakup.

Hsiang and Faeth (1992) and Guildenbecher et al (2009) showed that for this range of \( \text{We}_D \) and \( \text{Oh}_D \), the aspect ratio and droplet deformation linearly changes with time. For an order of magnitude calculation we neglect the 3rd term in the denominator, which is expected to be smaller than other two terms due to the presence of \( d_D^3 \). Here droplet diameter, \( d_D \), is in the order of microns. Thus, an order of magnitude analysis shows that Equation (4.9) can be written as.
\[ d_{32} = \frac{d_D}{1 + \frac{8K_2}{20} \gamma} \]  

(4.10)

With the assumptions that \( K \sim 10/3 \) [O’Rourke and Amsden (1987)] and \( \gamma = 1 \) for breakup to occur we deduce \( d_{32} \sim d_D/2.33 \). Figure 55 shows the calculated Sauter mean diameter of the daughter droplets after the first secondary breakup for both the nozzles. The plot also shows the Sauter mean diameter of first measurements after the film length (\( Z = 1.3 \) and 2.6 mm for N1 and N2 respectively) for both the nozzles. The proposed simplified theoretical formulation of Sauter mean diameter is a conservative estimate and is used only for order of magnitude analysis.

![Figure 55: Comparison of Sauter mean diameter (SMD) between theory (after secondary breakup: stage1) and PDPA measurement at - a) \( Z = 1.3 \) mm nozzle N1, b) \( Z = 2.6 \) mm nozzle N2. The PDPA data also shows the +/-3\( \sigma \) range of the distribution.](image)

Theoretically, the liquid film goes through different stages of breakup as the droplet moves downstream (shown in Figure 48). However, the first few stages occur almost simultaneously near the film length, making it difficult to identify a fixed \( Z \)-location where only primary or even first stage of secondary breakup occurs. The predicted diameters for first
theoretical stage of secondary breakup are plotted in Figure 55. The first stage breakup profile yields higher theoretical diameters compared to the first measurement possible in the spray and decreases with Weber number, \( We \) (Weber number based on liquid film). The first stage breakup measurements are difficult to make using optical diagnostics due to the coexistence of the film and ligaments. The first set of PDPA measurements beyond the liquid film zone is made at \( Z = 1.3 \) mm for the smaller nozzle (N1) and at \( Z = 2.6 \) mm for the larger (N2) nozzle. The PDPA measurements at any location can be statistically described by a sauter mean diameter along with a diameter distribution (\( +/-3\sigma \) of the measured droplet diameters). Hence the expected diameter distribution after first stage of secondary breakup is well represented by the PDPA data as shown in Figure 55. These measured range of droplet diameters at 1.3 mm and 2.6 mm for N1 and N2 are smaller than the theoretical Sauter mean diameter estimated after the first stage of breakup. But the difference diminishes with increase in Weber number. Thus, it is possible that the first two stages of secondary breakup occur before reaching these measurement points.

4.3.2: Centrifugal Effects due to Pressure Swirl

The other aspect which needs to be considered is the effect of pressure swirl on the droplet distribution. In a pressure-swirl atomizer the internal design of the nozzle, imposes a tangential motion on the liquid film, which imparts a tangential velocity component on the droplets. Although the axial motion is stronger than its tangential counterpart, this pressure swirl affects the droplet diameter distribution in the spray cone. The swirling motion of the droplets creates a centrifugal effect and moves the larger droplets towards the perimeter of the spray. If
we consider a balance between the centrifugal force ($F_c$) acting radially outward and the
aerodynamic drag force ($F_{CD}$) acting against that motion,

$$F_c = \frac{\rho_l \pi d_0^3 V_T^2}{6R} \quad (4.11)$$

$$F_{CD} = \frac{c_{DT} \rho_g \pi d_0^2 V_R^2}{8} \quad (4.12)$$

where $V_T$ and $V_R$ are the tangential and radial component of the velocity due to pressure swirl;
$C_{DT}$, the drag coefficient against radial motion, $\rho_g, \rho_l$ are gas and liquid density; $d_0$ droplet
diameter and $R$: radial location. Now, computing Reynolds number based on radial velocity,

$$Re_{RD} = \frac{\rho_g d_0 V_R}{\mu_g} < 1 \quad (4.13)$$

$$C_{DT} = \frac{24}{Re_{RD}} \quad (4.14)$$

and

$$F_{CD} = 3 \mu_g \pi d_0 V_R \quad (4.14)$$

At equilibrium, $F_c = F_{CD}$ and

$$V_R = \frac{\rho_l V_T^2 d_0^2}{18 \mu_l R} \quad (4.15)$$

This shows that the radial velocity at any given radius is stronger for a larger droplet. When the
droplets move downwards, larger droplets move towards outer periphery of the spray depleting
the larger droplets at the centerline. Thus, the average droplet diameter along the centerline
sharply drops. This is corroborated by the decrease in droplet diameter in Figure 26 beyond \( Z = 5-10 \) mm, even though primary and secondary breakup mechanisms are much weaker and coalescence probability is significantly low for all Reynolds numbers. This behavior is validated through determining the breakup Weber number and the breakup time similar to what was done in the previous section for the axial location.

As for the radial case, similar analysis was done for all radial locations at the two axial zones. Figure 56-61 show how the breakup Weber number (\( W_e_D \)), breakup time (\( t_b \)), and the maximum Weber number (\( \max W_e_D \)) are affected by the radial locations and Reynolds number for the two axial zones respectively. The first two figures (Fig 56 & 57) showcase the breakup Weber number for both nozzles at different injection pressures; 0.5MPa (\( \text{Re}_p = 9,500 \) & \( 18,000 \), Fig 56) and the breakup time for 0.5MPa (\( \text{Re}_p = 9,500 \) & \( 18,000 \), Fig 57). In Figure 56a we can see that the breakup Weber number is much higher at the center of the nozzles than towards the periphery. This validates that the larger droplets are being trapped towards the core due to the weak swirl force generated from nozzle N1 and by Figure 57a where the breakup time is roughly the same for all locations thus indicating secondary breakup is still present throughout the radial locations. At the further Z location, Figure 56b this trend is not observed but all locations have fairly small Weber number and large breakup times (Figure 57b) indicating that breakup is no longer dominate and coalescence and centrifugal effects has taken over, which was collaborated in Figure 32. As for the larger nozzle N2 where the swirl force is a little stronger due to the higher mass flow, Figure 56c & 56d a different behavior is shown. At the first axial location (Figure 56c & 57c) all radial measurements showcase a low breakup Weber number and low breakup time. This indicates that both breakup and the centrifugal effects are present which
explains why at this particular location the diameter is increasing as well as the velocity. For the later axial location (Figure 56d & 57d) the breakup Weber number is seen to decrease and breakup time increasing. This behavior indicates the presence of only coalescence.

Figure 56: PDF of $W_e_D$ at different axial locations along the center line of the spray at 0.5MPa injection pressure - a) Nozzle N1 at $Z = 10$mm, b) Nozzle N1 at $Z = 63$mm, c) Nozzle N2 at $Z = 10$mm, d) Nozzle N2 at $Z = 63$mm
Figure 57: PDF of $t_b$ at different axial locations along the center line of the spray at 0.5MPa injection pressure - a) Nozzle N1 at $Z = 10$mm, b) Nozzle N1 at $Z = 63$mm, c) Nozzle N2 at $Z = 10$mm, d) Nozzle N2 at $Z = 63$mm

The in the next set of figures (Figures 58 & 59) the injection pressure was increased to 2MPa. For both nozzles a similar behavior is seen at the axial location $Z = 10$ mm where at all radial the breakup Weber number is larger towards the periphery and the breakup time is small. According to Figure 33 and Figure 35 the diameter increases throughout the radial locations. This indicates that even though the diameter is increasing suggesting coalescence is happening this is not...
completely true. Since the breakup Weber number is much higher with small breakup time which is an indication of secondary breakup present then the only way to explain the increase of diameter is the centrifugal effect of sending the larger droplets towards the outside periphery of the cone. Were as at the later axial location the breakup Weber number is much lower with a higher breakup time clearly indicating that the increase in diameter observed in Figures 34 & 36 is due to coalescence.

Figure 58: PDF of WeD at different axial locations along the center line of the spray at 2MPa injection pressure - a) Nozzle N1 at Z = 10mm, b) Nozzle N1 at Z = 63mm, c) Nozzle N2 at Z = 10mm, d) Nozzle N2 at Z = 63mm
Due to the overlap of Reynolds numbers for the two particular nozzles a comparison between the two nozzles can be observed. Figure 60 shows how the maximum breakup Weber number behaves in the radial location for the two nozzles. It can be observed that for both nozzles the trends at each of the axial locations are very similar. At the axial location $Z = 10\text{mm}$ the values are slightly higher for nozzle N1 than for N2 but this can be associated with the Reynolds numbers not being perfectly matching with nozzle N1 having slightly higher value. The
interesting thing to note is that although at $Z = 10\text{mm}$ the breakup Weber number is high a different dominating effect is causing the increase in diameter for the two particular nozzles. Looking at Figure 56c-d and Figure 58a-b similar effects can be seen at the later axial location (Figure 56d and 58b) but different trends can be seen at the first axial location while at both locations the breakup time is similar for both nozzles. For nozzle N1 the centrifugal effects are present and much stronger than for nozzle N2 where it is seen that diameter increase is affected more from coalescence than the centrifugal dispersion effect. This could be due to the fact that for nozzle N1 the Reynolds number is still slightly higher than for nozzle N2. Indicating that somewhere between Reynolds number 18,000 and 21,000 the increase in diameter is in transition from coalescence being the driving mechanism and centrifugal dispersion effect being the driving mechanism.

![Figure 60: Maximum breakup Weber number comparison for the two nozzles at both axial locations](image-url)

Figure 60: Maximum breakup Weber number comparison for the two nozzles at both axial locations
4.4 Summary

The breakup characteristics of two hydraulic injector nozzles were studied experimentally as a function of Reynolds number (injection pressures) both axial and radially. Liquid was injected into the testing zone at 0.5MPa to 2MPa (Re_p = 9,500 – 35,000) depending on the parameter being consider. The experimental study consisted of using PDPA and Shadowgraph to understand the breakup regimes of the two simplex nozzles.

The long and short wavelength breakup show that the ligaments breakup into droplets of size~500\(\mu\)m. These droplets further disintegrate through a vibrational type of breakup and create smaller droplet. The PDPA measurement was not possible at this location. Comparison of daughter droplet diameter with the first measurement shows that for lower Weber numbers, there are successive secondary breakups for both the nozzles before axial location of 1.3mm. Stage 2 breakup compared well with the theory for both nozzles at this first location. At higher Weber numbers (higher pressure), droplets undergo only a single breakup prior to this measurement location. The actual estimation of the droplet size distribution requires a full scale simulation of the spray modeling which could be validated using current measurements. In this work, a simple analysis shows that the droplet size distribution for different pressure or Weber number follows the breakup models closely.

