Title
Liquid Fuel Emulsion Jet-in-Crossflow and Dispersion Under High Pressure Conditions

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Liquid Fuel Emulsion Jet-in-Crossflow Penetration and Dispersion Under High Pressure Conditions

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE
in Engineering

by

Guillermo Andres Gomez

Thesis Committee:
Professor G. Scott Samuelsen, Chair
Professor Vincent G. McDonell
Professor Derek Dunn-Rankin

2014
Dedication

To:
My Grandmother Blanca Celena Villamizar de Gomez for inspiring me to live a life of kindness, nobility, and peace. Despite the many difficulties experienced in her life she found happiness in loving others and appreciating the simple things in life. I can only strive to be half the person she was and I wish she could have been around longer to see the fruits of her sacrifice emerge through the opportunities I have had.

My Grandmother Maria Ines Suarez for her constant nurturing, prayer, and love throughout my life. I have never met anyone with more courage and strength to overcome challenges. I am very inspired by her altruism as she has dedicated her life to caring for others.

My Grandfather Guillermo Ignacio Pena for leaving behind his home country to emigrate to the U.S. He has made it possible for me to enjoy the freedoms, rights, and opportunities that this country has to offer. His courage to pave a path of success in a new environment has inspired me to do the same throughout my college career.

My mother Vilma Amelia Gomez for her unconditional love and support. I am awed by her day in and day out hard work to provide for me and my siblings. I am truly blessed to have such a compassionate, intelligent, and loving woman as my mother. She has taught me that success is relative and that striving for perfection in the process of accomplishing goals is more important than the actual goals.

My father and best friend Ciro Hernando Gomez for supporting me through my successes and downfalls. His constant advice and recommendations have driven me to accomplish what I have thus far. At times of struggle and adversity I am reminded of his perseverance to survive in this country and provide better opportunities for me and my siblings. The lessons I learned through assisting him with physical labor growing up are more valuable than anything I can learn from a university, laboratory, or scientific endeavor.

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My niece and nephews Nicole, Thomas, and Jay for motivating me to become a better person and uncle.

My friends for their patience and encouragement while I completed this work.
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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Absorbance</td>
</tr>
<tr>
<td>a.u.</td>
<td>Arbitrary Units</td>
</tr>
<tr>
<td>c</td>
<td>Concentration</td>
</tr>
<tr>
<td>( C_d )</td>
<td>Nozzle Discharge Coefficient</td>
</tr>
<tr>
<td>CPS</td>
<td>Counts per Second</td>
</tr>
<tr>
<td>( \text{cm}^2 )</td>
<td>Square Centimeter</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>d</td>
<td>Droplet Diameter</td>
</tr>
<tr>
<td>( d_0 )</td>
<td>Fuel Discharge Orifice Diameter (Meter)</td>
</tr>
<tr>
<td>DF2</td>
<td>Low Sulfur Diesel Fuel #2</td>
</tr>
<tr>
<td>D-PLIF</td>
<td>Dual-Planar Laser-Induced Fluorescence</td>
</tr>
<tr>
<td>ETM</td>
<td>Edge Trace Method</td>
</tr>
<tr>
<td>fps</td>
<td>Frames per Second</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>I</td>
<td>Light Intensity</td>
</tr>
<tr>
<td>JNC</td>
<td>Jet-in-Crossflow</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>l</td>
<td>Path Length</td>
</tr>
<tr>
<td>LIF</td>
<td>Laser Induced Fluorescence</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>( \text{m}^2 )</td>
<td>Square Meter</td>
</tr>
<tr>
<td>( \text{m}^3 )</td>
<td>Cubic Meter</td>
</tr>
<tr>
<td>ms</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>( \dot{m} )</td>
<td>Mass Flow</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>Oxides of Nitrogen (NO &amp; NO(_2))</td>
</tr>
<tr>
<td>Oh</td>
<td>Ohnesorge Number</td>
</tr>
<tr>
<td>PITM</td>
<td>Pixel Intensity Trace Method</td>
</tr>
</tbody>
</table>
PSI: Atmospheric Pressure (Pounds Per Square Inch)
PSIG: Gauge Pressure (Pounds per Square Inch Gauge)
ΔP: Injector Pressure Drop
Q: Volume Fraction
q: Liquid-to-Gaseous Momentum Flux Ratio
r: Liquid sheet length
Re: Reynolds Number
s: Second
T: Light Transmittance
t: Liquid Film Thickness
U: Mean Velocity
u: Velocity
UCI: University of California, Irvine
UCICL: University of California, Irvine Combustion Laboratory
VMD: Volume Mean Diameter
\dot{\dot{V}}: Volume Flow Rate
W: Water
We: Weber Number
W/O: Water-to-Oil Mass Ratio
ε: Molar Absorptivity
Φ: Water Mass Fraction
Φ_v: Water Volume Fraction
ρ: Density
σ: Surface Tension (Liquid-Gas)
μ: Dynamic Viscosity
μm: Micrometer (Microns)
Abstract of the Thesis

Liquid Fuel Emulsion Jet-in-Crossflow Penetration and Dispersion Under High Pressure Conditions

By

Guillermo Andres Gomez

Master of Science in Engineering

University of California, Irvine 2014

Professor G. Scott Samuelsen, Chair

The current work focuses on the jet-in-crossflow penetration and dispersion behavior of water-in-oil emulsions in a high pressure environment. Both fuel injection strategies of using a water-in-oil emulsion and a jet-in-crossflow have demonstrated unique benefits in improving gas turbine performance from an emissions and efficiency standpoint. A jet-in-crossflow is very practical for use in gas turbine engines, rocket propulsion, and aircraft engines since it utilizes already available crossflow air to atomize fuel. Injecting water into a combustion chamber in the form of a water-in-oil emulsion allows for pollutant emissions reduction while reducing efficiency loses that may result from using a separate water or steam injection circuit. Dispersion effects on oil droplets are expected, therefore investigating the distribution of both oil and water droplets in the crossflow is an objective in this work. Understanding the synchronization and injection behavior of the two strategies is of key interest due to their combined benefits. A water-to-oil ratio and an ambient pressure parameter are developed for emulsion jet-in-crossflow trajectories. To this end, a total of 24 emulsion jet-in-crossflow tests
were performed with varying ambient pressures of 2-8 atm and momentum flux ratios of 50, 85, and 120. Sobel edge filtering was applied to each averaged image obtained from a high speed video of each test case. Averaged and filtered images were used to resolve top and bottom edges of the trajectory in addition to the overall peak intensity up to 40 mm downstream of the injection point. An optimized correlation was established and found to differ from literature based correlations obtained under atmospheric pressure conditions. Overall it was found that additional parameters were not necessary for the top edge and peak intensity correlations, but a need for a unique emulsion bottom edge and width trajectory correlation was recognized. In addition to investigating emulsion jet-in-crossflow trajectory correlations, a unique Dual Planar Laser Induced Fluorescence (Dual-PLIF) method was applied for the first time on emulsions at elevated pressure conditions. From the Dual-PLIF results, qualitative observations provided insight into the unique dispersion of oil and water concentrations within a cross-sectional plane down stream of the jet-in-crossflow injection.
1 Introduction

1.1 Overview

Combustion of hydrocarbon fuels is predominantly responsible for transportation, industrial power generation, and residential power generation. Despite its importance in society, it is also responsible for health hazards, smog, acid rain, global warming, and ozone depletion (Turns, 2000). The process of combustion contributes to approximately 85% of the energy consumed in the United States (Turns, 2000). Combustion is the process of transferring chemical energy into thermal energy by reacting fuel with oxidant. In gas turbine combustion, there are various types of liquid and gas fuels utilized. Accompanying the fuels used, various pollutants are produced as an end product of the process. The demand for efficient fuels with low pollutant emissions is greater now than ever with today’s growing energy demand and stringent government emission standards. Although gas fuels such as natural gas are popular for use in gas turbines due to their abundance and low emissions, there continues to be a great need for liquid fuels due to their high energy density and availability for certain applications. Some applications for the use of liquid fuels include electric utilities, oil pipeline service stations, ship propulsions, railroad locomotive, and aircraft propulsion. Stationary liquid fired gas turbines have a power output range of 5 – 113 MW and high efficiencies of greater than 34% for a simple cycle and greater than 53% for a combined cycle (Siemens energy, n.d.). Despite the fuel flexibility and efficiency of liquid fired gas turbines, the liquid fuel preparation requires 5% of the overall system energy (Siemens energy, n.d.). The preparation and atomization of fuel into the combustion chamber is influential to engine efficiency, flame stability, and pollutant formation.
More specifically these parameters are affected by the combustion flame temperature, fuel droplet size, and fuel droplet spatial distribution in the chamber. The combustion chamber although small compared to the entire engine, is the heart of the engine due to the impact its design and fuel injection strategy has on the overall engine performance (Lefebvre & Ballal, Gas Turbine Combustion, 2010). Figure 1.1 depicts a stationary gas turbine with the fuel delivery ports and combustion chamber encircled. Figure 1.1.2 is a zoomed in image of one of the combustors.

Figure 1.1 Stationary gas turbine highlighting the combustion section of interest
The ultimate goal in advancing gas turbine technology is to obtain high efficiencies and low pollutants. There is much emphasis in the gas turbine industry for reducing pollutants, especially Nitrous Oxides (NO\textsubscript{x}). Three mechanisms responsible for NO\textsubscript{x} formation in gas turbine engines are fuel, thermal, and prompt. Fuel NO formation results from Nitrogen bound to fuels such as coal. Prompt NO formation is evident in the initial stages of combustion as hydrocarbon radicals promptly bond to N\textsubscript{2} molecules in the ambient air. Thermal NO is the dominant mechanism at temperatures greater than or equal to 1800 K (Bowman, 1992). Formation of NO begins to increase exponentially at this temperature of 1800 K as seen in Figure 1.4 which is problematic due to the fact that this is also the temperature at which efficient combustion of fuel can occur. Both equivalence ratio and temperature determine the onset of NO and other pollutants such as CO and unburned hydrocarbons. Figure 1.3 depicts the relationship between temperature, equivalence ratio, and pollutant concentration growth (Heywood, 1998).
As demonstrated in Figure 1.3, the growth of NOx, CO, Soot, and unburned hydrocarbons HC can be significantly reduced by reducing the combustion chamber temperature and avoiding the stoichiometric equivalence ratio $\Phi$ of 1.0. In addition to the importance of combustion chamber temperature, proper atomization of liquid fuels provides high efficiency and low emissions for both aero and stationary gas turbine applications. To achieve this, an increase in fuel spray specific area (droplet spatial distribution) and a decrease in mean droplet size is necessary. Increase in specific area provides high rates of fuel mixing and evaporation. A decrease in mean
drop sizes provides higher volumetric heat release rates, lower pollutant emissions, larger fuel to air ratio ranges, and more efficient light off conditions. Several strategies have been developed over the years to reduce combustion temperatures and improve fuel atomization. To reduce combustion chamber temperatures, the direct addition of steam or water into the chamber is a strategy that has been used in gas turbine combustion over the years as illustrated in Figure 1.5.

![Figure 1.5 Reduction of NOₓ emissions over the years with implementation of water injection (Boyce, 2002)](image)

The addition of water to the fuel in the form of a water-in-oil emulsion prior to injection is an alternative fuel that is being considered. In addition to lowering the combustion chamber temperature, it is hypothesized that water-in-oil emulsions can increase combustion efficiency by further breaking down fuel droplets in the atomization process as well as promoting a more evenly distributed fuel burn (Kadota & Yamasaki, 2002). Although emulsions are predicted to improve the overall combustion process, special care must be taken when designing their optimal injection strategy since these emulsion fuels may behave differently than traditional single phase fuels.

An injection strategy for fuel break up in gas turbine combustors is the use of a jet-in-cross flow. Combustors utilize dilution holes to cool the combustor liner, reduce pollutant formation, and enhance atomization of the fuel. A jet-in-crossflow consists of a liquid jet of fuel
interacting with the surrounding fluid of moving air that is being injected. Although the jet-in-crossflow strategy has been investigated and optimized for the injection of neat fuels, application of this strategy on emulsion fuels is hypothesized to vary from the neat fuels in both far edge jet penetration and droplet dispersion behavior.

Previous research provides water droplet size data resulting from various water-to-oil ratios, shear rates, and atomization pressures (Christopher D. Bolszo, 2010). This thesis focuses on the use of water-in-oil emulsions for a jet-in-crossflow fuel injection strategy. Of particular interest are the penetration trajectories and fuel/water distribution of these emulsions as they are being injected from a plain jet orifice into a crossflow of air. Previously, emulsion jet-in-crossflow experiments were performed at atmospheric conditions to investigate the need for an optimized jet-in-crossflow penetration trajectory equation that incorporates emulsion quality. This atmospheric experimentation resulted in the conclusion that the existing jet-in-crossflow equation framework for pure fluids correlated well without the need for a modification that accounts for emulsion quality but differences in the instantaneous spray break up dynamics were observed. Despite the validity and importance of testing at atmospheric conditions, testing at elevated pressures is of great interest to both scientific research and industrial combustor design. In addition to investigating the elevated pressure influence further, jet-in-cross flow testing in a separate testing facility serves as a great validation for the atmospheric testing.