When looking in the radial direction three mechanisms can be driving the behavior of the droplet profile. At the first axial location it was observed that at low Reynolds numbers the droplet diameter behavior tends to be deceasing indicating breakup is occurring at all radial locations. As the Reynolds number increases the coalescence tends to take over the driving
mechanism. What was interesting was that between Reynolds number 18,000 and 21,000 a transition was seen where the diameter increase change from coalescence being the driving force to centrifugal dispersion being the driving force with coalescence still possibly being present was observed, but will be looked at in more detail in the next chapter.
CHAPTER FIVE: RESULTS ON DROPLET COALESCENCE FOR SIMPLEX NOZZLES

5.1 Introduction

The new experimental techniques described in chapter one are highly effective and are needed in order to understand the atomization process in detail, but has become expensive and time consuming for the average researcher. Therefore, numerical simulations are needed to guide the experiments. Experimental studies are now conducted to help researchers develop numerical models which are implemented into a numerical simulation which can run various system parameters. Researchers in the past decade have developed important numerical models that reasonably predict the spray atomization characteristics when introduced into a static or dynamic air stream. Although these models are reasonably correct there still lies a big concern in its accuracy. One of the big concerns is the ability to adequately predict droplet breakup regimes and coalescence during the initial injection of the liquid into a cross flow or co-flow environment. The models lack the ability to predict liquid breakup length, ligament breakup, and drop size if coalescence occurs, which in turn can have a major impact on the spray development and combustion characteristics due to the change in time scale [Qian et al. (1997), Ahmed et at. (2009), Shinjo et al. (2010)]. The characterization of liquid breakup length, ligament breakup, and secondary breakup has all been observed in previous chapters to help understand the atomization characteristics of simplex nozzles.

The last important regime that needs to be fully understood to correctly model is droplet coalescence. This usually takes place once the local critical Weber number has been reached.
This is where the droplets can no longer reduce in size due to secondary breakup. One of the first experimental studies conducted on coalescence modeling was done by Qian and Law (1997), whom discovered different types of droplet collisions and when they occur. In their research they focused on generating a map of all collision regimes for water and hydrocarbons based off of two important parameters, Weber (We) number and impact number (B and sometimes I) shown in the following equations

\[ \text{We} = \frac{\rho d_s v_r^2}{\sigma} \]  

\[ B = \frac{2 \delta}{d_s + d_l} \]  

The \( \delta \) symbol is the distance from the center of one droplet to the center of the second droplet as described in Figure 61.

![Figure 61: Definition of impact parameter \( \delta \)](image)
According to Qian et al (1997), hydrocarbons tend to produce five distinct collision regime; coalescence after minor deformation, bouncing, coalescence after substantial deformation, coalescence followed by separation for near head-on collisions, and coalescence followed by separation for off-centre collisions at atmosphere pressure. Water, on the other hand, at atmospheric conditions produces only three of the collision regimes, coalescence, off-center separation, and near head-on separation. Such regime maps are shown in Figure 62. These collision regimes are highly dependent on the Weber number and the Impact number. By knowing these regimes and where they occur, it can be determined whether or not the increased diameter that is observed in various parts of the spray is truly caused by coalescence.

![Figure 62: Schematic of various collision regimes at 1 atm based on the literature— a) Water, b) Hydrocarbons](image)

Similar research has been conducted by Estrade et al. (1999) and by Post et al. (2002), who found similar results using Ethanol [Estrade et al. (1999)] and diesel [Post et al. (2002)]. The biggest contribution made in this paper is the development of a numerical coalescence model to
predict the behavior of the droplet interactions. In Post et al. (2002) work, he proposed to separate the droplet interaction model into two separate parts: the first was to calculate the collision rate between particles, and the second to calculate the probability of coalescence once collision has occurred. Using the computation methods for solving combustion engines developed in the 80’s, the gas phase is solved using an Eulerian reference frame and the liquid phase using a Lagrangian reference frame. Although these results show promise in adequately simulating droplet coalescence they only experimentally visualized two droplets that are forced to collide. This would not necessarily be the case in real world applications, and hence more experimental studies are needed to fully understand when and where coalescence begins with various parameters in order to develop a droplet coalescence model. The next step in this research area would be to see how a spray of dense poly-disperse droplets containing various conventional and biofuels especially under different injection pressures would compare to models already generated and make improvements where needed.

5.2 Experimental Setup

The schematic diagram of the experimental setup utilized in this chapter is shown in Figure 63. As describe in the previous chapters the system uses an autoclave (injection pressures up to 7.5MPa), test nozzles, and a three axis transverse system. This study utilizes only PDPA and Shadowgraph techniques to quantify the velocity, droplet interactions and diameter distributions. The Shadowgraph technique used a 532nm (maximum energy 70 mJ per pulse) dual pulsed Nd-YAG laser (2 mm beam diameter) with a synchronized CCD camera (pixel resolution of 1376 x
1040) similar to the PIV setup. A 90° turning mirror and a circular diffuser (20°) were used to convert the 2 mm beam into a diffused mode to provide adequate backlighting for the spray. The camera along with a Navitar zoom lens was placed in front of the spray. The setup with the zoom lens allowed a viewing window of 0.9 mm x 0.9 mm with a depth of field of approximately 200 µm. For shadowgraph, the spatial resolution achieved through this camera-lens setup was around 1µm/pixel. The PDPA system consisted of a 632 nm He-Ne laser with three adjoining photomultiplier tube receiver set at the appropriate receiving angle of 70° based on the Brewster effect on the surface of the water droplet for first order refraction angle (Figure 63).

This chapter will explore the coalescence regimes of the two simplex nozzles and the results obtained in the previous chapter of the breakup regimes. The results will be centered on
determining the coalescence probability throughout the spray in both the axial and radial locations. This will help understand the transition from the breakup zone to coalescence. This section will help understand the reason for the increase in diameter at a certain radial location even when the velocity increases. This coalescence behavior will also be observed by altering the Reynolds number and nozzle geometry. The injection pressures will range from 0.5 - 2MPa (Reₚ = 9,500 – 21,000), depending on the type of analysis being conducted and will be specified in the following sections.

5.3 Results and Discussion

5.3.1: Coalescence Dynamics

When two droplets collide in a spray, either they bounce off each other or they coalesce. As the outcome largely depends on collision Weber number,

\[ \text{We}_{\text{cot}} = \frac{\rho_l U_{\text{rel}}^2 d_0}{\sigma_l} \]  (5.3)

where \( \rho_l \) is liquid density; \( d_0 \) droplet diameter, \( U_{\text{rel}} \) relative velocity between the colliding droplets and \( \sigma_l \) liquid surface tension) and impact parameter (B). Jiang et al [1992] and Qian and Law [1997] constructed regime diagram of collision outcome based on these two non-dimensional numbers. Qian and Law [1997] showed that coalescence occurrence depends on the rate of dissipation of collision kinetic energy through liquid viscosity after the two droplets collide. Thus, for head-on collision (B=0) of same size droplets coalescence will occur if the
collision Weber number ($We_{col}$) is less than a critical value ($We_{crit}$), which depends on liquid viscosity and can be expressed as:

$$ We_{crit} = 30 \times Oh_{col} $$  \hspace{1cm} (5.4)

where $Oh_{col}$ is the collision Ohnesorge number defined by

$$ Oh_{col} = \frac{16\mu_l}{(\rho \sigma_d)^{0.5}} $$  \hspace{1cm} (5.5)

In the current work, the probability of coalescence is calculated based on this principle. For a conservative estimate, head-on collision was only considered of the same size droplet, for which the relative velocity will be twice that of the individual droplet velocity. Using PDPA data for 10,000 samples at each measurement location, $We_{col}$ and $We_{crit}$ was calculated for each individual droplet to evaluate statistical probability of $We_{col} < We_{crit}$, at which coalescence occurs otherwise the droplets, would collide and bounce off one another. Mathematically, the coalescence probability can be cast as,

$$ Probability of Coalescence = \frac{Number of droplets with We_{col} \leq We_{crit}}{Total number of droplets} $$  \hspace{1cm} (5.6)

Note that in a spray, different droplets may possess all three velocity components, albeit with strong downward axial component. Thus, there can be four different types of collisions, namely, a) same size, (b) different size head-on collisions ($B=0$), and c) same size, (d) different size off-center and non-head-on collisions ($B>0$), as shown in Figure 64. For the same size droplet
collision of water, nevertheless, head-on collisions provide more chances of separation. For other types of collisions, the critical or transition Weber number increases with impact parameter (B) and large to small droplet size ratio increasing the probability of coalescence. In other words, the reported probability in this work is a first order estimate and a conservative calculation which represents a lower bound.

Based on this analysis, the collision probability is calculated and shown in Figure 65 for Nozzle N1 at different Re along the axial distance from the nozzle tip. The probability is very low close to nozzle, reducing the chances of diameter increase through coalescence. At higher Z locations, i.e. Z > 15mm, on the other hand, the probability of coalescence continues to increase with Z and plays a major role in increasing the droplet mean diameter as seen in Figure 65a.
coalescence probability of the droplets along the radial location at Z=10 and 63 mm are shown in Figures 65b and 65c. The probability increases significantly with radius due to the presence of smaller droplets with lower velocity. Furthermore, we also notice that different radial locations at Z = 63 mm show higher coalescence probability compared to Z = 10 mm, due to lower axial velocity, thus, lower collision Weber number (Wecol). Nozzle N2 shows very similar coalescence probability when compared to N1 nozzle (Figure 65b). In reality, the coalescence probability at the outer radius of the spray will be higher due to strong tangential component resulting in frequent off-center and unequal droplet collisions. The coalescence results are consistent with the observations in Figure 26 which show an initial decrease in diameter and then a steady increase around Z = 15-20 mm. Figure 65 shows that the first order estimate of coalescence probability exhibits a significantly high magnitude around Z = 20 mm for Reynolds numbers of 21,000 and 26,000. The coalescence probability is quite low for Z<10 mm signifying a regime dominated by breakup and centrifugal dispersion. For Rep=10,500, Figure 26 suggests that the diameter inflection occurs around Z=35-40 mm. Figure 65a corroborates the fact that this inflection is indeed a coalescence effect since the probability increases to 30% at Z ~ 40 mm for Re = 10,500. Similar effect can be seen for both the nozzles N1 and N2 (Figure 65b).
The variation of coalescence probability in the radial direction is reported in Figure 65c and 65d for nozzle N1. Coalescence probability shows steady increase in the radial direction particularly at Z=63 mm (Figure 65d). At Z=63 mm, it is expected that both primary and secondary breakup mechanisms are very weak as evident in Figures 26a, 30c and 33c. However the low velocity scale (~ 2 m/sec) aids in intense coalescence as seen in Figure 65d. Hence, coalescence will be very strong at all radial locations at Z=63 mm. This is further corroborated by the steady increase in average droplet diameter in the radial direction as seen in Figures 30c
at Z=10 mm, the coalescence probability is much lower at all radial locations since the velocity scale is still very high (~ 25 m/sec) as seen in Figures 6b and 9b. The resultant diameters (Figures 29c and 32c) are also almost two times lower at Z=10 mm at all radial locations compared to those for Z=63 mm. This further indicates lower coalescence probability which is shown in Figure 65c. At z=10mm, we see that the coalescence probability is lower for higher Reynolds number (Figure 65c). Higher Reynolds number induces stronger swirl which is due to an increase in spray cone angle. Pressure swirl pushes the larger droplets towards the outer periphery of the spray. Thus, at higher Reynolds number and stronger swirl intensity, number of larger droplets increases towards the outer periphery of the spray, resulting in low coalescence probability.

5.4 Summary

The coalescence characteristics of two hydraulic injector nozzles were studied experimentally as a function of Reynolds number (injection pressures) both axial and radially. Liquid was injected into the testing zone at 0.5MPa to 2MPa (Re_p = 9,500 – 35,000) depending on the parameter being considered. The experimental study consisted of using PDPA and Shadowgraph to understand the coalescence probability of the two simplex nozzles. Shadowgraph was only used for visualization purposes.

If we combine the effects of coalescence, break up and centrifugal dispersion from the previous chapter, we can divide the spray in three zones as shown in Figure 27. The first zone or
zone A, is very close to the nozzle consists predominantly of film and ligament regime, where primary breakup is very dominant with some secondary breakup as shown by $\text{We}_D \sim 1$ and small breakup time, $t_b$ (Figure 53). In zone B, the secondary breakup process continues. But the process becomes weaker as shown by larger breakup time, $t_b$. The centrifugal dispersion, however, becomes dominant removing the larger droplets towards the outer periphery of the spray and we see sharp decrease in droplet diameter. For both Zones A and B, the coalescence process is present but very weak due to high collision Weber number ($\text{We}_{\text{col}}$) which is reflected by the lower coalescence probability (Figure 65). However, beyond $Z \sim 15\text{mm}$, this process becomes stronger and dominant over other competing effects of breakup and centrifugal dispersion. Thus, we expect the droplet diameter to increase sharply beyond this point. This zone with a high probability of coalescence is labeled as Zone C. For the radial locations it was observed that coalescence is not the sole cause of the droplet diameter increase at the first axial location especially at high Reynolds numbers. Centrifugal dispersion was also present at these high Reynolds numbers causing the larger droplets to be swept to the outside increasing the overall diameter profile. It was also observed that at low Reynolds number the centrifugal dispersion is not as strong compared to larger Reynolds number thus allowing breakup to still occur towards the periphery of the spray at the first axial location.
CHAPTER SIX: VISCOSITY AND SURFACE TENSION EFFECTS ON ATOMIZATION CHARACTERISTICS

6.1 Introduction

The most common atomizer used in the IC and aero-engines is the pressure-swirl nozzle (Simplex nozzle). The liquid is ejected out of the nozzle in the form of a liquid sheet or film. Once this film has been ejected into the surrounding fluid it undergoes different aerodynamic instabilities to disintegrate into ligaments and eventually droplets. In a simplex nozzle, with increase in pressure, the spray characteristics change and it has been observed that before the spray becomes fully developed, the liquid passes through four stages of spray development; dribble stage, distorted pencil stage, onion stage, and Tulip stage [Lefebvre (1999)] where the last three stages are usually dominated by long wavelength film breakup as explained in chapter four. Once the spray becomes fully developed, short wavelength film breakup becomes dominant. This was shown analytically [Senecal et al. (1999), Schmidt et al. (1999)] using a linear instability analysis which allowed the prediction of film length based on Weber number which correlated to a certain type of wavelength breakup. Once the Kelvin-Helmholtz instabilities and wave propagation attain the maximum growth, the liquid sheet will shear off to produce liquid ligaments beginning the onset of the breakup process [Saha et al. (2012)].

The breakup process consists of two steps: a) a primary breakup regime induced by hydrodynamic instabilities and relatively large drag forces that cause the formation of ligaments or other irregular liquid elements and b) a secondary breakup regime which is caused by aerodynamic instabilities resulting in larger droplets deforming and breaking up into smaller
daughter droplets [Saha et al. (2012)]. The secondary breakup mechanism progresses until the aerodynamic breakup time become too large (mainly due to small droplet size and lower relative velocity), which leads to higher coalescence probability. This increased coalescence probability will shift the dominating spray characteristics from secondary breakup to coalescence resulting in an increase in the average droplet size [Saha et al. (2012)]. Research performed in the last decade has been focused on developing and improving the numerical models which predict the droplet distribution profiles for water and other liquids with different physical properties [Tratnig and Brenn (2010)]. Since the experimental studies performed with pressure-swirl nozzles have reported contradictory results over the last few years [Shi and Kleinstreuer (2007)] fundamental research has been conducted on these types of nozzles utilizing water [Saha et al. (2012)] and for liquids with different physical properties [Dorfner et al. (1995), Tratnig and Brenn (2010)].

One of the key reasons for utilizing a simplex nozzle is the uniform distribution of liquid that is generated. This uniform distribution helps increase overall combustion efficiency in IC and aero-engines. Unfortunately, IC and aero-engines use liquids much more complicated than water. For this reason the breakup and coalescence characteristics need to explore more with liquids presenting different physical properties like surface tension and viscosity. The literature is very limited on this particular aspect of experimental investigation on the liquids physical properties effects on the droplet distribution. However, Dorfner et al. (1995) and Tratnig and Brenn (2010) are this topic in great detail. Dorfner et al. (1995) focused more on the droplet distribution throughout the sprays trajectory whereas Tratnig and Brenn (2010) focused more on predicting the global Sauter mean drop size spectra. Both works have shown a tremendous effect on the spray by altering the liquids physical properties. Unfortunately, these studies did not fully
characterize the spray by understanding how the transition from secondary breakup to coalescence is effected by the change of these physical properties. Thus, the fundamentals of spray dynamics, such as spray formation, liquid breakup length, and droplet breakup regimes that was presented in previous few chapters will be extended for liquids with different physical properties.

### 6.2 Experimental Setup

The schematic diagram of the experimental setup utilized in this study is shown in Figure 66. The system uses an autoclave (injection pressures up to 7.5MPa), and a three axis transverse system which precisely controlled the placement of the nozzle (25.4 µm increments) with respect to the diagnostic systems. The nozzle N1 will be utilized in this study as shown in Table 2. This work utilizes the non-intrusive laser technique Phase Doppler Particle Anemometry (PDPA) to determine the velocity and diameter distributions with a 4% diameter and 1% velocity uncertainties respectively. The PDPA setup uses a 632 nm He-Ne laser along with a photo-multiplier tube positioned at a receiving angle of 70° as stated in previous chapters. The choice of the angle of collection is based on the Brewster effect on the surface of the liquid droplet for 1st order refraction angle. For measuring the spray angle a high speed Phantom V12.1 camera was used. Images were captured at 2000 fps at full resolution.
The data reported in this section is recorded on the vertical plane (z-axis) which passes through the center of the nozzle as was done in chapter 4 for water. For PDPA to make simultaneous diameter and velocity measurement the two laser beams were allowed to intersect directly below and in the center of the nozzle exit by moving the nozzle with the traverse system. In order to gather data at different axial or radial distances with respect to the tip, the nozzle was moved using the traverse system without disturbing the optical setup. The autoclave was pressurized with both liquid solutions and air ranging from 0.3-3 MPa (Reₚ = 9,000 – 23,000) and was allowed to equilibrate for 20 minutes. The liquid was then injected into atmospheric conditions (25°C and 1.01 kPa). Surfactant was added to water at different volumetric
percentages to alter the surface tension. Polysorbate 80, 20, and soap were used to engineer three liquids L1, L2, and L3 with customized surface tension. Once the correct volume percentage was added to water, the mixture was placed in a sonicator for an hour to ensure adequate mixing. The solution was then allowed to rest until room temperature was reached before the surface tension was measured using a tensiometer with a 1% measurement uncertainty. Glycerol was used to alter the viscosity with limited change in the surface tension (A1 & A2). The properties of the solutions are compiled in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Liquid properties</th>
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<tr>
<td>Liquids</td>
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<tr>
<td>Water</td>
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The main objective of this chapter is to experimentally investigate the effects of surface tension and viscosity on the liquid breakup regimes including droplet coalescence compared to water. This study intends to identify the spray characteristics and droplet diameter and velocity profiles at different Reynolds number (injection pressure) in the axial and radial direction for different surface tension and viscosity liquids. This chapter will extend the theory of liquid film breakup which showed the importance of long and short wavelength instabilities for low and
high Weber number ranges respectively. The dependence of liquid breakup characteristics was validated with experimental data for the first time in the context of pressure-swirl nozzle in chapter four utilizing water as base fluid and extended for this chapter. Coalescence probability and swirl induced dispersion will also be studied in conjunction with breakup to provide a holistic view of droplet dynamics in these types of pressure atomizers for low surface tension and high viscosity fluids.

6.3 Results and Discussion

6.3.1: Surface Tension Effects

The spray cone angle was obtained using a Phantom V12.1 high speed camera and high power LED light source for backwards lighting. The images were captured at 28,000fps at 520x480 resolutions. The images were then imported into Matlab for edge detection. The grey scale image was converted to a black and white image by generating the image matrix in binary form. To determine the spray cone angle the intensity of the image was controlled by the edge detection function “canny” within Matlab with appropriate lower and upper bound limits that would determine how dark the pixel needed to be for it to be counted as 1 on the image matrix. These values were also compared with calculated values from geometric considerations. By moving the PDPA probe volume radially, the edge of the spray was also located. The edge of this spray is determined by the peak in the data rate near the nozzle due to the hollow cone swirl effect of the nozzle and at by the minimum value at far field locations. Figure 67 shows how the spray cone angle varied as a function of Reynolds number for the liquids being tested. The plot
also shows how the calculated value based on the data rate from PDPA. The edge of this spray is determined by the minimum value of the PDPA data rate. The slight difference between the two techniques may be attributed to the centrifugal acceleration of the droplets in the swirl type nozzle. This makes the high speed images to overestimate the cone angle. It can be seen clearly that by reducing the surface tension the spray cone angle increases. A reduction in the surface tension for pure liquids results in an increase in the growth rate in instabilities, ultimately leading to earlier sheet breakup but a wider spray cone angle [Butler Ellis et al. (2001)].