1.2 Goals

The overall goals of this research investigation are to 1) understand the impact of water-in-oil emulsions on the top edge trajectory, peak intensity trajectory, bottom edge trajectory and
spray plume width of a jet-in-crossflow and 2) understand the in-situ water and oil dispersion within an emulsion jet-in-crossflow spray.

1.3 Objectives

To meet the goals of the research, the following six objectives are necessary:

1) Retrofit UC Irvine High Pressure Facility to run emulsion jet-in-crossflow experiments
2) Characterize air flow through jet-in-crossflow test section
3) Utilize high speed video cinematography to produce time averaged images of emulsion jet-in-crossflows
4) Perform image analysis procedures to acquire top edge trajectory, peak intensity trajectory, bottom edge trajectory and spray plume width of emulsion jet-in-crossflows
5) Develop trajectory correlations from image analysis data
6) Perform Dual-PLIF diagnostic for emulsions jet-in-crossflows and report any observations on oil and water droplet dispersion behavior
2 Background

2.1 Emulsions

Combustion fuel quality is of great importance due to limited fuel availability and wide gas turbine engine applications. Fuel flexibility in heavy-duty gas turbine engines is in demand since gas turbines are expected to operate on lower-grade fuels in order to reduce fuel distillation costs. Some of these lower grade fuels include crude oils, residual oils, and fuels with lower heat content gases (A.D. Foster). Between 1950 and 1960, 78 gas turbines were installed to operate with heavy fuels for electric utilities, oil pipeline service stations, ship propulsion, and railroad locomotives. The use of heavy fuels in gas turbine greatly impacts the gas turbine design and materials used for construction. Fuel cost is the largest expense when it comes to power generation and due to this, fuel flexibility has been a principle design parameter for several gas turbine manufacturers despite the design complications that come about (A.D. Foster). The need for liquid fuel combustion strategies that promote fuel flexibility is a motivation for the study of emulsion fuels in addition to adding water as a method of reducing combustion temperatures.

An emulsion is a mixture of more than one fluid, with at least one of the fluids being immiscible. Emulsions have been used to control a product’s physical properties for centuries. Emulsions can be used to dilute materials that are either too expensive or too hazardous in their current concentration. Some examples of commonly used emulsions include pharmaceuticals, cosmetics, paints, and food products. Due to the immiscible condition of the fluids, the mixture is very unstable and surfactants are sometimes necessary to stabilize them. Without surfactants the two distinct fluids will separate from one another making the emulsion impossible to achieve. Surfactants accomplish this by reducing the interfacial tension of the fluids involved. A
surfactant molecule is part soluble in water and part soluble in oil which allows the mixing of two immiscible fluids; this maintains the molecules of the immiscible fluids as separate microscopic droplets (Randy Shueller, 2008).

In the application of emulsions in gas turbines there are two types of emulsions: oil-in-water and water-in-oil. An oil-in-water emulsion is made up of fine oil droplets dispersed in a continuous phase of water and water-in-oil being just the opposite with the water droplets dispersed in the oil (Kadota & Yamasaki, 2002). Adding water to the fuel in the form of an emulsion will reduce the overall viscosity of fuel and make it easier to atomize and burn fuels that are low grade with high viscosity. Water is typically added into the combustion chamber separate from the fuel line to lower combustion temperatures. Injecting water in the form of a water-in-oil emulsion will simplify the water injection process by reducing piping materials. In addition to the reduction of piping the atomization of emulsions has also been seen to promote the production of microexplosions where the water in an emulsion droplet will vaporize before fuel droplet which will cause the water vapor to expand and overcome the surface tension of the surrounding fuel creating smaller droplets (Christopher D. Bolszo, 2010). Combustion of these emulsions can have multiple benefits. Diluting oil with water will lower the droplet temperature during evaporation, resulting in a decrease in pyrolytic reactions. Pyrolytic reactions lead to carbonaceous residue and higher emissions in gas turbines; a consequence which is pertinent to the current resources. The time available for pyrolytic reactions is also reduced by decreasing droplet size. The smaller the size of the droplets, the less time there will be for the formation of carbonaceous residue. This not only lowers emissions but also improves the combustion efficiency within the combustion chamber. For a fuel to be ideal for combustion, the droplets must be large enough for penetration into the combustion chamber yet small enough for fast
gasification (Kadota & Yamasaki, 2002). Due to this, an emulsion can make a fuel more ideal for combustion. An emulsion will not only reduce the amount of fuel droplets that are left in the combustion chamber but will also increase the efficiency of low-volatile fuels and reduce thermal stress on the materials of the combustion chamber. Fluid properties of emulsions vary depending on the mixing ratio of water to oil. The properties that fluctuate depending on this ratio are viscosity, density, surface tension, and interfacial tension. The density of an emulsion, which depends on the concentrations of the water, oil, and surfactants, is directly proportional to the water/oil surfactant ratio. Viscosity affects the patternation or volume distribution of a spray when the emulsion is released into the combustion chamber. Viscosity is known to increase as water is added to the water-in-oil emulsion due to the increased density of water compared to oil. Surface tension is another important aspect of emulsions and it affects the size distribution of droplets within the emulsion. If the surface tension in the emulsions is altered with the addition of surfactants; low interfacial tension is obtained with increasing surfactant concentration which allows the emulsion to stay intact. The interfacial tension is the tension between the oil and water. Although droplets of either oil or water are formed in the emulsion they are likely to deform or combine with other droplets. Lower surface tension is possible with an increase in surfactants and this may provide more effective atomization.

2.2 Atomization

Atomization plays an important role in the area of combustion in furnaces, gas turbines, automobile engines, and rockets. Atomization is the process of breaking down a fluid and transforming it into a fine mist or spray. Atomization accomplishes the breakup of bulk fluids by applying external forces to the surface tension of the fluid. When these external forces are
applied, the fluid’s surface tension promotes the formation of spherical droplets and thus changing the geometry of the bulk fluid. The volume of the droplets formed from primary atomization can be further reduced through secondary atomization as the initial droplets continue to interact with exterior forces. The final volume and volume distribution of these droplets is of great importance to the overall combustion efficiency of an engine. The atomization process can be further understood by focusing on the breakup of a single droplet. When a liquid droplet is suspended in air, aerodynamic forces due to pressure distributions deform the droplet until a state of equilibrium is achieved between the aerodynamic forces and forces due to surface tension. Droplets become stable in size when the pressure at all points is in equilibrium with the surface tension of the droplet and at this stage the critical droplet size is reached and no further break up occurs. Fluid viscosity of the droplet is proportional to the time at which the droplet reaches this critical droplet size. The breakup of a droplet as it interacts with aerodynamic forces can be further demonstrated by Figure 2.1.

![Figure 2.1 Droplet interaction with aerodynamic forces](Lefebvre, Atomization and Sprays, 1989)
As depicted above, the droplet initially forms an ellipsoid shape as it is being flattened by pressure forces due to the surrounding air. Following this the droplet begins to elongate into a horizontal ligament until it bursts into small droplets out of the middle portion. The final outcome is a distribution of various size droplets. The main contributing parameters to final droplet size, distribution, and break up timing are the dynamic pressure from surrounding air, liquid surface tension, and liquid viscosity (Lefebvre, Atomization and Sprays, 1989). The Weber number is an important parameter used in atomization research to relate some of these parameters to one another. The aerodynamic Weber number is the ratio of aerodynamic force from dynamic pressure to force from surface tension.

\[ W_{e_{\text{aero}}} = \frac{\rho_g U_g^2 L}{\sigma} \]  

In the above Weber number \( (We) \) equation, \( \rho_g \) is the gas density, \( U_g \) is the gas velocity, \( L \) is the length of the stream, and \( \sigma \) is the liquid surface tension. The Weber number may also be defined based on the liquid density. Weber numbers above a critical value result in dominating aerodynamic forces which lead to further droplet breakup. Critical Weber numbers depend on the relative air to liquid velocity. Atomization strategies seek to increase this Weber number in order to accomplish fine droplet sizes (Sirignano, 2010). Several injector designs and injection strategies have been developed to control and optimize the atomization process. Of particular interest in the current study is the use of a plain jet injector and jet-in-crossflow strategy.

### 2.2.1 Plain Orifice Atomizer

One of the key mechanisms that occurs in atomization is the creation of disturbances in liquid jets and formation of waves. Both primary and secondary atomization require the
formation of instabilities. These instabilities can be observed from looking at a simple laminar jet exiting a circular orifice. In Figure 2.2 demonstrates that disturbances in the liquid jet lead to the growth of more disturbances forming wave like boundaries on the jet. The ends of these waves come together forming a neck which breaks due to surface tension and the jet transforms into droplets with some satellite droplets forming in between. The increase in jet velocity decreases the wavelength of the disturbances/oscillations which results in lower droplet sizes. From these observations, modes of atomization are classified into four groups based on the relative velocity between the liquid jet and surrounding air. The first group for low velocity results in a Rayleigh type mechanism where droplets are uniform in size, but tend to be twice the size of jet diameter. In the second mode also known as the first wind induced mode, velocity is increased leading to a decreased wavelength and a smaller droplet size that is close to the jet diameter length.

Figure 2.2 Liquid break up out of plain orifice atomizer (Lefebvre, Atomization and Sprays, 1989)
In the third break up mode also known as the second wind-induced mode, the fluid velocity further increases forming small wave ligaments immediately at the orifice exit that quickly break up into droplets smaller than the jet diameter. The fourth break up mode also known as the atomization mode is for very high jet velocities. Droplet formation occurs immediately in this mode at a short distance from the orifice exit without the formation of ligaments. Very small droplet diameters of less than 80 µm can be obtained at this mode, this mode is also known as the prompt atomization mode (Lefebvre, Atomization and Sprays, 1989). These four break up modes can be further described in Figure 2.3.

![Figure 2.3 Break up regimes for plain orifice atomizer (Lefebvre, Atomization and Sprays, 1989)](image)

Mapping Reynolds number for the liquid and the Weber number for the air allow for a better classification of the breakup modes and determination for the parameters is necessary to induce each mode. Increasing both Reynolds number and Weber number leads to the occurrence of each mode. Another dimensionless parameter used for mapping these modes is the Ohnesorge in Equation 2.2 which like the Weber number, relates viscous forces of the air to surface tension
forces of the fluid. The break up modes are identified in Figure 2.4 with a plot of Ohnesorge vs Reynolds number (Reitz, 1978).

\[ Oh = \frac{\mu}{(l_\rho \sigma)_{1/2}} \]  \hspace{1cm} 2.2

A plain orifice atomizer is the most commonly used atomizer due to its simple design. Its design is applied to garden hoses, shower nozzles, industrial spraying, inkjet printers, gas turbine engines, and rocket engines. The plain orifice atomizer is also commonly referred to as a pressure atomizer since its atomization depends mostly on the pressure drop across the nozzle. An example plain orifice atomizer is illustrated in Figure 2.5.
The atomization mechanism of these atomizers follows the previously described Rayleigh Mechanism where increases in jet velocity improve atomization and decrease droplet size. Discharge coefficients for plain jet orifices are dependent on the ratio of the inlet length to orifice diameter. Injectors with longer inlets tend to have lower discharge coefficients (Heister, 2011). The break up length or length between the nozzle tip and atomized droplet formation is dependent on the injection velocity and can be further described by the jet stability curve in Figure 2.6.
In the jet stability curve regime A-B-C results in dripping flow mode where the droplets are about twice the size of the orifice diameter. Regime C-D consists of the Rayleigh breakup mode where the drop diameter is about the same as the injector diameter. Regime D-F is mode three where droplets are produced from the growth of small waves at the injector exit. The atomization regime falls into the curve at F-G or H where the break up length lengths becomes close to the nozzle and small droplet diameters are obtained (Heister, 2011).

2.2.2 Jet-in-crossflow

The application of liquid jets in subsonic crossflows is evident in propulsion systems for turbojet sections, ramjet combustors, and scramjet combustors. The liquid jets are injected from the combustor walls perpendicular to the air stream, therefore utilizing high subsonic and supersonic crossflows that are available in the engine combustion chambers. For characterization of a jet-in-crossflow spray behavior, correlations for penetration heights and plume trajectories are of special interest. The maximum penetration height is considered the distance required to
redirect the liquid jet injection momentum flux to the direction of the airstream. In the work by (Wu, Kirkendall, & Fuller, 1997) penetration height was measured at 6.25 jet diameters downstream and correlated with the momentum flux ratio \( q \) which is the momentum of the liquid jet to the momentum of the crossflow air.

\[
q = \frac{\rho_l U_l^2}{\rho_g U_g^2}
\]

The momentum flux ratio is a key indicator for jet penetration heights with a higher momentum flux ratio resulting in greater penetration heights. It is important for the momentum flux ratio to be at a value where it is high enough to allow the jet to penetrate well into the air flow of a combustion chamber but not too high where the liquid jet comes into contact with the combustion chamber walls (Schetz, 1977).

While various correlations from Ingebo, Chelko, and Inamura have been developed for maximum penetration, these were all developed for 10 diameters downstream of the nozzle exit, which lacks information regarding the near-field structure and breakup process. Results from Reichenbach and Horn found that jet trajectories were insensitive to liquid property variations and could be solely correlated using momentum flux ratio average (Reichenbach, 1971). Similarly Nejad and Schetz found that surface tension was negligible for penetration heights but that jets with smaller surface tension had a faster jet disintegration process and produced smaller droplets (Nejad & Schetz, 1984). The formation of spherical droplets in an airflow is due to aerodynamic forces acting on the fluid (Wu, Kirkendall, & Fuller, 1997). In the work of Wu et al. liquid jets from a tapered nozzle were injected vertically and perpendicular to a subsonic
crossflow and a frequency-doubled YAG laser was used to freeze the motion of the liquid column and droplets providing shadowgraphs of the spray. The liquid composition, nozzle diameters, injection velocities and air velocities were varied in (Wu, Kirkendall, & Fuller, 1997). These shadowgraphs allowed for the characterization of the near field liquid breakup regimes in an air crossflow as presented in Figure 2.7. When a crossflow of air is introduced to a jet of liquid vortex shedding of the liquid occurs producing oval shaped ligaments. Clark et al. have modeled the occurrence of vortex shedding taking place behind the jet and counter-rotating vortex pairing occurring throughout the jet as seen in Figure 2.8. These different break up regimes can also be quantified and plotted on a regime map as described in Figure 2.8 (Clark, 1964).

Figure 2.7 Schematic of jet-in-crossflow near field liquid jet break up (Wu, Kirkendall, & Fuller, 1997)
In Figure 2.7 it is seen that the liquid jet bends and begins to deform with waves beginning to propagate on the windward side of the jet. The waves are seen to grow until column break up begins to occur leading to the onset of the column break at a point known as the fracture point. At the fracture point ligaments are formed on the windward side of the jet and on the lee side of the jet or the bottom, droplets begin to shed off. Previous jet in crossflow experiments have introduced the concept of two-stage jet break up. These two stages consist of primary and secondary breakup for which research and understanding of the two has been ongoing. It has been found that when liquid/gas density ratios are large, the liquid jets exhibit low turbulence intensity and that the jet breakup process is dominated by wall boundary-layer vorticity along the nozzle passage, also known as liquid turbulent eddies. It has also been observed that when the liquid/gas density ratios are low the secondary break up stage combines with the primary. The secondary break up stage consists of four major breakup regimes: 1) bag, 2) multimode, 3) shear, and 4) catastrophic breakup. In the secondary breakup processes, small
droplets are stripped along the edge of the parent drops and correlations have been obtained from approximating final drop sizes with boundary layer thickness on the all windward side of the droplet surface. The jet-in-crossflow liquid break up process is divided into a primary breakup mode where the fracture point occurs along with surface break up and a secondary break up mode further downstream where the smaller droplets are present (Wu P. K., 1998). Ligament break up in the primary break up mode was modeled by Clark et al. in Figure 2.9. In this figure, aerodynamic forces from the crossflow come into contact with the windward liquid jet surface resulting in a pressure distribution the surface of the jet that then flattens the jet into an elliptical shape allowing for ligaments to be torn off the jet as a result of tangential shear forces.

![Figure 2.9 model of ligament formation caused by jet deformation (Clark, 1964)](image)

Atomization and droplet production in the secondary break up mode is modeled and described by Hinze et al. in Figure 2.10 (Hinze, 1995).
In this break up mode large droplets produced form the primary mode are flattened into a flat oval shape and stretched to point where it bursts and converts into smaller atomized droplets. In Figure 2.10 the large droplet transforms into three shapes being lenticular, cigar-shaped, and bulgy prior to being broken down into the atomized droplets (Hinze, 1995).

### 2.2.3 Penetration Correlations

There have been several studies focused on the development of jet-in-crossflow theories and correlations. Both empirical and analytical models have been produced to describe the jet trajectory as well as average drop size distributions for the jet-in-crossflow. The overall observation from the studies is that larger droplets form the jet-in-crossflow can be found at the core of the plume and smaller droplets near the leeward side. The existence of atomized droplets is dependent on the momentum flux ratio value and the onset of secondary atomization (Leong Y., 2000).

Leong et al. have applied a Lagrangian-based analysis to the droplet break up process in a jet-in-crossflow by equating droplet motion with both viscosity and pressure related drag forces. Figure 2.11 provides the free body diagrams and equations for this this break up phenomenon. The assumptions used to proceed with the analysis are the following: droplet is spherical, droplet
does not undergo additional break up, vaporization of the droplet is neglected, lift is neglected, virtual mass is neglected, and Basset force is neglected. With these assumptions, only the drag and body forces are considered.

Figure 2.11 Jet-in-crossflow diagram describing the droplet dynamics and free body diagrams

The first step in the analysis is to establish a general force balance of the forces acting on the droplet in equation 2.4 with \( F_d \) being the net force moving the droplet. The drag force is displayed in equation 2.5 with the magnitude of the droplet relative velocity \( |U_R| \) displayed in equation 2.6 and the buoyant or body force in equation 2.7.

\[
F_d = -F_{\text{drag}} + F_{\text{body}} \tag{2.4}
\]

\[
F_{\text{drag}} = -\frac{1}{2} \rho_g U_R |U_R| A_d C_D \tag{2.5}
\]
\[ |U_R| = \sqrt{(u_d - u_g)^2 + (w_d - w_g)^2} \]

\[ F_{body} = (\rho_d - \rho_g)V_d g \]

The velocity in the x-direction is denoted as \( u \) and the velocity in the z-direction is denoted as \( w \) while the subscript “\( g \)” refers to the crossflow air and the subscript “\( d \)” refers to the droplet.

Putting together the above equations allow for the derivation of momentum equations in the x and z directions as demonstrated in equations 2.8 and 2.9. (Leong Y., 2000).

\[ \rho_d V_d \frac{du_d}{dt} = -\frac{1}{2} \rho_g (u_d - u_g)|U_R| A_d C_d \]

\[ \rho_d V_d \frac{dw_d}{dt} = -\frac{1}{2} \rho_g (w_d - w_g)|U_R| A_d C_d + (\rho_d - \rho_g)V_d g \]

\[ \frac{dx}{dt} = u_d \]

\[ \frac{dz}{dt} = w_d \]

In addition to identifying the physical forces that act on jet-in-crossflow droplets, looking at the overall penetration of the jet. Wu et al. have developed correlations that balance liquid acceleration forces with the aerodynamic forces from the crossflow (Wu, Kirkendall, & Fuller,
The schematic used to proceed with development of these correlations is presented in Figure 2.12.

![Figure 2.12 Force diagram schematic demonstrating interaction of forces aerodynamic forces on surface tension forces (Wu, Kirkendall, & Fuller, 1997)](image)

With the use of the above schematic, correlations were developed for column trajectory, transverse height of the column fracture point, and axial distance of column fracture point.

\[
\frac{y}{d} = 1.37 \sqrt{q\left(\frac{x}{d}\right)} \tag{2.12}
\]

\[
\frac{y_b}{d} = 3.44 \sqrt{q} \tag{2.13}
\]

\[
\frac{x}{d} = 8.06 \tag{2.14}
\]
The differences in liquid composition and viscosity between cases were taken into account in the calculation of the discharge coefficient which is used to calculate the velocities for the momentum flux ratio \( q \). Interestingly the axial distance of the column fracture point was found to be a constant distance of 8.06 +/- 1.46 Jet diameters downstream of the nozzle. This is due to force balances between aerodynamic and surface tension forces because although larger aerodynamic forces increase the axial liquid acceleration, they also reduce the time required for the column to fracture and the two effects cancel each other out resulting in a constant axial distance of column fracture. Effects of aerodynamic forces on liquid turbulence and cavitation were neglected; therefore, the authors suggest future research on correlations that account for these effects (Wu, Kirkendall, & Fuller, 1997).

Several penetration correlations have been developed by various authors. Each correlation is specific to a momentum flux ratio range. The equation framework in equation 2.15 for penetration heights includes momentum flux ratio \( q \), nozzle diameter \( d \), and downstream distance \( x \) in order to predict the penetration height \( y \). This equation was developed for a \( q \) range of 5-50 (Wu P. K., 1998). Equation 2.16 is a modification of equation 2.15 by Hassa et al. for elevated pressure conditions and a \( q \) range of 1-40 (Rachner, 2002). Equation 2.17 by Stenzar et al. took the aerodynamic Weber number into consideration in addition to fluid viscosity of the fuel in comparison to water (Stenzler, 2003). Equation 2.18 by Biorouk et al. is similar to 2.17 but does not take Weber number into account (Birouk, 2007). Equation 2.19 produced by Lee et al. was developed for a large \( q \) range of 3-200 takes into consideration the discharge coefficient. Since equation 2.19 has such a large range of momentum flux ratio it may be useful for applicable gas turbine conditions.
\[
\frac{y}{d} = a q^b \left( \frac{x}{d} \right)^c \quad 2.15
\]

\[
\frac{y}{d} = a q^b \ln \left( 1 + c \left( \frac{x}{d} \right) \right) \quad 2.16
\]

\[
\frac{y}{d} = a q^b \left( \frac{x}{d} \right)^c We^e \left( \frac{\mu_l}{\mu_w} \right)^f \quad 2.17
\]

\[
\frac{y}{d} = a q^b \left( \frac{x}{d} \right)^c \left( \frac{\mu_l}{\mu_w} \right)^f \quad 2.18
\]

\[
\frac{y}{dq} = \sqrt{\pi \left( \frac{x}{C_d \ dq} \right)^a} \quad 2.19
\]

### 2.3 Atomization of Emulsions

#### 2.3.1 Penetration of Jet-in-Crossflow

The above equations have been developed for neat fuels and although some take into consideration water viscosity it is only as a viscosity reference. Bolszo et al. has taken these equations into consideration for the development of an emulsion jet-in-crossflow penetration correlation. For emulsion fuels it was found that that equation 2.15 developed by Wu et al. gave the best fit linear correlation of the emulsion experiments performed at atmospheric conditions. A linear least squares regression analysis was performed on the emulsion jet-in-crossflow data providing the correlation plot in Figure 2.13. The test matrix for the experiments performed in this study consisted of using two nozzle diameters, two emulsion concentrations, and three
crossflow air flow rates. Top edge traces were made of the jet-in-crossflow plumes by averaging frames taken of the high speed video footage.

![Graph showing correlation of emulsion trajectories using coefficients optimized for atmospheric pressure.](image)

**Figure 2.13** Correlation of emulsion trajectories using coefficients optimized for atmospheric pressure

Bolszo et al. found the best optimized coefficients for equation 2.15 to be $a=1.32$, $b=0.46$, and $c=0.45$ with an $R^2$ value of 0.97149. These results in comparison to those of Wu et al. demonstrated the leading coefficient “a” was the only one seen to vary between studies of neat fuels and emulsions fuels allowing them to attribute differences to momentum flux ratio and emulsion density. This concluded that an addition equation framework or correlation from neat fuels to emulsion fuels is not necessary for atmospheric conditions based on the average penetration behavior. Although on average emulsions were not observe to impact penetration
trajectories, the researchers noticed deviations from neat fuels in the breakup mechanism of the jet breakup behavior by visual observation (C.D. Bolszo G. G., 2012).

2.3.2 Component Specific Behavior

Unlike a single component liquid, an emulsion features multiple components, each with its own physical properties such as density, viscosity, and surface tension. Because the emulsion is unstable, the components will separate over time. As a result, due to differing physical properties, it is possible that each component will behave differently within the spray plume. As a result, a means to study the behavior of each component is of interest. Patternation methods have some potential to help isolate the two components and provide a means for determining the water to oil distribution throughout an emulsion spray.

2.3.2.1 Mechanical Patternation

Mechanical patternation is a straightforward way of obtaining the volume distribution of an emulsion spray. Bolszo carried out mechanical patternation experiments for both stable and unstable emulsions. This procedure consists of placing a row of glass sampling tubes directly under the spray. The sampling tubes are covered until the desired emulsion quality is reached and are then quickly uncovered to allow the test tubes to fill. This experimental set up is displayed in Figure 2.14 (Bolszo, 2011).
Since water and oil in both stable and unstable emulsions will eventually separate, their volumes within the sample tubes can be measured. These measurements provide both the pattern of the spray in addition to the individual water and oil component distributions. Bolszo concluded from this study that stable and unstable emulsions behave similarly when atomized. Bolszo also concluded that larger water to oil ratios are present at wider spray angles which is due to the relative densities of the liquids. Bolszo also found that a water to oil mass fraction of 0.38 was optimal for obtaining the best atomization in terms of smallest most well dispersed oil droplets (Bolszo, 2011).