Figure 67: Reynolds number effect on spray angle with different surface tension liquids with representative high speed images for liquid L2 at different Reynolds number.
To determine the effects of surface tension on the diameter profiles throughout the spray, several axial and radial locations were considered. Measurements were made at two axial locations, one relatively close to the nozzle at $Z = 10$ mm and one far away at $Z = 63$ mm. In Figures 68a and 68b, a clear distinction can be seen between the three solutions and water for the axial cases at $Re_p = 15,000$ for both the diameter and velocity values respectively. The diameter values are nearly 20% less than that of pure water for solution L1 and nearly 50% less for solutions L2 and L3, Figure 68a. However, it is also noticeable that once the surface tension reaches a certain value ($\sigma = 48\text{mN/m}$) the average diameter becomes constant even for lower surface tension liquids. The inflection point which distinguishes secondary breakup to coalescence shifts towards the nozzle for liquids with a lower surface tension, indicating a slight relative change in the secondary breakup and coalescence zones. Near the nozzle, a significant decrease in velocity is noted for liquid solutions of lower surface tension compared to water, (Figure 68b). The velocity for all three liquid solutions is seen to be very similar. However all liquids exhibit lower velocity up to $Z=40$ mm when compared to water beyond which all the velocities merge to attain similar values. This is consistent with the diameter values being much smaller in region of the spray due to the breakup of the droplets and momentum conservation.
Since the surface tension had little effect on the change in the diameter profile in the axial direction past $\sigma = 48\text{mN/m}$ for simplicity water and liquid L2 were only considered for Reynolds number effects. Figure 69a and 69b show the diameter profiles for Reynolds number $\text{Re} \approx 9,500$ and 21,000 respectively. It can be noticed that at low Reynolds number a decrease in the diameter profile of 25-30% is seen by lowering the surface tension whereas at higher Reynolds number the values are very similar. With this observation it is reasonable to conclude that at low injection pressures, the diameter of the droplets become affected by the change in the surface tension. However, at higher injection pressures this is not the case. This could indicate that even though the Reynolds numbers is playing a role the surface tension force is the dominant force (Weber number) in controlling the diameter profile.
To understand these dominate forces the diameter was plotted against the Weber number based on the film thickness, equation 3.4. Since the trend of the diameter profile is based on the first few initial diameter values the first point that was captured for all the tests was utilized ($Z = 5$ mm). Figure 70 represents all the liquids tested with different surface tension and water. By utilizing the Weber number based on the film thickness ($We_L$) one can see how this behavior is associated with the long and short wavelength behavior that was previously defined in chapter 3. This behavior was found to match the water data which will be shown in the next section. The figure is plotted with both a dimensional axis with diameter (Figure 70a) and non-dimensionalized with the film thickness (Figure 70b). Both figures show similar trends at low Weber numbers where the initial diameter is high but as the Weber number increase the initial diameter decrease. This decrease continues until it reaches the critical Weber number which showcases the transition from long wavelength to short wavelengths at which point the diameter reaches an asymptotic value. This clearly indicates that the initial size of the droplets is highly

Figure 69: Centerline diameter measurements for two different surface tension liquids using PDPA: a) Rep ~ 9,500, b) Rep ~ 21,000
dependent on whether the spray is fully developed (short wavelength) or not (long wavelength). By utilizing the same type of analysis we can see from Figure 71 why the surface tension has little affect on the overall diameter profile beyond \( \sigma = 48 \text{ mN/m} \) and at higher Reynolds numbers the values for the two different liquids are similar. From Figure 71a it is observed that water at different Reynolds number and the engineered liquids at similar Reynolds number with different surface tension show similar behavior. This trend was similar to Figure 70 which shows the diameter constantly reducing in the long wave length zone but becoming constant in the short wave length region. Since both exhibit similar diameter reduction trends based on the Weber number it is reasonable to have the overall diameter profile to be consistent with what was obtained in the previous figures. Figure 71b illustrates that in the long wavelength regime the effects of Reynolds number is not as great as in the short wavelength regime. Concluding that at this particular transition of wavelengths zones also causes a shift in the dominant force causing the reduction in the diameter profile.

![Figure 70: Weber number effects on all liquids and Reynolds numbers tested – a) Diameter, b) Non-dimensionalizing diameter with film thickness](image)

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As for velocity measurements, for the lower and higher Reynolds numbers shown above, similar trends were obtained as shown in Figure 68b. The lower surface tension liquid produced slightly lower velocity values near the nozzle for both Reynolds number and similar values at the end. This is in agreement with the diameter profile. Since the breakup process is happening at a slightly faster rate near the nozzle for the lower surface tension liquid the velocity is expected to be lower. At higher Reynolds number, the difference between the two liquids reduces causing both liquids to produce very similar results, which is reasonable since the diameter values are very similar. Similar to what was observed in Figure 68b, the trends are similar for both Reynolds number with the higher Reynolds number having a steeper slope in the beginning stages of breakup, Figure 72.
For the radial cases (Figure 73 and 74) the diameter and velocity values are shown. Figure 73 shows the effect of surface tension on the droplet diameter in the radial direction (Figure 73a) and velocity (Figure 73b) at low Reynolds number. Results are very similar for axial locations $Z = 10$ mm and show similar behavior at $Z = 63$ mm with solution L2 exhibiting lower values. At $Z = 10$ mm, the diameter exhibits a linear decay indicating that for both liquids secondary breakup is still present and droplet dispersion towards the peripheral is low due to the weak swirl force at this low Reynolds number. At $Z = 63$ mm, the diameter increases for both liquids radially. This indicates coalescence is dominant at all radial locations. The fact that water has larger average diameter at all radial locations is due to the fact that the diameter is consistently larger for water droplets after primary breakup.

In Figure 74 the results are presented at higher Reynolds number ($Re_p = 21,000$). For both axial locations, it is observed that the diameter is increasing which is the opposite of what was seen at the lower Reynolds number with water having an overall larger diameter. At $Z = 10$ mm,
the diameter increases due to the combined effects of both coalescence and centrifugal dispersion of larger droplets due to the increased swirl intensity. While at Z = 63 mm, the increase of the diameter is caused by coalescence only. This is justified by the velocity values captured at these locations. For the lower axial location (Z = 10 mm), the velocity still increases for majority of the locations which in theory would not validate an increase in diameter due to coalescence. Thus the presence of centrifugal dispersion of droplets is high which would cause the larger droplets to be swept towards the periphery. This is unlike in the later axial locations where the velocity decreases with an increase in diameter indicating presence of coalescence.

Figure 73: Radial measurements for two different surface tension liquids using PDPA at Rep ~ 9,000: a) Diameter, b) Velocity
All the results presented for axial and radial measurements for the liquids indicate that droplet breakup dynamics (primary and secondary) and coalescence are affected by surface tension. To fully understand its effects, a detailed analysis is done on the liquid film breakup and secondary breakup and coalescence part of the spray for solution L2 and compared to water, as presented in the previous chapters.

It was shown in chapter 4 that based on the Weber number (We); the linear instability in liquid films can be categorized into long wavelength and short wavelength with a critical Weber number (We_c) of 27/16. The long wavelength instability occurs for We<We_c and the short wavelength occurs for We>We_c, where We is a function of the liquid film velocity calculated from the mass flow rate and the film thickness, as follows:

$$We = \frac{\rho_x U^2 l}{\sigma} \quad (6.1)$$
where $\rho_g$ is the gas phase density, $U_l$ is liquid film velocity, $t$ is half of film thickness ($t=h/2$, $h$: film thickness) and $\sigma$ is the surface tension of the liquid. At the nozzle exit, the liquid film forms a rim-like structure, which can be unwrapped to form a two-dimensional sheet, Figure 44. Based on the film breakup theory (shown in more detail in chapter 3), the instability grows very rapidly in a sinusoidal manner. The wave number of this instability can be expressed in the following two ways,

\[
\begin{align*}
K_{1,t} &= \frac{We}{2} \quad \text{(for Long wavelength)} \\
K_{2,t} &= \frac{2We}{3} \quad \text{(for Short wavelength)}
\end{align*}
\]

(6.2)

Using the relation between wavelength and wave number ($K_s=2\pi/\lambda$) one can write:

\[
\begin{align*}
\frac{\lambda}{h} &= \frac{2\pi}{We} \quad \text{(for Long wavelength)} \\
\frac{\lambda}{h} &= \frac{3\pi}{2We} \quad \text{(for Short wavelength)}
\end{align*}
\]

(6.3)

To determine the most unstable wavelength experimentally, high speed images were taken with the Phantom V12.1 camera at 28,000fps. As shown in Figure 75, the pixel lengths were measured for 20-30 frames to obtain the wavelength for a statistical average for different Reynolds numbers and surface tensions. Once the wavelengths were gathered, they were plotted against the theoretical model with the results obtained in for water in Figure 76. Considering the critical Weber number, $We_c=27/16$, the figure displays two zones which are based on the Weber numbers where both long and short wavelength breakups dominate as shown by the dashed and solid lines respectively. The figure also shows the theoretical $\lambda/h$ for long and short wavelengths.
The experimental data seems to still follow the theoretical profile closely and match with the water data shown in chapter 3. Variations can be attributed to the measurement uncertainty and small oscillations in operating pressure during the experiments.

Figure 75: Sample of high speed image for measuring the wavelength
Secondary breakup consists of several types of breakup depending on the droplet Weber number. In this experimental investigation, $We_b < 11$ for all cases and at all locations. In this situation, the vibration-type secondary breakup mechanism is still dominant. In order to distinguish the end of secondary breakup and the beginning of coalescence, the breakup time and coalescence probability will be considered next. Using the PDPA data which encompassed 10,000 droplets the breakup time was calculated using Equation 6.4 for each droplet.

\[ \frac{t_b}{t^*} = C \]  

(6.4)

where $C$ is constant and approximated as 5.0 and $t^*$ is
\[ t^* = \frac{d_0 \rho_l}{U_0} \]  \hspace{1cm} (6.5)

where \( d_0 \) and \( U_0 \) represent the droplet diameter and velocity and \( \rho_l \) and \( \rho_g \) are liquid and gas densities respectively.

In the chaotic nature of sprays, droplets are bound to interact with other droplets at all locations of the spray. To determine when the droplets will coalesce or bounce after the droplets come in contact with one another is determined when the critical Weber number is reached. This critical Weber number was found by Qian and Law which is a function of Ohnesorge number.

\[ We_{crit} = 30 \times Oh_{col} + 15 \]  \hspace{1cm} (6.6)

Where Ohnesorge number is defined as

\[ Oh_{col} = \frac{16 \mu_l}{(\rho_l \sigma_l d_0)^{0.5}} \]  \hspace{1cm} (6.7)

To find the probability for coalescence, the ratio of collision Weber number to critical Weber number was found. Where collision Weber is written as:

\[ We_{col} = \frac{\rho_l U_{rel}^2 d_0}{\sigma_l} \]  \hspace{1cm} (6.8)

where \( \rho_l, \sigma_l, \) and \( \mu_l \) represent the density, viscosity and surface tension of the liquid; \( d_0 \) droplet diameter, and \( U_{rel} \) the relative velocity between the two colliding droplets.