2.3.2.2 Optical Patternation

Optical patternation is another method of obtaining spray patterns and component distributions. The benefit of optical penetration is that it is non-intrusive and the concentration of individual components can be calculated from the fluorescence intensity of component molecules. This can be described from the theory of absorption spectroscopy. Absorption
spectroscopy deals with electron absorption of photons. Electrons absorb photons and move into an excited molecular orbital. Once this excited orbital is reached, energy is released and the electron transitions to a ground state orbital. As the electron transitions to the ground state orbital it passes through several vibrational levels releasing energy in the form of fluorescence at different wavelengths at each level also known as electronic states. This process of releasing energy at the different states can be better described in Figure 2.15.

![Figure 2.15 Electronic transition energy level diagram (Skoog, 2007)](image)

As demonstrated in Figure 2.15 light energy of a certain wavelength is initially absorbed exciting the electron and then vibrational relaxation occurs where energy is released in the form of vibrational energy. Following vibrational relaxation, energy release further occurs in the form of fluorescence where a photon is emitted as the molecule’s electrons transition from an excited singlet electronic state to a lower state or singlet transition state where the electron has the same spin multiplicity. The next stage in the energy release process is phosphorescence where another
photon is released as the electrons transition from an excited triplet state to a lower state but with a different spin multiplicity. In order to obtain a fluorescence emission spectrum, the excitation wavelength must be held constant in order to measure the fluorescence emission spectrum. The excitation spectrum is expected to closely mirror the absorption spectrum since emission intensity is proportional to the absorbance spectrum of a molecule (Skoog, 2007).

The wavelengths at which certain substances absorb photons vary and a spectrophotometer is used to discover these wavelengths (Lakowicz, 2006). The spectrophotometer is used to measure the transmittance and absorbance as shown in equations 2.20 and 2.21.

\[ T = \frac{P}{P_0} \tag{2.20} \]

\[ A = \log_{10}\left(\frac{P_0}{P}\right) \tag{2.21} \]

T= Transmittance

P= Photons exiting sample

P_0= Photons entering sample

A= Absorbance

Transmittance is the ratio of light that exits a sample to the light that enters a sample. Absorbance is the logarithm of this ratio’s inverse and this is the value used in the investigation of a substance’s absorption at various wavelengths (Lakowicz, 2006).
2.3.2.3 Planar Laser Induced Fluorescence

Planar Laser Induced Fluorescence (PLIF) is a non-intrusive diagnostic for measuring species concentration, temperature, and velocity. PLIF utilized a laser sheet to induce fluorescence out of species. The fluorescence signal from the species is then captured by a CCD (Charged Coupled Device) camera. This camera is able to capture intensity images with unique intensity values pertaining to each pixel. CCD cameras tend to be very sensitive to light signals which is needed for low fluorescence intensities. Since fluorescence signal will vary based on the fluorescence properties of the fluorescing molecule and the power intensity of the incident laser, CCD cameras come with adjustable gains depending the order of magnitude of the signal. For some flows external tracers must be added but for many applications such as combustion, combustion radicals will naturally serve as fluorescent tracers. Relevant results from PLIF experiments will result in molecular concentrations being proportional to fluorescence signal (Hecht, 1998). An example experimental set-up of PLIF is illustrated below in Figure 2.16.

Figure 2.16 Example PLIF set up utilizing a 266 nm YAG Laser (Leong Y., 2000)
The set up in Figure 2.16 utilizes dichroic mirrors in order to produce 532 nm and 1024 nm wavelengths from a laser beam of 266 nm wavelength. The beam of interest in this set up is the 532 nm wavelength beam therefore it is passed on to be spatially filtered and transformed into a laser sheet. The 532 nm wavelength laser light will then be absorbed by the experimental substance causing it fluoresce at a longer wavelength. Optical filters are then used to capture fluorescence of specific wavelength light in order to detect the concentration of the species under investigation (Leong Y., 2000).

2.4 Summary of Background

A review of literature on jet-in-crossflow and water-in-oil emulsions demonstrates their advantages in gas turbine fuel injection technology from both a pollution control and engine efficiency standpoint. From a pollution control standpoint, the use of an emulsion can allow for a reduction in NOx, CO, and unburned hydrocarbons by improved temperature control and fuel atomization within the gas turbine. From an efficiency standpoint the jet-in-crossflow injection strategy allows for the utilization of combustion chamber air to break down and atomize liquid fuel saving on the efficiency cost of having to largely increase the injection pressure using a pressure atomizer. Previous research on water-in-oil emulsions also highlights improvements in fuel atomization with the use of emulsions due to flow instabilities that result from water in oil interaction in the flow in addition to improved atomization from the phenomenon of microexplosions. Background research on diagnostics for evaluating component specific behavior highlights both an opportunity and a challenge. This work involves running experiments at elevated pressure conditions which requires much attention to detail and safety. In order to provide high pressure conditions, the test area must be enclosed and therefore making it
impossible to perform the mechanical patternation technique described in section 2.3.2.1. An optical patternation approach will be necessary for this work and it will require developing a technique that can optically single out both oil and water components. The Planar Laser Induced Fluorescence Technique reviewed in section 2.3.2.3 can serve as a foundation for developing a technique that can optically separate both oil and water within an emulsion spray. This thesis utilizes these diagnostics to bridge the gap between atmospheric behavior on emulsions jet-in-crossflows and their behavior at elevated pressure conditions.

From reviewing literature on emulsion studies, no current research for emulsion jet-in-crossflow correlations at elevated pressure conditions exists. Elevated pressures result in an increase in ambient pressure density which increases the aerodynamic Weber number. Previous research on emulsions in a jet-in-crossflow highlights the relationship between Weber number, momentum flux ratio, and jet-in-crossflow break up regimes but does not highlight any elevated pressure effects that may be present. Recent work by Bolszo et al. on emulsion jet-in-crossflows at ambient pressure conditions resulted in momentum flux ratio being the main driver for penetration trajectories rather than emulsion quality. In order to conclude that additional correlations for the plume top edge trajectory or bottom edge trajectory are not necessary for emulsions in a jet-in-crossflow, experiments must be observed at elevated pressure conditions that are applicable to actual gas turbine engine conditions. To fill the void on the study of emulsions jet-in-crossflows and address the question whether elevated pressures effect emulsion penetration behavior, it is necessary to apply the diagnostics used for the atmospheric pressure conditions on the elevated pressure cases. This will allow for the discovery of any new equations necessary for adequately predicting the penetration and dispersion behavior of emulsions in a jet-in-crossflow.
3 Goals and Approach

The background research described in section 2 has aided in developing a strategic approach to accomplish the overall research goals of investigating the impacts of water-in-oil emulsions on both spray plume trajectories and the water and oil droplet distributions for jet-in-crossflows. The research tasks necessary to accomplish these goals consists of test facility development, laser diagnostic development, generating image analysis procedures, and performing statistical operations. The specific tasks are described below:

Task 1: Retrofit UC Irvine High Pressure Facility to run emulsion jet-in-crossflow experiments

The UC Irvine high pressure facility was previously in use for the testing of gaseous fuels. To accommodate for liquid fuel emulsion experiments pumps must be installed, plumbing systems are needed, and inside of the pressure rig must be customized to run jet-in-crossflow experiments. Design and manufacturing of a custom test section is also necessary to run experiments inside of the rig.

Task 2: Characterize air flow through jet-in-crossflow test section

One of the key design criteria for designing the jet-in-crossflow test section is a low turbulent intensity and uniform flow. Previous research on jet-in-crossflow break up regimes demonstrated the importance between the interaction of gaseous flow aerodynamic forces and liquid viscosity forces. In order to verify the uniformity of the crossflow air in the experiments, a laser Doppler velocimetry diagnostic will be used. This diagnostic also allows for boundary layer observation. Several points on the test section must be used for flow velocity measurements.

Task 3: Utilize high speed video cinematography to produce time averaged images of emulsion jet-in-crossflows
Capturing high speed video of the jet-in-crossflow will be the primary diagnostic used for obtaining spray plume trajectories and widths. High speed videos will be captured for various liquid compositions, momentum flux ratios, and ambient pressures. Two test matrices will be developed to run experiments using two different diameter plain jet injectors. Emulsions will be tested at two different water to oil ratios in addition to testing neat DF2 and water. Several experiments will be repeated to confirm experimental results.

**Task 4: Perform image analysis procedures to acquire top edge trajectory, peak intensity trajectory, bottom edge trajectory, and spray plume width of emulsion jet-in-crossflows**

Several frames obtained from high speed videos will be averaged into a single picture of the spray plume. Each averaged image will then be filtered using an edge Sobel filtering operation. The edges will be traced following the appropriate edge filtering. In addition to tracing the top edge of the spray using edge detection techniques, a pixel intensity approach will be used for top edge tracing. The intensity value of each pixel must be evaluated in order to locate the peak intensity, top edge, and width at each section of the spray.

**Task 5: Develop trajectory correlations from image analysis data**

Emulsion trajectory correlations for testing at various ambient pressures will be developed and compared to those obtained from previous atmospheric testing. In previous atmospheric testing it was concluded that top edge penetration trajectories for emulsions in a jet-in-crossflow were not significantly different than those for neat liquids. Using the same equation framework from previous atmospheric testing, new coefficients for the elevated pressure spray tests will be calculated. The coefficient deviation from the atmospheric coefficients will determine the necessity of a secondary correlation for emulsion jet-in-crossflow trajectories.
Task 6: Perform Dual-PLIF diagnostic for emulsions jet-in-crossflows and report any observations on oil and water dispersion behavior

An understanding for the spatial distribution of water and oil in emulsion jet-in-crossflows is of great interest. The penetration trajectories alone may not be sufficient to characterize key differences between using emulsions instead of neat fuels. To have a better understanding on how oil and water will separately be dispersed when injected as an emulsion, the Dual-PLIF diagnostic must be further developed and applied to emulsion jet-in-crossflows. The Dual-PLIF diagnostic has never been applied at high pressure conditions or for emulsions in a jet-in-crossflow. This task will primarily address the research goal of understanding the in-situ water and oil distribution of an emulsion jet-in-crossflow and bring about some qualitative observations regarding the distribution of water in oil in the spray plume.

Task 1 regarding the retrofitting of the high pressure facility is addressed in section 4.3. Task 2 of characterizing airflow of test section is addressed in sections 4.4.2 and 5.1. Task 3 involving the acquisition of picture frames from high speed video cinematography is described in section 4.4.1. Task 4 of extracting trajectory data points from images is described in section 4.4.1.1. Task 5 pertaining to the development of trajectory correlations for top edge, peak intensity, and plume width is provided in section 5.2. Task 6 involving the investigation of water and oil dispersion of emulsion jet-in-crossflows is found in sections 5.3 through 5.3.4.
4 Experiment

4.1 Test Liquids

Liquids used to generate unstable water-in-oil emulsions for experimentation include filtered water and low sulfur diesel distillate fuel #2 (DF2). Table 4.1 lists these liquids with some of their corresponding fluid properties.

Table 4.1 Table of liquids used with properties based on atmospheric conditions

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Formula</td>
<td>H₂O</td>
<td>C₁₀₋₁₄H₂₀₋₂₈</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>1012</td>
<td>825</td>
</tr>
<tr>
<td>Viscosity, kg/m-s</td>
<td>1.37E-03</td>
<td>2.93E-03</td>
</tr>
<tr>
<td>Surface Tension, kg/m²</td>
<td>0.0693</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

Emulsion fluid properties have also been previously measured at the UCICL (UCI Combustion Laboratory) using a graduated cylinder, electronic mass scale, falling ball viscometer for viscosity measurements, a stalagmometer for surface tension measurements, and the pendant drop method for interfacial tension. Surfactants were utilized to stabilize the emulsions and make these measurements possible. The table below depicts these measurements emulsion property characterization.
4.2 Injectors

Three plain jet orifices were fabricated based on a specific hole diameter and length that was indicated by Siemens (project sponsor). The orifices were fabricated with a through hole length of 8 mm and diameter of 0.57, 0.60, and 0.72 mm. For simplicity and reduction in fuel costs, the 0.6 mm orifice was not used. Figure 4.1 is a computer aided design of the orifice.

Figure 4.1 Computer aided design drawing of orifice nozzle. (Left to right) View positioned into axial jet axis and alongside cross-section profiles. All dimensions in millimeters.

Although the hole length and diameter were key design instructions, the remaining design of the injectors was based on the test section parameters. Initially these injectors were used in atmospheric jet-in-crossflow testing and designed to fit the existing jet-in-crosflow injection wall. In order to fit the injector piece into the small confinements of the high pressure rig, the injection tube was customized to fit well into the injector and test section. For simplicity the injectors were designed to fit into a Swagelok half inch nut using readily available tubing and other Swagelok
nuts. This injection tube displayed in Figure 4.2 conveniently connects to a quarter inch flex line on the other side.

Figure 4.2 Fuel injection tube made of Swagelok pieces and connecting with plain jet orifice

4.3 High Pressure Jet-in-Crossflow Facility Modifications

The elevated pressures combustion facility at UC Irvine has been commissioned for various projects over the years. Most recently the facility was used for flashback, blowout, and emissions studies burning high hydrogen content fuels. Many of the fuel lines, valves, controls, and display monitors were customized to run these gaseous fuels. In order to proceed with the emulsion spray experimentation, several modifications to the facility were necessary. A new test section was fabricated to fit the hardware inside the rig and perform the jet-in-crossflow experiments. An airbox was also installed inside of the rig to direct air flow through the test section. The bottom of the rig was also changed out for the collection of liquids in addition to the installation of steel wool downstream of the test section to prevent upwards movement of liquid droplets. Although it was fairly simple to reinstall a previous existing fuel line, an entire new
plumping system for water injection was introduced to the high pressure facility increasing its fuel flexibility.

4.3.1 Test Section

The test section, shown in Figure 4.3 was designed and fabricated to smoothly transition the cross flow air from the airbox into a two inch by two inch cross section. The two inch dimension was set based on expected trajectory calculations. The test section was also modified to fit the same plain jet orifice injectors used in past atmospheric tests and allow for a laser sheet through the middle for future diagnostics. A schematic cross-section of the test section is depicted installed in the high pressure rig in Figure 4.4.

![Figure 4.3 Test section design based on trajectory calculations](image-url)
4.3.2 Pressure Readings and Fuel Circuit

In order to compensate for any air leaking past the air box or even minor window and airline leaks, pressure taps were added to calculate the effective area through the jet-in-cross flow section. With this information, the actual mass flow of air through the test section could be determined. Check valves were also added upstream of the emulsion injection line to prevent back flow into both DF2 and water pumps. Static fuel filters were added inline in order to create a fine emulsion quality upon combining water and oil in the T-junction. The filter contained a matrix with a 190 micron diameter hole size. The pressure taps, valves and fuel flow circuit leading into the test section are shown in Figure 4.5.
In addition to the pressure taps used to measure rig pressure upstream and downstream of the test section, a pressure transducer was added upstream of the fuel emulsion line. This pressure transducer in addition to Emerson Elite Series Coriolis Flow meters allow for liquid flow velocity measurement out of the nozzle. The pressure transducer measures the pressure drop across the injector while the flow controllers measure the mass flow rate of the fuel and water through the injector. The flow controllers allowed for both rough and fine control of the diesel fuel and water as demonstrated in Figure 4.6.
4.3.3 Rig Rotation & Bottom Change Out

The test rig was rotated (~74°) to allow for high-speed cinematography, Laser Doppler Velocimetry, and Dual-PLIF to probe the spray through access windows in the rig, as shown in Figure 4.7.
The bottom of the test rig was switched out to allow for the use of liquid fuels. The bottom displayed at position 2 is more well suited for the collection and exhausting of liquids compared to the bottom piece used for gaseous fuels in position 1, shown in Figure 4.8.

![Figure 4.8 Transition of rig bottom](image)

### 4.3.4 Air Box Switch

An air box was installed in the high pressure rig in order to develop the flow of air injected into the jet-in-cross flow area. To minimize air leakage, a rope seal was added to the area surrounding the air box, shown on the left in Figure 4.9. Despite the use of rope seal and other sealants some leakage is inevitable making the use of pressure taps necessary for the determination of effective areas and thus crossflow velocities.
4.3.5 Fluid Pumping System

Originally it was planned to use the liquid fuel infrastructure associated with the atmospheric test stand. However, operation at elevated pressure significantly increased the liquid flow rates and therefore the existing system was determined to be insufficient. As a result, separate pumps were installed for pumping both DF2 and water into the high pressure rig. The DF2 pump is a internal gear pump model CIG 22005A RDW. This internal gear pump has a suction inlet that can simply be dipped into the DF2 barrel for DF2 pumping. The water pump installed is a diaphragm pump model Hydra Cell P200 Metering Pump requiring an inlet pressure of at least 15 psi and therefore was connected to an existing water line in the laboratory. A combined 80 feet of tubing was installed to pump fluids from both pumps. The water pump required an additional dampener for flow stability while the DF2 pump did not. Figure 4.10 shows the two pumps utilized and Figure 4.11 presents an overall piping and instrumentation diagram for the liquid injection subsystem.
Figure 4.10 DF2 and water pumps installed behind testing facility

Figure 4.11 DF2 and water flow schematic for high pressure facility
4.4 Diagnostics

4.4.1 High Speed Cinematography

A Phantom v7.1 (Vision Research) digital high speed camera is used at a 7 µs exposure time, with 100 µs interval at 1,400 frames per second (fps). Attaching an infinity long distance microscopic lens (model K2/SC) onto the high speed camera allowed for a well-focused video of the spray plume from the injection point to 40 mm downstream. One of the challenges associated with the installation of the camera was obtaining clear images through the front window of the test rig displayed in Figure 4.12. A back light was installed on the opposite window to provide enough luminescence for the high speed capture of spray frames in the videos. Lighting required care in order to provide sufficient intensity while maintaining a relatively uniform intensity. A diffuser was used in front of this back light to help with maintaining this uniform intensity. Another issue associated with the experimental set up was window wetting on the front window. An air knife was installed parallel to the window to prevent the settling of droplets on the window, but at higher pressures the air knife lost its effectiveness due to the limited back pressure of the air feeding the air knife. When the window was maintained clear throughout testing, a computer aided image analysis of the high speed videos was possible.

High speed videos were recorded for jet-in-cross flow experiments of unstable emulsion samples with a W/O ratio ranging from 0 to 0.60. The video for each case was trimmed to 300 frames at a rate of 20 frames/second. An edge Sobel vertical filter is applied to each video. The filter uses a Sobel operator which is a discrete differential operator that calculates the image intensity gradient at each image point. The Sobel operator outputs the corresponding gradient vector or the vector normal to it. This gives the direction of the largest change from light to dark.
and rate of change in that direction. The resulting image after the Sobel operator is applied demonstrates the smoothness of the image as it transitions at a certain point allowing for edge detection. The gradient vector is calculated by derivatives in both the horizontal and vertical direction. Since interest is in detecting the top edge of the spray plume, the Sobel filter is used to output an image containing the gradient vectors in the vertical direction, for this reason the edge Sobel vertical filter included in the high speed cinematography Phantom Camera Control software is used. When the filter is applied, any region of constant intensity values is transformed into a zero vector. Doing this allows us to filter out background regions that are not of interest.

Figure 4.12 High speed cinematography set up for high pressure facility

Bolszo et al. develop a method for tracing the top edge of a jet-in-crossflow spray by detecting the pixels at the max distance location from the injection point which will be referred
to as the Edge Trace Method (ETM). This method will serve as a means of detecting the top edge of the spray at elevated conditions in order to compare elevated pressure results to results obtained from atmospheric testing. The current research endeavor also seeks to obtain trajectory correlations for the spray plume peak intensity, bottom edge, and width. In order to do this a Pixel Intensity Trace Method (PITM) will be developed and applied to the processed images used for the ETM.

**4.4.1.1 Edge Trace Method**

After the edge Sobel vertical filter is applied to the video clips, each image frame in the video is further processed to filter out any noise and interferences that are not relevant to the spray plume. This is done by first converting the frame into a black and white binary image. The MATLAB function to convert into a binary image allows the user to select a cut-off intensity or level value for which it will only accept pixels of intensity (0-1) above that value and convert them to one. It is difficult to assign a constant value for level for all of the cases since the variation in water concentration will affect the light luminosity for each image. Due to this, a different level value must be applied to each individual frame. The level value is chosen using MATLAB’s GRAYTHRESH function which implements Otsu’s method to determine a cut-off intensity value. Otsu’s method classifies the pixels into either foreground or background pixels and calculates the optimal threshold value that separates the two classifications. This is then the threshold value used in place of level. Once all 300 frames are converted to binary images they are time averaged into one image as displayed in Figure 4.13.
After obtaining images such as the one in Figure 4.13, the Edge Trace Method can be applied to trace the top edge of the spray plume. The Edge Trace Method consists of a MATLAB code developed to map the pixels on a y vs. x plot, tracing the pixels with the highest y coordinate value for every x coordinate. In order for the code to trace the top edge of the plume, the image is converted to binary again so that all pixels regardless of value are given a value of one as demonstrated in Figure 4.14. This allows the code to simply trace the pixels with the highest y coordinate using a programming loop as displayed in Figure 4.15.
Figure 4.14 Binary image of Figure 4.13, displaying white spots that are out of the plume area of interest

Figure 4.15 Trace of plume prior demonstrating points that throw off trajectory trace
In observing Figure 4.14 it is seen that a few white spots are present and away from the main spray plume. These points demonstrate that liquid droplets exist outside of the spray plume area possibly due to window wetting. These points interfere with the trace of the spray plume edge by not allowing for a smooth trajectory as shown in Figure 4.15. In order to ignore the interference of the white spots, MATLAB’s BWAREAOPEN function is utilized. This function removes clusters of pixels that are connected in groups of less than a given integer. An integer value of 200 was visually determined as a sufficient value to discriminate unnecessary pixels. Application of this function removes the unwanted spots from Figure 4.14, but does not remove any spots of interest for the trace as demonstrated in Figure 4.16 and Figure 4.17.

![Figure 4.16 Binary image of Figure 4.14 from the BWAREAOPEN function is applied](image)
The data used to obtain Figure 4.17 is exported to excel where an x-axis boundary is applied and the data is used for spray plume penetration analysis. Further adjustments are made to remove the pixel data detected at the far right of the graph. For some of the binary images it was necessary to manually trace the edge due to spots on the window that interfere with the MATLAB code for tracing. Tracing manually an image such as Figure 4.16 gives exactly the same trajectory tracing as the MATLAB code except that some of these traces do not extend as far due to the window wetting issue as well. This Edge Trace Method is efficient for isolating the top edge of the plume and ignores the intensity values of the pixels and, cannot provide use with additional spray plume measurements such as peak intensity trajectory.

Figure 4.17 Trace of plume obtained from Figure 4.16
4.4.1.2 Pixel Intensity Trace Method

The Pixel Intensity Trace Method (PITM) allows for the trajectory trace of the top edge, peak intensity, bottom edge, and width of the spray plume. In terms of tracing the top edge, it should bring about the exact same results as the ETM. PITM multiplies together the images in Figure 4.13 and Figure 4.16 to produce and an intensity image that lacks spots outside of the plume area as demonstrated in Figure 4.18.

![Figure 4.18 Example of processed emulsion imaged used in PITM](image)

From the processed image above, the intensity matrix of the picture is extracted to an excel spread sheet and each column of the matrix is evaluated to determine max intensity, top edge location, and bottom edge location. Excel was utilized for this evaluation rather than MATLAB because using excel allows us to visually determine at what x axis point to cut off irrelevant data. This point was chosen at the point of width the width of the plum no longer continued to
increase. Despite the image processing that has already taken place to filter out unwanted pixels from the image, some areas of high intensity away from the trajectory of the plume continue to exist. This may be due to reflections from devices in the test area in addition to window wetting interfering in areas near the plume trajectory. These interference pixels showing high intensity can be detecting in the matrix and the individual cells can be given a value of zero to not interfere with detection of the peak intensity trajectory. Figure 4.19 is an example of the pixel matrix and Figure 4.20 displays this matrix in a three dimensional surface area plot.
Figure 4.20 is a good representation of the peak intensity trajectory of a jet-in-crossflow. From evaluating this plot it can be determine that calculating peak intensity location from the pixel values is a good approach. The peak values appear to be located exactly in the location expected and follow a smooth trajectory.

![Intensity Profile](image)

Figure 4.20 3D surface plot of sample emulsion spray image from Figure 4.19

### 4.4.2 Laser Doppler Velocimetry

Laser Doppler Velocimetry utilizes the Doppler shift to non-intrusively measure the velocity of a particle through a flow medium. In this technique, two monochromatic coherent laser beams cross at a point creating an interference fringe pattern. The particle of interest passes
through the interference fringe pattern scattering phase shifted light that is captured by a photo
detector. The particle velocity $V_{pt}$ can then be calculated with the known wavelength of the laser
beam $\lambda_b$, known incident angle $\Theta$, scattered frequency of the first beam $f_1$, and the scattered
frequency of the second beam $f_2$.

$$V_{pt} = \frac{(f_2 - f_1) \lambda_b}{2 \sin\left(\frac{\Theta}{2}\right)}$$

Figure 4.21 Demonstration of LDV fringe pattern for measuring particle velocity
A TSI TR20 Laser Doppler Velocimetry (LDV) system was installed in the high pressure facility for the characterization of the air cross flow. Installation of this system includes pumping a laser beam from an argon ion laser into a Fiberlight multi-color beam separator which then transforms the beams into a fiber optic cable. The fiber optics then connects to the LDV transmitter/transceiver. While this unit transmits beams into the desired test area it also receives the scattered light signal which then provides velocity measurements back to the digital processor and data acquisition software. The LDV system also utilizes a droplet seeding tank and nozzle which provide fine water droplets that are introduced into the air flow for flow seeding.