When the ratio is less than unity, coalescence is expected to occur. In this analysis, only the head on collisions were considered, which would represent the lower bound. Figure 77 provides
the comparison of coalescence probability for water and solution L2 at $Re_p \sim 9,000$ and Figure 78 at $Re_p = 21,000$. It can be seen that coalescence is present at all locations of the spray with solution L2 having a higher probability up to 40 mm from the nozzle tip and lower at the far field locations at the lower Reynolds number. In the radial direction the coalescence probability is significantly lower at $Z = 10$ mm than at $Z = 63$ mm. This helps justify the reason why at $Z = 10$ mm the droplet diameter is seen to decrease as the radial distance is increased. Even though the coalescence probability increases towards the periphery the breakup time is still quite small thus allowing breakup to still be dominating. At the further axial location $Z = 63$ mm the coalescence is quite high thus fully concluding that the cause for increased diameter at this location is due to coalescence. Since coalescence is present and the diameter is still decreasing, the breakup time needs to be considered for solution L2 to fully understand why the mean droplet diameter reduces locations close to the nozzle. At the higher Reynolds number case, Figure 78 the results in both the axial and radial locations are similar which is in good agreement since the diameter values and trend is similar for this case. It was also observed that at higher Reynolds number the coalescence probability peaked at ~50% twice as much as the lower Reynolds number case in the axial direction. For the radial case similar profiles are seen with the coalescence being nearly 100% for the radial locations at $Z = 63$ mm. At $Z = 10$ mm the opposite is seen where the coalescence probability is higher near the center of the spray and then on the periphery. Suggesting that the increase in diameter in radial direction at this particular axial location is due to the centrifugal droplet dispersion characteristics associated with these nozzles and not coalescence, which is shown later by the looking at the breakup time. An interesting thing to notice is that at both Reynolds number the trends are similar for liquid L2 but not for
water. This is associated to the spray regime. For water at this low Reynolds number the onion regime was observed while for liquid L2 this was not the case. Thus suggesting that once the flow goes beyond the first couple of spray regimes (pencil and distorted pencil) into the later stages of the spray regimes (onion, Tulip, and fully developed) this coalescence profile is expected.

Figure 77: The Coalescence probability for water and solution L2 at Rep ~ 9,000 (a) Measurements made along centerline, (b) Measurements made radial

Figure 78: The Coalescence probability for water and solution L2 at Rep ~ 21,000 (a) Measurements made along centerline, (b) Measurements made radial
Figure 79 illustrates the breakup time for all 10,000 droplets and compared to each other at different axial locations and radial conditions. It can be seen that for axial location Z < 20mm, Figure 79a, the breakup time is small with coalescence probability also being small indicating that at these locations the secondary breakup occurs much faster than coalescence, thus becoming the dominant mechanism. This in turn enables the overall mean diameter to reduce in this region of the spray. Once the breakup time begins to increase at later locations in the spray the coalescence probability increases which reduces the amount of breakup that can occur in a short distance enabling the shift from secondary breakup to coalescence. For radial locations similar behavior can be seen in Figures 79b and 79c, but at axial location Z = 10mm the coalescence probability begins to increase towards the periphery to about 25% for solution L2 and 35% for water due to the larger breakup time and the swirl effect from the nozzles. Due to centrifugal force the swirling action will force the larger droplets towards the outer edges of spray causing a higher coalescence probability in this zone. However since the breakup times are still very small the overall effect will cause the droplets to still experience secondary atomization. The droplet diameter is still decreasing radially even though there exist a probability for coalescence. At the later axial location the coalescence probability is high at all radial locations indicating a clear coalescence zone. These values obtained are slightly lower than what was found for water. Thus it can be seen that at a Reynolds number of 9,500, the coalescence probability decreases for lower surface tension fluids.
Similar results are presented for higher Reynolds number ($Re_p = 21,000$) in Figures 80. As for the radial cases it was noticed that the coalescence probability trend was opposite at the first axial location $Z=10\text{mm}$ compared to the values at the lower Reynolds number. The interesting thing to note here is that at this particular location the coalescence probability starts off high in the center of the spray and decrease radially even though the overall diameter is still increasing throughout the periphery. This is justified by the breakup time shown in Figure 80b where at this
particular location the breakup time is still very small thus concluding that coalescence is not causing the increased diameter but the centrifugal force associated with the swirl intensity is the driving factor. This, in turn, causes the majority of the larger droplets to be swept towards the outside of the spray cone. Further downstream in the axial direction in Figure 80c, one can see that the breakup time for all radial locations is high. With this and the coalescence probability being much higher throughout the entire radial zone a clear conclusion can be made that coalescence is the sole reason for the increased diameter at this particular zone of the spray.

**Figure 80:** PDF for breakup time $t_b$ at $\text{Re}_p \approx 21,000$ (a) Measurements made along centerline, (b) Measurements made radial at $Z = 10\text{mm}$, (c) Measurements made radial at $Z = 63\text{mm}$
6.3.2: Viscosity Effects

Utilizing the same techniques as described in the previous section the spray cone angle was determined for the liquids A1 and A2 with comparison to water. Figure 81 shows how the spray cone angle varied as a function of Reynolds number for the liquids being tested. It can be seen that both liquids A1 and A2 show similar trends as water. The only initial difference is that the trends are shifted to the left due to the viscosity being higher which reduces the Reynolds number. From the figure, the high viscosity liquid, (A2) shows a slightly higher increase in the spray angle compared to liquid A1 and much larger compared to water. This indicates that with an increase in viscosity, the spray cone angle increases but the rate at which the spray angle increases from one high viscosity fluid to another starts to taper off. The interesting thing to note is that although the two engineered liquids show higher spray angles, they potentially converge near the same maximum spray cone angle. However, both reach a higher spray angle than water.

Figure 81: Reynolds number effect on spray angle with different viscosity liquids.
For comparison, the values obtained in the axial direction for both liquids A1 and A2 are shown below in Figure 82. The liquids were all run at $\text{Re}_p = 15,000$ varying the injection pressure to counteract the viscosity term. It can be observed that the trends for liquids A1 and A2 are very similar to that of water and illustrate that the droplet diameters increase with an increase in viscosity which is also corroborated in the literature. This is more evident in the primary and secondary breakup regime where $\sim 10\%$ and $\sim 30\%$ increase in diameter is observed for liquids A1 and A2 respectively but $\sim 5\%$ and $\sim 20\%$ increase is seen in the coalescence regime for these liquids. This indicates that as the viscosity increases, the reduction in droplet diameter increases making the slope much sharper in the secondary breakup zone. At the same time the transition point from secondary breakup to coalescence begins roughly in the same location for all three liquids. However, it seems that as the viscosity increases this transition zone also increases. This suggests that a different mechanism is causing the larger separation in the secondary breakup regime than in the coalescence regime. With the increase in viscosity, the liquid is allowed to hold onto the nozzle orifice walls longer, thus creating a thicker liquid film when injected into the atmosphere. This increased thickness will cause the ligaments that shear off from the most unstable wave to have a larger cross sectional diameter which would eventually cause larger droplets to form. This is a plausible explanation that the average diameter is larger for the larger viscosity liquid. However, it does not explain why this separation between the liquids in the initial stages of breakup shrink as it approaches the transition point. It is important to remember that the Reynolds number was kept constant thus as the viscosity increased the velocity component must change to counteract to balance the Reynolds number, thus making the injection pressure increase. Since this is the case, the injection velocity for the
liquids with higher viscosity, experience an increase in drag force due not only to the size increase but also the droplet velocity. This would cause the breakup to happen more rapidly in the beginning to middle stages of secondary breakup. To understand why this separation is constant throughout the coalescence zone, the coalescence probability is determined.

![Figure 82: Viscosity effects of diameter profile for nozzle N1 at Re_p = 15,000](image)

By calculating the coalescence probability for the different liquids it was observed that all three liquids have a similar trend where the percentage is low in the initial stages of breakup then increases before reaching an asymptotic value. The interesting thing to notice in Figure 83 is that the coalescence probability for both liquids A1 and A2 become constant near the same value. They both show a much higher value than water. An interesting observation is that it takes liquid A2 longer to reach the asymptotic value than liquid A1. This is associated with the fact that as the viscosity increases, the transition zone gets larger, thus allowing liquid A2 to take a longer
time (distance on the axis) to reach the asymptotic value. Also, it is noticed that even though the coalescence probability is much higher, the increased diameter is about the same as that of water in the coalescence regime. This suggests that due to the increased injection velocity for the two engineered liquids, breakup could still occur, although not enough to dominate the coalescence process. It is important to note that the coalescence probability only suggests that if two droplets were to collide in any form or even touch, then the probability of coalescence is higher than bounce-off. Thus, the probability of coalescence is the sole reason why the average diameter increases.

![Figure 83: The Coalescence probability along the centerline for different viscosity liquids at Rep ~ 15,000 for nozzle N1](image-url)

Figure 83: The Coalescence probability along the centerline for different viscosity liquids at Rep ~ 15,000 for nozzle N1
6.3.3: Droplet Diameter Prediction

It has long been known that the liquid properties relevant to atomization are density, surface tension, and viscosity. After numerous studies for both hydraulic and air blast atomizers, it was observed that within the range of practical use, density has little effect on the droplet size and can be neglected (Wang and Lefebvre, 1987). Thus for any kind of study the important liquid properties for atomization is surface tension and viscosity. Researchers have tried to find a correlation that could predict the droplet diameter based on these parameters but many tended to resort to various empirical correlations due to the complex nature of the atomization process. Unfortunately, these equations have shortcomings both in a theoretical and practical sense. To eliminate these shortcomings, Wang and Lefebvre (1987) proposed an alternate equation from the physical process involved in atomization in pressure-swirl nozzles rather than a mathematical treatment of the problem. A detailed account of their derivation can be found in their work listed in the references and will be summarized below. Due to the severe complexity of atomization for hydraulic based swirl nozzles it was found to be well-suited to subdivide the two main stages of atomization. According to Wang and Lefebvre (1987), the first stage represents the generation of surface instabilities due to the combined effects of hydrodynamics and aerodynamic forces while the second stage is the conversion of surface protuberances into ligaments and droplets. This allowed them to form an equation for the Sauter Mean Diameter (SMD).

\[
\text{SMD} = \text{SMD}_1 + \text{SMD}_2
\]

(6.9)

\(\text{SMD}_1\) and \(\text{SMD}_2\) represent the first and second stages respectively. It was determined that the magnitude \(\text{SMD}_1\) depends on both the Reynolds number and Weber number. The Reynolds
number helps provide a measure of the disruptive forces present while the Weber number helps govern the development of capillary waves. Thus, creating an expression for SMD$_1$ as followed:

$$\frac{SMD_1}{t_s} \propto (Re \times \sqrt{We})^{-x}$$  \hspace{1cm} (6.10)

where

$$Re = \frac{\rho_i U_i t_s}{\mu_i}$$  \hspace{1cm} (6.11)

$$We = \frac{\rho_a U_a^2 t_s}{\sigma}$$  \hspace{1cm} (6.12)

and $t_s$ is the initial sheet thickness at the nozzle exit. By utilizing both Reynolds and Weber number SMD$_1$ represents how the surface tension and viscous forces act together in opposing the disruptive actions of the hydrodynamic and aerodynamic momentum forces (Wang and Lefebvre, 1987). To determine the value of $t_s$, simple geometrical consideration is needed. Once the initial liquid sheet is discharged, one can relate the film thickness within the final orifice, $t$, by utilizing the following equation:

$$t_s = t \cos(\theta)$$  \hspace{1cm} (6.13)

where $\theta$ is the half angle of the spray cone. Suyari and Lefebvre (1986) captured the film thickness, $t$, using the following equation.

$$\frac{(1-X)^3}{1+X} = 0.09 \left[ \frac{A_p}{D_3d_0} \right] \left[ \frac{D_2}{d_0} \right]^{0.5}$$  \hspace{1cm} (6.14)

where
\[ X = \frac{(d_0 - 2t)^2}{(d_0)^2} \quad (6.15) \]

By substituting equations 6.13 – 6.15 into equation 6.10 with the corresponding Reynolds and Weber number coefficients the new SMD\(_1\) becomes,

\[
SMD_1 \propto \left( \frac{\sigma_{0.5} \mu_l}{\rho_A^0 \rho_l U_R L_l} \right)^x (t \cos \theta)^{1.5x} \quad (6.16)
\]

Since majority of the time the nozzle sprays the liquid into a stagnant or slow moving surrounding air \(U_R\) can be approximated as \(U_l\) and \(\Delta P_l = 0.5 \rho_l (U_l)^2\) which will simplify equation 6.16 to

\[
SMD_1 \propto \left( \frac{\sigma_{0.5} \mu_l}{\rho_A^0 \rho_l \Delta P_l} \right)^x (t \cos \theta)^{1-1.5x} \quad (6.17)
\]

In the final stage of the atomization process where the conical sheet causes the protuberances generated in the first stage to detach and break into ligaments and then droplets, it was found that Weber number, and not Reynolds number, is the relevant parameter. Thus SMD\(_2\) can be initially expressed as the following equation.

\[
\frac{SMD_2}{t_s} \propto We^{-y} \propto \left( \frac{\sigma}{\rho_A U_R t_s} \right)^y \quad (6.18)
\]

Utilizing the same substitution for \(t_s\), the \(\Delta P_l\) equation, and \(U_R = U_l\) equation 6.18 can be simplified and becomes the following.

\[
\frac{SMD_2}{t_s} \propto We^{-y} \propto \left( \frac{\sigma \rho_l}{\rho_A \Delta P_l} \right)^y (t \cos \theta)^{1-y} \quad (6.19)
\]
Now that both SMD$_1$ and SMD$_2$ have been determined, they can be put into equation 6.9 and become

$$SMD = A \left( \frac{\sigma}{\rho_0 A \Delta P_l} \right)^x (t \cos\theta)^{1-1.5x} + B \left( \frac{\sigma \rho_0}{\rho_0 A \Delta P_l} \right)^y (t \cos\theta)^{1-y}$$  \hspace{1cm} (6.20)

where A and B are constants determined from the nozzle design and X and Y from the experimental data. To determine constants A and B from the nozzle design Wang and Lefebvre (1987) used the following equations,

$$A = 2.11 \left[ \cos^2 (\theta - 30) \right]^{2.25} \left( \frac{0.00034}{d_0} \right)^{0.4}$$  \hspace{1cm} (6.21)

$$B = 0.635 \left[ \cos^2 (\theta - 30) \right]^{2.25} \left( \frac{0.00034}{d_0} \right)^{0.2}$$  \hspace{1cm} (6.22)

where $d_0$ and $\theta$ are the orifice diameter and half spray angle at fully developed conditions respectively. For this comparison, constants A and B from the nozzle design were left similar as values used in Wang and Lefebvre (1987) work and then modified based on the nozzle used in the current study. The nozzle they utilized was a Delavan nozzle which produced values for A and B as 4.52 and 0.39 respectively. To see how this correlation compared to the data captured in this thesis, the same x and y values of 0.5 and 0.25 were used. Since this equation was developed under the assumptions that the atomization occurs in two stages incorporating both the surface instabilities to the development of ligaments and further in to droplets, the comparison was done at the end of primary breakup and the beginning stages of secondary breakup. Figure 84a shows how the predicted SMD compared to the measured SMD from the data in this thesis at the first point taken for each case. It can be seen that the values match well with the empirical correlation.
with predicted values over shooting most of the measured values. Since this is an empirical correlation, the values for A, B, X, and Y would normally be iterated to find the best fit. Utilizing equations 6.21 and 6.22, constants A and B were found based on nozzle N1 since they were utilized throughout this study. They were found to be 2.11 and 0.62 respectively. Once these values have been calculated values for X and Y have been iterated to determine the best fit, and were found to be 0.5 and 0.1 respectively. This provides the following equation.

\[ SMD = 2.11\left(\frac{\sigma_{\rho A}}{\Delta P_l}\right)^{0.5}(t\cos\theta)^{0.25} + 0.62\left(\frac{\sigma_{\rho l}}{\rho_A\Delta P_l}\right)^{0.1}(t\cos\theta)^{0.9} \]  \hspace{1cm} (6.23)

This comparison is seen in Figure 84b where it is noticeable that the data matches the modified correlation as well. Thus, suggesting that Wang and Lefebvre’s empirical equation is the best fit for predicting the initial SMD for different hydraulic pressure-swirl nozzles. Since the values for water and the engineered liquids both surface tension driven and viscosity driven were all plotted against the correlation equation and found to match well it is reasonable to conclude that the data obtained for the engineered liquids are reasonable.

![Figure 84: Experimental results compared to predicted at the onset of atomization breakup for nozzle N1– a) Correlation found from Wang and Lefebvre (1987), b) Modified Correlation based on water solutions L1, L2, L3, A1 and A2.](image)
6.4 Summary

In this part of the experimental study, the effects of surface tension and viscosity on the liquid breakup regimes including droplet coalescence are compared to water. The spray characteristics, droplet diameter, and velocity profiles at different Reynolds number (injection pressure) in the axial and radial direction for different surface tension liquids was observed. This section extended the use of the theory of liquid film breakup which shows how the long and short wavelength instabilities are important and matched the experimental results found for water and from theory for low and high Weber number ranges respectively. From the results presented, it was found that when the surface tension falls below $\sigma = 48\text{mN/m}$ the effects of surface tension is no longer present. It was also found that at low Reynolds number the driving force for the reduction of the diameter profile is dominated by the surface tension whereas at high Reynolds number this is not the case where the results are similar. The inflexion point of the transition from secondary breakup to coalescence is seen to shift closer to the nozzle for lower surface tension liquids. For majority of the cases, it was seen that the coalescence probability was higher for the lower surface tension solution than water. Similar to the diameter profile at larger Reynolds numbers the coalescence probability became similar to that of water. This suggests that although using a liquid with lower surface tension decreases the overall diameter profile throughout the measurement locations for low Reynolds number, the chances of coalescence increases as two droplets collide. At higher Reynolds number it seems the inertia force is the dominant mechanism for coalescence.
When the surface tension was left the same and the viscosity was altered a similar scenario was seen. As the viscosity increased the spray cone angle was seen to increase and shift to the left when compared to water due to reduction in the Reynolds number. The larger the viscosity the higher the diameter profile becomes. The slope for decreasing droplet diameter in the secondary breakup regime was found to be sharper for higher viscosity liquids. Therefore, the diameters for the engineered liquids are smaller in the transition zone. Due to the higher initial injection velocities for the higher viscosity liquid the drag force was increased thus promoting more breakups at a faster rate. Once the liquids reached the coalescence zone, no difference between the droplet profiles was seen, since the coalescence profile shows that both engineered liquids reach a constant but high coalescence probability of nearly 95%.

In order to determine whether the data obtained for this section was accurate, results were compared to a physical process involved in atomization of a pressure-swirl nozzles rather than a mathematical treatment of the problem which was conducted by Wang and Lefebvre (1987). Due to the severe complexity of atomization for hydraulic based swirl nozzles they found it convenient to subordinate the two main stages of atomization. The first stage represents the generation of surface instabilities due to the combined effects of hydrodynamics and aerodynamic forces while the second stage is the conversion of surface protuberances into ligaments and droplets. It was observed that when utilizing Wang and Lefebvre’s constants the values matched well with the empirical correlation with predicted values slightly overshooting the measured values. This was improved by generating constants A and B from the nozzles that were utilized in the data. Through an iteration process, the constants X and Y in equation 6.20 were determined, and the equation predicted our data very well.
CHAPTER SEVEN: COMPARISON OF ENGINEERED LIQUIDS TO REAL FUELS

7.1 Introduction

Research performed in the last decade has been focused on developing and improving the numerical models which predict the droplet distribution profiles. The most common atomizer used in the IC engines and aero-engines is the pressure-swirl nozzle (Simplex nozzle). Since the experimental studies performed with pressure-swirl nozzles have reported contradictory results, over the last few years, fundamental research have been conducted on these types of nozzles to explore this topic. However, the research has always utilized water and further investigation is still needed for fuels. While some research has been attempted to study various types of liquid fuels, the research has been very limited and needs further investigation into how they fuels behave and if a surrogate liquid is a viable replacement for experimentation needs.

Phase Doppler Particle Analyzer (PDPA) system is capable of simultaneous measurements of the diameter and velocity of spherical particles in liquid flows. Therefore, the analysis of the correlations between droplet size and velocity as well as the examination of the overall volume droplet size distribution across the spray is feasible. To investigate how fuel formulations affect spray characteristics, a detailed study of different fuels is necessary. In this work, the focus is on three different fuels, Ethanol, Jet-A, and Kerosene, to determine how diameter profiles are influenced in comparison to an engineered liquid.
7.2 Experimental Setup

The schematic diagram of the experimental setup utilized in this part of the study is similar to the previous section and is shown in Figure 66. The data reported in this section is recorded on the vertical plane (z-axis) which passes through the center of the nozzle. The autoclave was pressurized with both all the liquid solutions and air at 1 MPa (Rep = 9,500) and was allowed to equilibrate for 20 minutes. The liquid was then injected into atmospheric conditions (25°C and 1.01 kPa). A few common fuels were observed and compared to an engineered liquid. The engineered liquid was composed of surfactant (Polysorbate 20) and pure Glycerol to alter both the surface tension and viscosity. Once the correct volume percentage was added to water, the mixture was placed in a sonicator for an hour to ensure adequate mixing. The solution was then allowed to rest until room temperature was reached before the surface tension and viscosity was measured using a tensiometer and viscometer with a 1% measurement uncertainty. The fuels tested were Ethanol, Kerosene, and Jet-A. The properties of the liquids are compiled in Table 5.