Figure 4.22 LDV computer hardware, laser, and multi-color beam separator
Figure 4.23 LDV transmitter/transceiver with a display of the beams crossing in the section and the measurement points of interest.

Figure 4.24 Seeding tank on the left used to provide water for fogging nozzle on the right (picture provided by McMaster-Carr)
4.4.3 Dual-Planar Laser Induced Fluorescence

A clear visualization depicting oil and water droplets separately within an emulsion spray has not been developed in previous emulsion studies. Acquiring this image data can improve the current research on droplet size and distribution. Although droplet counting and sizing within a spray has been accomplished using laser diagnostics, locating where oil and water droplet formation occurs can allow for a more in depth analysis of how emulsions can improve gas turbine combustion. The oil used in experimentation is low sulfur No. 2 diesel fuel (DF2). Fluorescing DF2 and water requires the addition of laser fluorescing dyes that will fluoresce both fluids at different wavelengths so they can be optically separated using optical filters. Initially, Fluorescein and Rubrene were identified as possible dyes due to Fluorescein’s solubility in water and Rubrene’s solubility in oil. Figure 4.25 illustrates a 50/50 blend of water and DF2. The beaker on the left is DF2 dyed with Rubrene and the beaker on the right is the water dyed with Fluorescein (C.D. Bolszo G. G., 2011).

![Figure 4.25 50/50 blends of DF2 and water and their respective dyes](image)

Figure 4.25 50/50 blends of DF2 and water and their respective dyes
The incident laser on both of these beakers is of a 514.5 nm wavelength. The beaker on the right portrays bright fluorescence from the Fluorescein dyed water. Fluorescein dye is designed to greatly fluoresce at the incident wavelength of 514.5 nm. In addition to the fluorescence from the dye, the beaker on the right portrays fluorescence from the DF2 without dye. The significance of this is that it may not be necessary to dye the DF2. If this is true then a different dye must be selected for the water that will fluoresce at different wavelengths than the DF2 in order to optically separate the two fluids. To verify that the DF2 is naturally fluorescing without a dye an absorbance test must be administered using a spectrophotometer.

With the cooperation of the University of California Irvine Biomedical Engineering Department, a spectrophotometer was made available and absorbance data was obtained. Figure 4.26 is an Absorbance vs. Wavelength graph of hexane diluted DF2 with various concentrations.

![Absorbance vs. Wavelength graph of hexane diluted DF2 with various concentrations](image)

**Figure 4.26 Absorbance vs. Wavelength of DF2 with varying concentrations**
From Figure 4.26 it can be determined that there is absorbance at the 514.5 nm wavelength in the DF2 and where there is absorbance there is fluorescence. An absorbance value of 2 pertains to the liquid absorbing 99% of photons that pass through and an absorbance value of .005 pertains to a value 1.15% based on the absorbance and transmittance equations. At the wavelengths following 575 nm, the plots of each concentration begin to overlap each other. Overlapping is possibly due to noise and noise affects the accuracy of readings at very low absorbance levels.

Using 575 nm as a cut-off for wavelengths of light that will be absorbed by the DF2 provides a range for possible lasers that can be used. The laboratory is already in possession of a 488 nm Argon-Ion laser and based on the absorbance value at 488 nm in Figure 4.26 and using equations 2.20 and 2.21, approximately 4.5% of the photons in the incident laser light will be absorbed by the DF2. A 488 nm Argon-Ion laser will be adequate to achieve fluorescence from the DF2 within a spray. Knowing that fluorescence can be detected out of the DF2 without the need of a dye, a water-soluble and oil in-soluble dye must be obtained to cause fluorescence out of the water. This dye must absorb away from the 488 nm wavelengths at which the DF2 fluoresces. Oxazine 725Cl was chosen as a dye due to its water solubility, absorbance spectra, and emission spectra. Figure 4.27 illustrates both of these spectra superimposed on the same graph (C.D. Bolszo G. G., 2011). This dye’s emission wavelengths are away from the emission spectra of the DF2. To detect any wavelength interference between the DF2 emission and Oxazine 725Cl emission it is important to observe their emission spectra superimposed on the same graph. From Figure 4.28 it is evident that both spectra slightly interfere with one another, therefore optical filters are necessary.
Figure 4.27 Absorbance and Emission Spectra of water-soluble Oxazine 725Cl

Figure 4.28 Emission of DF2 and Absorbance Oxazine 725Cl dye overlaid on the same graph
The peak emission of the DF2 following the 488 nm incident laser wavelength is approximately 525 nm in Figure 4.28. A reasonable filter selection is a 550 nm band pass filter with a 10 nm bandwidth. This will filter out the incident 488 nm laser wavelength and isolate the fluorescence from the DF2. In order to similarly isolate fluorescence from the dyed water, a long pass 680 nm filter is necessary. This filter is chosen based on the DF2 emission spectra in Figure 4 where 680 nm is a wavelength of negligible fluorescence from the DF2. This long pass filter will block all incident laser wavelengths as well as DF2 fluorescence allowing for optical separation of dyed water. The long pass filter will transmit photons of wavelengths longer than 680 nm. The intensity units used for the spectra in Figure 4.28 are different due to obtaining the Oxazine 725Cl spectra from the company of purchase. The fact that they are of different units is not of much importance. Figure 4.28 allows for the identification of the two spectra and at which wavelengths they interfere (C.D. Bolszo G. G., 2011).

4.4.3.1 Results of Fluorescence Method

The success of the laser induced fluorescence method will result in the purchase of a red 655 nm laser which will be adequate to fluoresce the water dyed with Oxazine 725Cl within the spray. Purchasing a 655 nm laser with a power output comparable to that of the 5 W 488 nm laser is expensive; therefore, results must first be obtained using a low power 632 nm Helium Neon laser to verify that the method works. To verify this, water was dyed with the Oxazine 725Cl dye until reaching its saturation concentration. This dyed water was then poured into a beaker with DF2 until a 50/50 blend was reached. The 488 nm laser wavelength was set incident on the DF2 sitting on top of the dyed water in the beaker and the 632 nm laser wavelength was set incident on the dyed water. A CCD camera was then positioned perpendicular to these lasers
to detect light intensity. Figure 4.29 is an unfiltered picture taken with the CCD camera displaying both incident lasers and the fluorescence throughout both fluids.

![Unfiltered CCD camera picture of DF2 and dyed water and respective incident lasers](image)

**Figure 4.29 Unfiltered CCD camera picture of DF2 and dyed water and respective incident lasers**

To test if optical separation of the fluids is possible, Figure 4.30 is the same as Figure 4.29 only this time the filters are placed in front of the CCD camera optically separating each fluid’s fluorescence. Figure 4.30a displays the fluorescence of the DF2 caused by the 488 nm laser while Figure 4.30b displays the fluorescence of the dyed water caused by the 632 nm laser. In both figures, the light detected by the CCD camera is pure fluorescence due to the use of filters. In Figure 4.30a the 550 nm band pass filters out the 488 nm and 655 nm incident lasers as well as the fluorescence resulting from the 655 nm laser on the dyed water. In Figure 4.30b the 680 nm long pass filter blocks light of all wavelengths other than the dyed water fluorescence. These results verify that the fluorescence method works. Some questions to be addressed are how the fluorescence will be present in an emulsion and an emulsion spray. It is necessary to investigate this to verify the desired output power from a 655 nm red laser. Although fluorescence was achieved from the beaker set up in Figure 4.29, creating an emulsion out of the two fluids can alter how much fluorescence will be detected from the CCD camera. This can
result from the water and DF2 droplets intermixed within the beaker scattering fluorescent light in multiple directions. In addition to disoriented scatter of fluorescent light, a laser sheet rather than a focused laser beam will be used in the actual experimentation. Fluorescence will be altered using a laser sheet because the power in the volume of a single laser beam is now divided into the volume of a laser sheet. To investigate this effect, a stabilized emulsion was generated using an emulsion generator to blend the fluids together and create a 50/50 blend of DF2 and water droplets. Figure 4.31 displays this emulsion fluoresced with a laser sheet of the 488 nm 1.5 W laser beam created by a specialized lens.

Figure 4.30 Filtered CCD camera images displaying optical isolation of the DF2 (a) and Oxazine 725Cl dyed water (b)
The fluorescence in Figure 4.31 is of the DF2 because the 550 nm band pass filter is used. From this it is concluded that fluorescence can be obtained out of an emulsion. This same test was performed using the 4 mW 632 nm laser, but fluorescence was not observed due to this laser’s low power. To obtain similar results from the dyed water, it will be necessary to purchase a 655 nm laser with 1.5 W of output power.

The next question that must be addressed is whether fluorescence can be detected in an emulsion spray. To address this question an emulsion of 20% water was generated and sprayed using a Siemens macrolaminate injector at a pressure of 120 psi. Figure 4.32 displays fluorescence of the DF2 within the spray that will allow for a time averaged detection of water and DF2 droplet distribution. Once a 655 nm laser is purchased it will be possible to obtain similar results from the dyed water.
From this image it is evident that fluorescence is not detected at the bottom portion of the spray. This is due to the droplets being scattered in this part of the spray, especially due to the cross flow air flowing downward and perpendicular to the spray at a velocity of 25 m/s. Another reason for the lack of fluorescence detection is that the camera has a one second exposure time making it difficult to capture scattered, fast moving droplets at the bottom of the spray. These difficulties can be improved with a CCD camera that has a faster exposure time. The results presented verify that the fluorescence method will be successful in achieving optical separation of DF2 and water droplets within an emulsion spray.

**4.4.3.2 Dual-Planar Laser-Induced Fluorescence Experimental Set up**

Dual-Planer laser-Induced Fluorescence (Dual-PLIF) was installed in the high pressure facility. A portable optics table was constructed in order to facilitate the use of this technique in the high pressure facility as well as the atmospheric sprays facility at the UCI Combustion Laboratory. Figure 4.33 is a diagram of this optical set up. Two single wavelength diode lasers were purchased for the laser wavelengths of 447 nm and 655 nm. Since diode lasers do not
provide a round coherent beam, lenses were used to alter the beam shapes and provide round coherent beams for the production of a horizontal laser sheet. Prior to entering the cylindrical lens that provides the laser sheet, the two laser wavelengths were combined using a dichroic mirror. A laser sheet of the combined wavelengths is then created and used to optically fluoresce both water and oil within the spray plume. Two optical filters (550 nm band pass, 680 nm long pass) are utilized to isolate fluorescence from the DF2 and water dyed with Oxazine 725 Cl. The filters are placed directly and flush to the lens of a high intensity camera and switched back and forth between diesel detection and water detection.

Figure 4.34 a) Dual-PLIF setup for measuring emulsion concentration in UCI’s High Pressure Facility & b) averaged exposure of fluorescing plume cross section, 40 mm downstream of jet exit

Figure 4.34a is an actual representation of this optical set up displaying the optics train and high intensity camera looking down on the laser sheet intersecting the spray plume. During experimentation the 447 nm laser was maximized to 1.25 W and the 655 nm laser was maximized to 2.11 W. Water was saturated with Oxazine 725 Cl and mixed into 110 gallons of pure water making the concentration of dye 5% of the total volume. The high intensity camera was set to full optical zoom, aperture nine clicks open, and an exposure of 2 seconds. The gain for detecting fluorescence was set to 100 for the water and 100 for the DF2. Due to the existence of dye in the fluid lines it was necessary to let the water flush out in between emulsion cases and pure DF2 cases. One of the major challenges in this experimentation was calibrating the signal obtained from both the DF2 and dyed water fluorescence. It was also very difficult to prevent signal interference from hardware reflections, window reflections, and laser light penetration
from behind the high intensity camera. Figure 4.34b is a picture of the laser sheet intersecting the plume 40 mm downstream of the injection point. Behind the laser sheet some hardware reflections can be noticed. This Dual-PLIF technique was previously validated at atmospheric conditions for a downward spray cone, but was for the first time applied to a jet-in-crossflow at elevated pressure conditions.
5 Results

5.1 Test Section Air Velocity Characterization

Characterizing the cross flow air dynamics was of special interest in this experimentation. The shear forces acting on the liquid jet are associated with the cross flow air velocity profile. Points of interest along the test section area were chosen for velocity measurements. Figure 5.1 depicts the points chosen with respect the test section wall. Normal to each point, velocity measurements were taken using the LDV system along the 2 inch length of the section.