<table>
<thead>
<tr>
<th>Liquids</th>
<th>Surface Tension (m N/m)</th>
<th>Density (kg/m³)</th>
<th>Vapor Pressure (kPa)</th>
<th>Viscosity (N s/m²) x 10⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (20°C)</td>
<td>72</td>
<td>1000</td>
<td>1.5</td>
<td>1.01</td>
</tr>
<tr>
<td>Water (30°C)</td>
<td>71</td>
<td>995</td>
<td>2.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Ethanol</td>
<td>22</td>
<td>790</td>
<td>8.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Kerosene</td>
<td>25.6</td>
<td>800</td>
<td>0.28</td>
<td>1.5</td>
</tr>
<tr>
<td>Jet-A</td>
<td>26.3</td>
<td>820</td>
<td>0.45</td>
<td>1.6</td>
</tr>
<tr>
<td>H1</td>
<td>30</td>
<td>1005</td>
<td>1.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>
7.3 Results and Discussion

7.3.1: Liquid Fuel Effects

In a similar fashion as water and engineered liquids, the different fuels were tested. Figure 85 shows how Kerosene, Jet-A, and Ethanol all behaved along the centerline of the spray. These fuels were chosen due to their similarity in surface tension and viscosity, as seen in the table above. From the graph it is evident that the same trend seen in all previous cases for various types of liquids is still present. This is observed for both the diameter and velocity profiles. It should be noted that at the beginning axial locations where primary and secondary breakup occur, the droplet diameters for the three fuels are nearly identical. The transition point, the location where the secondary breakup and coalescence begins, even occurs near the same axial location and droplet diameter value. The unique phenomenon that occurs is in the coalescence regime, where the three fuels begin to separate with different diameter profiles. This is observed clearly in Figure 86 where the plot is focused on the coalescence regime only. This coincides and creates the same separation in the velocity plots where the velocity for Kerosene becomes much slower than that of Jet-A and Ethanol. To understand this behavior the coalescence probability was examined.
Figure 85: Centerline measurements for the different fuels using PDPA at Rep ~ 15,000 – a) Diameter, b) Velocity

Figure 86: Zoomed in centerline diameter measurements for the different fuels using PDPA at Rep ~ 15,000
Figure 87 shows the coalescence probability for the liquid fuels tested to understand the differences in diameter. Coalescence probability starts to separate from one another around the same location of transition. All three fuels show a similar trend with Kerosene leveling near 90% while Jet-A and Ethanol comes to a plateau around 75% and 60% respectively. This further explains why in this zone of coalescence, Kerosene shows the higher droplet diameter followed by Jet-A and then Ethanol. From Table 5 it can be seen that the values for the three fuels are very similar in density, surface tension, and viscosity. These three critical parameters help control the atomization and coalescence process. This has been proven true for the atomization zone since the values are very similar in the breakup regimes. However, in the coalescence zone, it may be hypothesized that vapor pressure is the property that plays a role in determining drop size. Vapor pressure determines the speed at which a liquid vaporizes. Table 5 also shows the vapor pressure of the three liquid fuels. It is observed that the values for Kerosene which produce the larger diameter droplets in the coalescence zone have the lowest vapor pressure. The other fuels follow suit with Jet-A and Ethanol.

The time of vaporization is determined by vapor pressure. When the droplets are in the coalescence zone, they move at a much slower rate, increasing the chances for coalescence to take place, thus increasing the drop size. To test this hypothesis whether vapor pressure has a profound effect on droplet diameter in the coalescence regime, some tests were performed by heating the water in the autoclave to higher temperatures and raising the vapor pressure.
7.3.2: Vapor Pressure Effects

It has long been known that the vapor pressure is correlated to the temperature of the liquid and that if the temperature is increased the vapor pressure is increased. For this preliminary testing, the autoclave was wrapped with a Brisk constant power heating tape and then wrapped with a fiberglass insulation tape. The objective is to use PDPA to capture the diameter of the droplets at different axial locations for the liquid at increased temperature. For safety reasons the fuels were not used at high temperatures and pressures. For testing this hypothesis, water was going to be used. The temperature of the water was elevated from 20°C to 30°C at the exit of the nozzle which will nearly double the vapor pressure while changing the density, surface tension and viscosity by a negligible amount. Values are located in Table 5. Once the liquid was heated
to around 60 - 65°C in the autoclave the pressure was then added to the corresponding testing pressure. For this particular test run 1MPa was used (Re_p = 15,000). The liquid was then injected through the nozzle into the atmosphere for 5 minutes to reach an equilibrium ejection temperature of around 30°C. The dramatic loss of temperature is due to the cooling effects of the rapid expansion of the liquid once ejected from the nozzle. From preliminary heat transfer calculations, the droplet temperature would lose no more than 0.5°C from the initial injection to the final axial location at Z = 63mm. Figure 88 shows how the temperature altered the diameter profile throughout the axial locations (Figure 88a) and how the diameter is effected by vapor pressure utilizing all the fuels and water (Figure 88b). From the plot it is easy to see that when the temperature of the water is increased (increased vapor pressure) the diameter is seen to decrease. This happens at all the axial locations thus, making the trend just below that of water at ambient conditions. It is important to note that when the liquid is heated, other thermal physical properties decrease like the viscosity which would naturally lower the droplet diameter as seen in the previous chapter. Since this change is small compared to that of the change in vapor pressure it is suggested that the vapor pressure is playing a larger role in controlling the diameters of the droplets. Unfortunately, how much of a role vapor pressure is playing versus the change in the other thermal physical properties cannot be determined with this test. Looking at the last axial location we can see that when the two water cases are plotted with the liquid fuels, a trend can be seen with vapor pressure. Although the property differences exist between heated water and fuels, there is a strong indication that vapor pressure causes the separation in droplet diameter observed in the coalescence zone for different liquid fuels. Thus this topic needs further investigation and needs to be explored in the next phase of this research.
7.3.3: Surrogate Liquid Comparison to Liquid Fuel

Due to the highly violent nature of liquid fuels testing at higher temperatures, further investigation of the effects of vapor pressure is very difficult. Thus, it is important to find an engineered liquid that could potentially represent the behavior of a liquid fuel. The key properties to focus on are surface tension and viscosity. A test to determine if it was possible to mimic the behavior of the liquid fuels a hybrid liquid was generated by mixing both glycerol and surfactant into water at various volume percentages to achieve similar surface tension and viscosity values as liquid fuels. This generated liquid was then tested in the same manner as all the other test cases. The only parameters that could not be recreated were the density and vapor pressure. However, density is not considered to be a significant factor as explained in section 6.3.3. Results are shown in Figure 89. Since the liquid had a surface tension of 30mN/m and viscosity of 1.6cP it was compared to Jet-A and Ethanol. As can be seen the hybrid liquid match
well with both liquids in the initial stages of primary and secondary breakup. In the coalescence regime although it matches both liquid fuels reasonably well, it most closely follows Ethanol. As stated in the previously this could be due to the fact that the vapor pressure for this hybrid case falls in between Jet-A and Ethanol. With this being the case an engineered liquid could be used to understand how the fuels behave in harsher environments which are not an ideal for safety for liquid fuels.

Figure 89: Centerline diameter measurements for the different fuels and engineered liquid using PDPA at Rep ~ 15,000
7.4 Summary

In this chapter, the behavior of liquid fuels such as Kerosene, Jet-A, and Ethanol was observed. This identified the spray droplet diameter and coalescence in the axial direction for the different liquid fuels. Testing was conducted at \( \text{Re}_p = 15,000 \) for nozzle N1 utilizing only PDPA. A comparison analysis was also done to see how a surrogate engineered liquid matched up to a similar liquid fuel.

From the results presented, it was found that the liquid fuels produce similar trends as seen for water and the engineered liquid. It was also found that in the primary and secondary breakup regimes the diameter values for each fuel was consistent with one another but in the coalescence zone this was not the case. Kerosene produced higher droplet diameter at the later axial location followed by Jet-A and Ethanol. It was seen that the coalescence probability was higher for Kerosene than the other fuels with the others following the same trend. It was hypothesized that the cause for this deviation in the coalescence zone could be due to the vapor pressure which coincides with the order of the liquids. After running a preliminary case of water at an elevated injection temperature which subsequently increases the vapor pressure, it was shown that for the higher injection temperature, the diameter profile was shifted downwards indicating that vapor pressure plays a role on drop size in the coalescence regime, allowing us to conclude that drop size decreases with an increase in vapor pressure. Due to safety precautions for fuels at elevated temperatures, an engineered surrogate liquid was used instead of the fuels, however future testing should involve real fuels to understand the vapor pressure effects. A case was run with a hybrid liquid that matched the surface tension and viscosity of the liquid for suitability. Their
drop size compared favorably with Ethanol due to the closer value in vapor pressure. It suggests that vapor pressure could also be a significant contributor in determining the droplet diameter in the coalescence regime.
CHAPTER EIGHT: CONCLUSIONS AND FUTURE WORK

8.1 Conclusion

To fully understand the droplet distribution profiles this thesis studied the breakup characteristics of various liquids with different thermal physical properties emanating from hollow cone hydraulic injector nozzles induced by pressure-swirling. The experiments were primarily conducted using two nozzles with different orifice diameters 0.3mm and 0.5mm and injection pressures ranging from 0.3-4MPa which correspond to \( \text{Re}_p = 7,000-31,000 \) depending on the liquids being tested and nozzle. For a complete study of all aspects of the flow, three laser based diagnostic techniques and high speed imagery was utilized. The three techniques are Shadowgraph, PIV (Particle Image Velocimetry) and PDPA (Phase Doppler Particle Anemometry).

To begin the study, a series of investigations were conducted for instrumentation accuracies. The cross-validation of the three techniques compared well with each other, but limitations were observed. It was discovered that PDPA and Shadowgraph were only limited by the film length. Measurements made close to the nozzle for PDPA had low spherical validation thus longer sample duration was needed for accurate measurements. Although these measurements can be made in specific regimes in the spray, caution should be taken due to the dependence on droplet aspect ratio. On the other hand, PIV was only valid in the later stages of secondary breakup and coalescence, where the droplet density was less. For radial data, measurements with PIV, PDPA and Shadowgraph at all zones could be made. Away from the axis near the periphery of the cone,
obtaining accurate peak to peak cross-correlation with PIV was limited due to a higher probability of large diameter droplets and/or a high density of spray which tended to increase the uncertainty in the measurement technique.

Once the instruments were compared for accuracy, the very complex atomization and coalescence characteristics were explored. If we combine the effects of coalescence, break up and centrifugal dispersion the spray can be divided into three zones. The first zone or zone A, is very close to the nozzle consists predominantly of film and ligament regime, where primary breakup is very dominant with some secondary breakup as shown by \( \text{We}_D \approx 1 \) and small breakup time, \( t_b \). The long and short wavelength breakup within this zone show that the ligaments breakup into droplets of size ~500 \( \mu \text{m} \). These droplets further disintegrate through a vibrational type of breakup and create smaller droplet. The PDPA measurement was not possible at this location. Comparison of daughter droplet diameter with the first measurement shows that for lower Weber numbers, there are successive secondary breakups for both the nozzles before axial location of 1.3mm. In zone B, the secondary breakup process continues. In the early parts of this breakup zone results compared well with the theory for both nozzles and liquids with different thermal physical properties at the first axial location. At higher Weber numbers (higher pressure), droplets undergo only a single breakup prior to this measurement location. The actual estimation of the droplet size distribution requires a full scale simulation of the spray modeling which could be validated using current measurements. In this work, a simple analysis showed that the droplet size distribution for different pressure or Weber number follows the breakup models closely.
In the later part of zone B the process of secondary breakup becomes weaker as shown by larger breakup time, \( t_b \). The centrifugal dispersion, however, becomes dominant removing the larger droplets towards the outer periphery of the spray and we see sharp decrease in droplet diameter. For both zone A and B, the coalescence process was always present but very weak due to high collision Weber number (\( We_{col} \)) which is reflected by the lower coalescence probability for all liquids and Reynolds numbers tested. However, beyond \( Z \sim 15\) mm, this process becomes stronger and dominant over other competing effects of breakup and centrifugal dispersion. Thus, we observe droplet diameter to increase sharply beyond this point. This zone with high probability of coalescence is labeled as zone C. It was also observed that at low Reynolds number the centrifugal dispersion is not as strong compared to larger Reynolds number thus allowing breakup to still occur towards the periphery of the spray at the first axial location.

When comparing the liquids with different thermal physical properties, it was discovered that when the surface tension falls below \( \sigma = 48\) mN/m the effects of surface tension is no longer present. In addition, at low Reynolds number the driving force for the reduction of the diameter profile is dominated by the surface tension whereas at high Reynolds number this is not the case where the results are similar. The inflexion point of when the transition from secondary breakup to coalescence is seen shifts closer to the nozzle for lower surface tension liquids. For majority of cases it was seen that the coalescence probability was higher for the lower surface tension solution than water. Similar to the diameter profile at larger Reynolds numbers the coalescence probability became similar to that of water. This suggests that although using a liquid with lower surface tension decreases the overall diameter profile throughout the measurement locations for low Reynolds number, the chances of coalescence increases as two droplets collide. At higher
Reynolds number it seems the inertia force is the dominant mechanism for coalescence. Investigating the sole effects of viscosity has shown that the higher the viscosity is the higher the droplet diameter becomes which is seen in the literature.

For comparison of real world liquids different fuels were also investigated. It was found that the liquid fuels produced similar trends as seen for water and the engineered liquids. Producing similar values for each fuel in the primary and secondary breakup regimes but deviating from one another in the coalescence zone. Kerosene was found to produce higher droplet diameters at the later axial locations followed by Jet-A and Ethanol. Since the fuels have similar surface tension and viscosity values it was hypothesized that the cause for this deviation in the coalescence zone could be due to the vapor pressure, which coincides with the order with the liquids. A preliminary case was done showing that the vapor pressure could be having an effect on the droplets in the coalescence regime. This causes the diameter to decrease with an increase in vapor pressure. For future testing of the vapor pressure effects a case was run with a hybrid liquid that matched the surface tension and viscosity of the liquid for suitability. This was shown to match both the liquid fuels that were compared but more so with Ethanol due to the closer value in vapor pressure. Suggesting that vapor pressure could also be a significant contributor in determining the droplet diameter once in the coalescence regime.
8.2 Future Work

8.2.1: Temperature Effects on Atomization Characteristics

As described in the previous chapter the potential effects of vapor pressure on the coalescence zone still needs further investigation. To do this a clear understanding is needed for various liquids and their behavior at elevated temperatures. To achieve such a goal, the spray facility needs modifications to ensure higher injected liquid temperatures with the reduction of heat loss from the injection lines. This can be done by incorporating heating tapes around the autoclave and insulating the autoclave and the injection lines. Several thermocouples should also be installed to measure the temperature drop along the injection lines for accurate temperature measurements. A detailed study should also be conducted on different surrogate fuels that compare reasonably well to the liquid fuels of interest for safety reasons. The system should also be updated for safety precautions due to the fuels that need to be tested at different temperatures.

Objective 1: Update the experimental setup to accommodate higher injection temperatures and safety by placing heating tapes, thermocouples, and insulation throughout.

Objective 2: Run the similar cases as done in this work with elevated temperatures while varying the pressure from 5bars, 10bars, 15bars, and 20bars. Repeat process for different nozzles and different surrogate liquids and fuels that will accommodate different vapor pressures.
8.2.2: Cross Flow Injection Setup

To further the understanding of the results obtained from the atomizer it is important to introduce a cross flow scenario. This will allow for further validation of the numerical results in real scenarios. The cross flow injection system in general will be an apparatus which will house an atomizing nozzle that would inject the liquid into a high temperature cross flow that will accommodate different laser diagnostic techniques to measure atomization/vaporization rates from the nozzle. The main components of the testing apparatus are a 250cfm variable speed blower connected to a three phase 240 volt 6kW heater. The heater has a maximum increase in temperature of 480°C at minimum flow rate and a minimum increase in temperature of 100°C at maximum flow rate, 110cfm. The blower is connected to the heater by a collapsible hose for mobility purposes. The heater lies on a two axis traverse system that allows the pipes with the nozzle to be moved in the X and Y plane for profiling the spray in all directions. After the heater lies a series of aluminum pipes and pipe fittings that are connected to make a 90° turn from the horizontal plane to vertically downward. This was done in order to get the appropriate measurements for the one dimensional PDPA system, PIV, and Shadowgraph. The last six inches of the downward pipe consist of 6 injection ports for the nozzle to be placed in. The different injection ports allows for different locations along the sprays trajectory to be measured. The complete setup can be seen in Figure 90 with the schematic shown in Figure 91.
Figure 90: Experimental setup for future results

Figure 91: Experimental schematic of future setup.
Objective 1: Run the test under ambient pressure and set the cross flow temperature from 20-100°C for one injection nozzle to study the fuel vaporization characteristics under different temperatures. Vary the fuel injection velocity when possible to obtain different fuel trajectories and fuel droplets data, such as velocity and size distributions.

Objective 2: Run the same temperature cases while varying the pressure from 5bars, 10bars, 15bars, and so on until 70bars is reached. Repeat process for different nozzle.

Objective 3: Use different biofuels and run the above tests under the same conditions, compare the different spray and vaporization characteristics for different fuels.

Objective 4: Using data from previous experiment as initial parameters in the numerical simulation validate results obtained experimentally with the numerical ones.
APPENDIX: DISCUSSION ON TAB MODEL
The most common analysis used to determine droplet breakup is the Taylor Analogy Breakup (TAB) model. This model is based on the oscillating and distorting of droplets similar to a spring mass system. Where the surface tension forces acts as the restoring force of a spring, the droplet drag force is the external force, and the viscosity forces is the damping force. The governing equation is as followed:

\[ F - kx - d \frac{dx}{dt} = m \frac{d^2x}{dt^2} \]  (A.1)

where \( x \) is the displacement of the droplet from its spherical position. These coefficients are then replaced by Taylor's Analogy.

\[ \frac{F}{m} = C_F \frac{\rho_g u^2}{\rho_l r} \]  (A.2)

\[ \frac{k}{m} = C_k \frac{\sigma}{\rho_l r^3} \]  (A.3)

\[ \frac{d}{m} = C_d \frac{\mu_l}{\rho_l r^2} \]  (A.4)

Within these coefficients \( \rho_l, \rho_g, u, r, \sigma, \) and \( \mu_l \) are the liquid and gas densities, the relative velocity, radius, surface tension and the viscosity of the droplet respectively. The coefficients \( C_F, C_k, \) and \( C_d \) are constants and will be defined later. For breakup to occur \( x > C_b r \) where \( C_b \) is a constant found to be 0.5. With the following equations a non-dimensionalized equation A.1 can be found by setting \( y = x/(C_b r) \) and is as followed.

\[ \frac{d^2y}{dt^2} = \frac{C_F \rho_g u^2}{C_b \rho_l r^2} - \frac{C_k \sigma}{\rho_l r^3} y - \frac{C_d \mu_l}{\rho_l r^2} \frac{dy}{dt} \]  (A.5)
Solving $y$ as a function $t$ gives the following equation:

$$y(t) = We_c + e^{-\left(\frac{t}{t_d}\right)} \left[ (y_0 - We_c) \cos(\omega t) + \frac{1}{\omega} \left( \frac{dy_0}{dt} + \frac{y_0 - We_c}{t_d} \right) \sin(\omega t) \right]$$  \hspace{2em} (A.6)

where

$$We = \frac{\rho_\ell u^2 r}{\sigma}$$  \hspace{2em} (A.7)

$$We_c = \frac{c_F We}{C_k C_b}$$  \hspace{2em} (A.8)

$$y_0 = y(0)$$  \hspace{2em} (A.9)

$$\frac{dy_0}{dt} = \frac{dy}{dt}(0)$$  \hspace{2em} (A.10)

$$\frac{1}{t_d} = \frac{C_d \mu_\ell}{2 \rho_\ell r^2}$$  \hspace{2em} (A.11)

$$\omega^2 = \frac{C_k \sigma}{\rho_\ell r^3} - \frac{1}{t_d^2}$$  \hspace{2em} (A.12)

From Experiments and theory $C_k$, $C_d$, and $C_F$ are 8, 5, and 0.33 respectively. When solved all droplets that produce a value of $y > 1$ will breakup. Once it is determined that the droplet will breakup it is important to determine the child droplets size and velocity. Given by the following equations:

$$r_{32} = \frac{r}{1 + 8K_y^2 + \frac{\rho_\ell r^3 (dy/dt)^2}{\sigma} \left( \frac{6K - 5}{120} \right)}$$  \hspace{2em} (A.13)

$$v_{normal} = C_v C_b r \frac{dy}{dt}$$  \hspace{2em} (A.14)

where $K$ is the ratio of the total energy in distortion and oscillation to the energy in the fundamental mode and on the order of (10/3) and $C_v$ is constant typically 1.


Chelko L.J., “Penetration of Liquid Jets into a High-Velocity Air Stream”, NACA Report RM E50F21 (1950)


Dumouchel, C., Cousin, J., Triballier, K., “On the role of the liquid flow characteristics on low-