Figure 5.1 Illustration of velocity profile interest points
a) $x = 0, z = 10$

b) $x = 10, z = 10$
c) \( x = 0, z = 20 \)

\[ 5 \text{ atm (} z=-20, x=0) \]

\[ \text{Velocity (m/s)} \]

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>( V_{\Delta P} )</th>
<th>( V_{LDV} )</th>
<th>TI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>10</td>
<td>35</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>50</td>
<td>15</td>
<td>0.04</td>
<td>0.01</td>
</tr>
</tbody>
</table>

\[ 5 \text{ atm (} z=-40, x=0) \]

\[ \text{Velocity (m/s)} \]

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>( V_{\Delta P} )</th>
<th>( V_{LDV} )</th>
<th>TI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>10</td>
<td>35</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>50</td>
<td>15</td>
<td>0.04</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 5.2 a-d Measured Velocity Profiles

In Figure 5.2 the velocity remains fairly stable throughout the two inch test section and is in good agreement as to what is observed between the pressure drop based value and the measured value. A slight increase in turbulence intensity is noted in the middle of the test section. Although the turbulence intensity does not go above 6% (indicating medium
turbulence), the air is more turbulent away from the test section walls. This increase in turbulence in the middle (15 mm – 40 mm) will affect the penetration of the jet-in-cross flow since it will interact with parts of the spray plume downstream from the injection point. Very near the walls, the turbulence intensity increases as expected due to the shear layer mixing in the boundary layer. Due to some difficulties with laser alignment and power output from the laser, two of the six desired measurement points are not available due to a low sample rate.

### 5.2 Emulsions-in-Gaseous Crossflow High Pressure Test Matrix

There were several variables to consider when running emulsion jet-in-crossflow experiments at high pressure conditions. In order to obtain a robust trajectory correlation, it was important to vary the ambient pressure, nozzle diameter, momentum flux ratio, and emulsion mass fractions. Table 5.1 presents the test matrix of this work in more detail and Figure 5.3 presents the coordinate system used to evaluate jet-in-crossflows. Running these jet-in-crossflow experiments at elevated ambient pressure allowed for conditions shift further into the surface break up regime as demonstrated in Figure 5.4. In comparison to conditions achieved at atmospheric conditions in Figure 5.5 it is evident that test conditions moved towards the right into the column, shear and surface break up modes. This shift further to the right of the momentum flux ratio vs Weber Number regime plot was due to an increase in air density which was due to an increase in ambient pressure. The density of the crossflow air is proportional to the Weber Number as seen in equation 5.1. Previous studies used conditions that straddled the regimes of column and shear mode breakup. The current effort straddles the breakup mode regimes in order to ensure that the pressure effect on both modes is captured in the study. The conditions tested previously are shown in Figure 5.5 for reference.
\[
W_{e\text{aero}} = \frac{\rho g U_g^2 d}{\sigma_s}
\]

Table 5.1 Elevated Pressure Jet-in-Cross flow test matrix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Pressure (atm)</td>
<td>2, 5, 8</td>
</tr>
<tr>
<td>Plain Jet Nozzle Diameter (mm), Length (mm)</td>
<td>0.57, 8</td>
</tr>
<tr>
<td>Crossflow Air Velocity (m/s)</td>
<td>15.0 – 50.0</td>
</tr>
<tr>
<td>Crossflow Mass Flow (kg/min)</td>
<td>6.0 – 54.0</td>
</tr>
<tr>
<td>Liquid Velocity (m/s)</td>
<td>5.4 – 39.0</td>
</tr>
<tr>
<td>Liquid Mass Flow (kg/min)</td>
<td>0.079 - 0.750</td>
</tr>
<tr>
<td>Emulsion Water Mass Fraction (\Phi=W/(O+W))</td>
<td>0.00, 0.23, 0.38, 1.00</td>
</tr>
<tr>
<td>Comparison Momentum Flux Ratio (q)</td>
<td>50, 85, 120</td>
</tr>
<tr>
<td>Liquid Injection Pressure (MPa)</td>
<td>0.0128 – 0.756</td>
</tr>
</tbody>
</table>
Figure 5.3 Coordinate system used to evaluate jet-in-crossflow
Figure 5.4 Current High Pressure Test Conditions Relative to Breakup Regime Map

Figure 5.5 Previous Atmospheric Test Conditions Relative to Breakup Regime Map (Bolszo, 2011)
5.2.1 Correlation Results Using Edge Trace Method

The Edge Trace Method described in section 4.4.1.1 was utilized in jet-in-crossflow trajectory tracing. Jet-in-crossflow tests were performed for emulsions varying the parameters displayed in Table 5.1. A total of 17 emulsion tests, 7 DF2 tests, and 7 water tests were completed for pressures varying between two and eight atmospheres.

\[ \frac{y}{d} = a q^b \left( \frac{x}{d} \right)^c \]

5.2
Both trajectory plots and correlation plots were generated for these test cases. Equation 2.15 is the framework equation used for the correlations of both the atmospheric and elevated pressure cases. Equation 2.15 will be repeated throughout the results as a new equation number for readability (i.e. equation 5.2). Figure 5.6 presents traced penetration trajectories for emulsions, DF2, and water cases. The ambient pressure $P$, orifice diameter $d$, momentum flux ratio $q$, and water mass fraction $\Phi$ were varied for each fluid. Figure 5.7 and Figure 5.8 present the traced plumes for the pure DF2 and pure water cases, respectively.
Figure 5.7 DF2 spray plume trajectories for both 0.57 & 0.72 mm orifices

Figure 5.8 Water spray plume trajectories for both 0.57 & 0.72 mm orifices
From these results it is apparent that momentum flux $q$ is the main driver in penetration of the jet in all cases. In observing the trajectories in the above figures it is evident that higher trajectories pertain to the larger $q$ values despite the varying of pressure and water to oil ratio. From comparing the trajectories of water, emulsions, and DF2 there are no visually apparent differences in the trajectory behavior of the three despite the penetration distances. To further determine that $q$ is the main driving parameter on these averaged trajectories, it is important to obtain trajectory correlations.

### 5.2.1.1 Top Edge Trajectory Correlations

The same analysis procedure used at atmospheric conditions was applied to emulsion cases. Figure 5.9 is a plot of the emulsions at 2-8 atm using the coefficients developed for atmospheric conditions to calculate $y/d$. Figure 5.10 uses the coefficients optimized for the new 2-8 atm emulsion cases. It is evident from the two that the newest coefficients correlate better for the newest elevated pressure cases. Table 5.2 summarizes the best fit coefficients for only the emulsion case for the atmospheric pressure and elevated pressure conditions. It is noted again that the atmospheric data were taken previously using an entirely different test facility. That the optimized coefficients are nearly identical attests to (1) the repeatability of the tests, (2) the data quality, and (3) a notable lack of significant impact of ambient pressure. The only coefficient that seems to vary much is “a” which is believed to be due to a much wider range of momentum flux ratios. To confirm the insignificant impact of ambient pressure to the jet-in-crossflow correlation, Figure 5.10 demonstrates an overlap between different pressures, momentum flux ratios, and emulsion qualities. The fact that the different cases all collapse and correlate using one set of coefficients affirms that adding an additional pressure term to equation 5.3 is not necessary.
Figure 5.9 Correlation of emulsion trajectories using coefficients optimized for atmospheric pressure
Figure 5.10 Correlation of emulsion trajectories using coefficients optimized for elevated pressure

Table 5.2 Coefficient comparison for emulsions

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 -8 atm ETM Median</th>
<th>2 -8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.32</td>
<td>2.25</td>
<td>2.22 - 2.23</td>
</tr>
<tr>
<td>b</td>
<td>0.46</td>
<td>0.42</td>
<td>0.41 - 0.42</td>
</tr>
<tr>
<td>c</td>
<td>0.45</td>
<td>0.39</td>
<td>0.39 - 0.40</td>
</tr>
</tbody>
</table>

In order to ascertain the degree to which a single correlation using the Edge Trace Method (ETM) can be applied to both emulsions and neat DF2, analysis was carried out on data sets including both emulsions and DF2. The regression behavior is shown in Figure 5.11 and optimized coefficients for both current elevated pressure data as well as the previous atmospheric data are shown in Table 5.3. Inclusion of the neat DF2 looks to increase the “a” parameter but decrease the “b” and “c” parameters. Although the “b” and “c” parameters are decreased, in both
plots they stay very close to each other. The inclusion of DF2 not only seems to somewhat change the fit but also changes the $R^2$ value which points to the possibility of some discrepancies in-between experiments. One key experimental discrepancy between the tests is that when running neat DF2 and neat water cases, only one pump was running and when running emulsion cases, two pumps were pumping simultaneously into the same line. It was noted during experimentation that when both pumps were running together the pressure drop measurement across the injector seemed to fluctuate substantially more than when running a single one. Out of both the DF2 and water plumbing systems, the DF2 plumbing system was more stable than the water one. The reason for this is that both systems had different type pumps and different pump inlet procedures. The DF2 pump was an internal gear suction pump that was able to steadily pump DF2 by simply placing an inlet tube inside of the DF2 barrel. The water pump was a diaphragm pump requiring a pulsation dampener and an inlet water pressure of at least 15 psi, therefore requiring the inlet to be connected to an existing water line in the laboratory. The water pump was only required for 5 atm and 8 atm tests and did not provide as stable of a flow as the DF2 pump. Specifics on the plumbing systems can be found in section 4.3.5. The stability of the two pumps has a direct impact on momentum flux ratio calculations which is used to calculate predicted $y/d$ values. Pumping instability results in some uncertainty due to injector pressure drop measurements for the 5 atm and 8 atm water and emulsion test cases. In addition to this uncertainty the pressure transducer used to measure the pressure drop across the nozzle has an uncertainty of 0.25% of full scale, which translates to an uncertainty of +/- 0.085 atm. This pressure reading uncertainty is small relative to most of the cases, but for cases requiring a low pressure drop reading the discharge coefficients, momentum flux ratio, and Reynolds number
vary fairly considerably and error bars account for this pressure transducer uncertainty but not for uncertainty due to pumping stabilities.

Figure 5.11 Correlation of emulsions and DF2 trajectories using coefficients optimized for high pressure

Table 5.3 Coefficient comparison for emulsions and DF2

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 -8 atm ETM Median</th>
<th>2 -8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>1.48</td>
<td>3.19</td>
<td>3.01 - 3.34</td>
</tr>
<tr>
<td>b=</td>
<td>0.44</td>
<td>0.35</td>
<td>0.35 - 0.36</td>
</tr>
<tr>
<td>c=</td>
<td>0.43</td>
<td>0.36</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Figure 5.12 and Table 5.4 summarize the results of the neat water cases as well. Note that no pure water results were obtained at atmospheric conditions. The overall values of the coefficients are fairly close to those derived for emulsions and pure DF2, but vary in comparison to the emulsion. Similar to the emulsion and DF2 combined plot, the emulsion, DF2, and water combined plot has a lower $R^2$ value compared to the emulsion only plot.

![Graph showing correlation of emulsion, DF2, and water trajectories using coefficients optimized for high pressure](image)

**Figure 5.12** Correlation of emulsion, DF2, and water trajectories using coefficients optimized for high pressure

**Table 5.4** Coefficients for emulsion, DF2, and water combined (no atmospheric tests for water to compare)

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 -8 atm ETM Median</th>
<th>2 -8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>NA</td>
<td>2.97</td>
<td>2.97 - 3.55</td>
</tr>
<tr>
<td>b</td>
<td>NA</td>
<td>0.36</td>
<td>0.33 - 0.36</td>
</tr>
<tr>
<td>c</td>
<td>NA</td>
<td>0.37</td>
<td>0.37</td>
</tr>
</tbody>
</table>
To determine if the coefficient variation is due to a need for an addition pressure term, a need for an emulsion quality term, error from the use of the water pump, or error associated with pressure drop measurements from the pressure transducer used it is necessary to plot emulsion cases separately for 2 atm, 5 atm, and 8 atm. Figure 5.13, Figure 5.14, and Figure 5.15 are plots of emulsions for their corresponding ambient pressures. In comparing the three, there appears to be a great difference between the 2 atm and the other two ambient pressures (5 atm and 8 atm). It is also noticed that coefficient value “b” for 5 atm and 8 atm appears to be identical. In addition to this, there is a much larger range in coefficient values for 5 atm in comparison to 8 atm and 2 atm. From these observations it is evident that the coefficient variation is either due to error associated with pressure drop measurements and the pressure transducer or that there is a need for an additional pressure parameter for emulsions. As previously explained, effect of pressure drop measurement error will be higher for cases with lower pressure drop. Coefficient variation is not due to the water pump because the water pump was on for most of the 5 atm and 8 atm tests and if it was due to error from the pump, the 5 atm and 8 atm coefficients would not match as closely as they do. Cases with the lowest pressure drops across the orifice pertain to mostly all 2 atm cases and some 5 atm cases. This explains why the 5 atm coefficients seem to vary more the 2 atm and 8 atm cases. The 2 atm cases correlate well with nearly all cases having low pressure drops and there exists some 5 atm cases with low pressure drop error as well.
Figure 5.13 Correlation plot for emulsions at 2 atm

Table 5.5 Coefficients for emulsions at 2 atm

<table>
<thead>
<tr>
<th></th>
<th>2 atm ETM Median</th>
<th>2 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.98</td>
<td>0.93 - 0.98</td>
</tr>
<tr>
<td>b</td>
<td>0.60</td>
<td>0.60 - 0.63</td>
</tr>
<tr>
<td>c</td>
<td>0.41</td>
<td>0.40 - 0.41</td>
</tr>
</tbody>
</table>
Figure 5.14 Correlation plot for emulsions at 5 atm

Table 5.6 Coefficients for emulsions at 5 atm

<table>
<thead>
<tr>
<th></th>
<th>5 atm ETM Median</th>
<th>5 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>2.11</td>
<td>1.72 - 2.30</td>
</tr>
<tr>
<td>b=</td>
<td>0.42</td>
<td>0.40 - 0.47</td>
</tr>
<tr>
<td>c=</td>
<td>0.40</td>
<td>0.39 - 0.41</td>
</tr>
</tbody>
</table>
From the above predicament that the coefficient variation is either due to a needed pressure term or just error associated with the pressure transducer it is necessary to set a cut off for low pressure drop readings that result in too much deviation in the coefficient values. From speculating the pressure drop readings and looking into the separations between cases in Figure 5.14 and Figure 5.15 it was determined to eliminate all cases with pressure drop readings below 20 psi. Figure 5.16, Figure 5.17, and Figure 5.18 with their corresponding coefficient tables demonstrate a coefficient match between combinations. The coefficients produced from these

**Figure 5.15 Correlation plot for emulsions at 8 atm**

**Table 5.7 Coefficients for emulsions at 8 atm**

<table>
<thead>
<tr>
<th></th>
<th>8 atm ETM Median</th>
<th>8 atm ETM Error Range</th>
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<tr>
<td>a=</td>
<td>2.86</td>
<td>2.86 - 3.12</td>
</tr>
<tr>
<td>b=</td>
<td>0.42</td>
<td>0.40 - 0.42</td>
</tr>
<tr>
<td>c=</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>
correlations are nearly identical and eliminate the need for an emulsion quality parameter confirming the findings of Bolszo et al. (Bolszo, 2011).

Figure 5.16 Correlation plot for emulsions after eliminating low pressure drop cases

Table 5.8 Emulsion coefficients after eliminating low pressure drop cases

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 -8 atm ETM Median</th>
<th>2 -8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.32</td>
<td>2.83</td>
<td>2.74 - 2.93</td>
</tr>
<tr>
<td>b</td>
<td>0.46</td>
<td>0.38</td>
<td>0.38 - 0.39</td>
</tr>
<tr>
<td>c</td>
<td>0.45</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Figure 5.17 Correlation plot for emulsions and DF2 after eliminating low pressure drop cases

Table 5.9 Emulsion and DF2 coefficients after eliminating low pressure drop cases

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 -8 atm ETM Median</th>
<th>2 -8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>1.48</td>
<td>2.98</td>
<td>2.82 - 3.12</td>
</tr>
<tr>
<td>b=</td>
<td>0.44</td>
<td>0.37</td>
<td>0.37 - 0.38</td>
</tr>
<tr>
<td>c=</td>
<td>0.43</td>
<td>0.34</td>
<td>0.34-0.35</td>
</tr>
</tbody>
</table>
Figure 5.18 Correlation plot for emulsions, DF2, and water after eliminating low pressure drop cases

Table 5.10 Emulsion, DF2 and water coefficients after eliminating low pressure drop cases

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 -8 atm ETM Median</th>
<th>2 -8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>NA</td>
<td>2.87</td>
<td>2.87 - 3.10</td>
</tr>
<tr>
<td>b=</td>
<td>NA</td>
<td>0.38</td>
<td>0.37 - 0.38</td>
</tr>
<tr>
<td>c=</td>
<td>NA</td>
<td>0.35</td>
<td>0.34 - 0.35</td>
</tr>
</tbody>
</table>

Applying the optimized coefficients in Table 5.8 to all the emulsion and neat fluid cases in Figure 5.10, Figure 5.19 is obtained with a high $R^2$ value of 0.96. From this $R^2$ value it is concluded that when the optimized coefficients in Table 5.8 sufficiently predict $y/d$ for a number of different emulsion cases that vary in emulsion quality, pressure, and momentum flux ratio eliminating the need for an extra pressure or emulsion quality parameter to equation 5.4.
\[ \frac{y}{d} = a q^b \left( \frac{X}{d} \right)^c \]

Figure 5.19 Emulsion correlation using coefficients optimized after eliminating low pressure drop cases

Table 5.11 Emulsion coefficients after eliminating low pressure drop cases

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>2 - 8 atm ETM Median</th>
<th>2 - 8 atm ETM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.32</td>
<td>2.83</td>
<td>2.74 - 2.93</td>
</tr>
<tr>
<td>b</td>
<td>0.46</td>
<td>0.38</td>
<td>0.38 - 0.39</td>
</tr>
<tr>
<td>c</td>
<td>0.45</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>
5.2.1.2 Top Edge Penetration Correlation Summary

To help summarize the impact of the small variation in the coefficients in Table 5.8, Table 5.9, and Table 5.10, Figure 5.20 and Table 5.12 are shown. In general, the latest correlations for 2-8 atm perform similarly but deviate from the atmospheric correlation found by Bolszo et. al. Some major differences between the 2-8 atm cases and previous atmospheric cases are (1) two separate test facilities were used, (2) different camera setting were used, and (3) trajectories for 2-8 atm cases were traced for much longer distances in the x-axis therefore covering near-field and far-field trajectory behavior while Bolszo et. al focused on the near field trajectory. From the elevated pressure data collected, a single correlation for emulsions even though the overall trajectories between elevated pressures and atmospheric pressures do not seem to match. One of the major differences is in the initial part of the trajectories below an x/d of 15. Since there were different cameras used and different facilities, the initial y and x values may have been considered differently. Another major difference between the two experiments was the crossflow section used for the atmospheric testing was of different dimensions from the one used for the elevated pressure experiments. The cross section area for the atmospheric testing was 4 inches by 3 inches while the dimensions for the elevated pressure data was 2 inches by 2 inches. In addition to the cross section area differences, test sections also differed in the geometries of their transition pieces. The air flow velocity profile through the test section used for elevated pressure conditions was characterized, but the air flow velocity profile through the test section for the atmospheric pressure conditions was not.
Figure 5.20 Trajectories for predicted y/d calculated with optimized coefficients for q= 85

Table 5.12 ETM optimized coefficients used to predict trajectories in Figure 5.20

<table>
<thead>
<tr>
<th></th>
<th>Median Values</th>
<th>Error Range Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emulsion Atmospheric</td>
<td>Emulsion 2 - 8 atm</td>
</tr>
<tr>
<td>a=</td>
<td>1.32</td>
<td>2.74 - 2.93</td>
</tr>
<tr>
<td>b=</td>
<td>0.46</td>
<td>0.38 - 0.39</td>
</tr>
<tr>
<td>c=</td>
<td>0.45</td>
<td>0.35</td>
</tr>
</tbody>
</table>
5.2.2 Correlation Results Using Pixel Intensity Trace Method

Test cases that resulted in clear image acquisition with minimal interference from window wetting were analyzed using the Pixel Intensity Trace Method (PITM). Using only these type of images, limits the amount of cases for use in (PITM) but the amount of cases was sufficient to validate the coefficients for the top edge trajectories discovered in section 5.2.1.1 A total of 13 cases were analyzed using PITM for the top edge and peak intensity trajectories of the spray plumes consisting of 6 emulsion cases, 4 DF2 cases, and 3 water cases. Trajectory and correlation plots are provided for peak intensity trajectories, top edge trajectories, bottom edge trajectories, and width trajectories. Top edge trajectories can be compared to those found using the Edge Trace Method, but intensity, bottom, and width trajectories are unique to PITM. Due to difficulty in obtaining clear images of the bottom edge, only 8 cases for the bottom edge and width of the spray plume consisting of 5 emulsion cases, 2 DF2 cases, and 1 water case were available.

5.2.2.1 Top Edge Trajectories and Correlations

Figure 5.21 is a plot of the trajectories for the cases used in the PITM method. Figure 5.22, Figure 5.23, and Figure 5.24 are correlation plots using the same coefficients optimized by the ETM method in section 5.2.1.1. Based on the high $R^2$ values above 0.96 in the PITM correlated plots, the ETM method for optimizing the coefficients in equation 5.5 is validated. It is not necessary to compare any new coefficients since the ETM optimized coefficients fit the measured PITM trajectories very well.

$$\frac{y}{d} = a q^b \left( \frac{x}{d} \right)^c$$  \hspace{1cm} 5.5
Figure 5.21 Top edge emulsion, DF2, and water trajectories

Figure 5.22 Emulsions correlation using ETM optimized coefficients
Figure 5.23 Emulsions and DF2 correlation using ETM optimized coefficients

Figure 5.24 Emulsions, DF2, and water correlation using ETM optimized coefficients
5.2.2.2 Peak Intensity Trajectories and Correlations

Peak intensity trajectories for emulsions, DF2 and water are plotted in Figure 5.25. The correlation plots below allow for a comparison of peak intensities between emulsions and pure fuels. Overall, a slight difference in optimized coefficients was demonstrated between emulsions and neat cases. This difference was mainly in the “a” and “b” coefficients and the effects of this difference on the peak intensity trajectories can be better described in section 5.2.2.3.

Figure 5.25 Peak intensity trajectories for emulsions, DF2, and water
Figure 5.26 Peak intensity trajectory correlation for emulsions, DF2, and water

Table 5.13 Peak intensity coefficients for emulsions, DF2, and water

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>2.04</td>
<td>2.01- 2.06</td>
</tr>
<tr>
<td>b=</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>c=</td>
<td>0.30</td>
<td>0.30 - 0.31</td>
</tr>
</tbody>
</table>
Figure 5.27 Peak intensity trajectory correlations for emulsions

Table 5.14 Peak intensity coefficients for emulsions

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.03</td>
<td>1.97 - 2.10</td>
</tr>
<tr>
<td>b</td>
<td>0.40</td>
<td>0.40 - 0.41</td>
</tr>
<tr>
<td>c</td>
<td>0.33</td>
<td>0.32 - 0.33</td>
</tr>
</tbody>
</table>
Figure 5.28 Peak intensity trajectory correlation for emulsions and DF2

Table 5.15 Peak intensity coefficients for emulsions and DF2

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.06</td>
<td>2.00 - 2.10</td>
</tr>
<tr>
<td>b</td>
<td>0.41</td>
<td>0.41 - 0.42</td>
</tr>
<tr>
<td>c</td>
<td>0.31</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Figure 5.29 Peak intensity trajectory correlation for DF2

Table 5.16 Peak intensity coefficients for DF2

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.82</td>
<td>1.79 - 1.84</td>
</tr>
<tr>
<td>b</td>
<td>0.44</td>
<td>0.44 - 0.45</td>
</tr>
<tr>
<td>c</td>
<td>0.30</td>
<td>0.29 - 0.30</td>
</tr>
</tbody>
</table>
Figure 5.30 Peak intensity correlation for water

Table 5.17 Peak intensity coefficients for water

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>1.85</td>
<td>1.75 - 1.95</td>
</tr>
<tr>
<td>b=</td>
<td>0.44</td>
<td>0.43 - 0.46</td>
</tr>
<tr>
<td>c=</td>
<td>0.30</td>
<td>0.30 - 0.31</td>
</tr>
</tbody>
</table>

5.2.2.3 Peak Intensity Correlation Summary

Figure 5.31 demonstrates how the optimized coefficients between emulsions, neat DF2 and water compare. The slight difference in trajectories allows us to conclude that a unique correlation for emulsion specific coefficients to determine peak intensity is not necessary. The
coefficient values for “a”, “b”, and “c” between the cases stay approximately the same as was the case with the top trajectory coefficient results.

Figure 5.31 Peak intensity trajectories for predicted y/d calculated with optimized coefficients for q= 85

Table 5.18 Summary of coefficients for peak intensity correlations

<table>
<thead>
<tr>
<th></th>
<th>Median</th>
<th>Error Range Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emulsions + DF2 + Water</td>
<td>Emulsions</td>
</tr>
<tr>
<td>a</td>
<td>2.04- 2.06</td>
<td>1.97 - 2.10</td>
</tr>
<tr>
<td>b</td>
<td>0.42</td>
<td>0.40 - 0.41</td>
</tr>
<tr>
<td>c</td>
<td>0.30 - 0.31</td>
<td>0.32 - 0.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Emulsions</th>
<th>Emulsions + DF2</th>
<th>DF2</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.04</td>
<td>2.03</td>
<td>2.06</td>
<td>1.82</td>
</tr>
<tr>
<td>b</td>
<td>0.42</td>
<td>0.40</td>
<td>0.41</td>
<td>0.44</td>
</tr>
<tr>
<td>c</td>
<td>0.30</td>
<td>0.33</td>
<td>0.31</td>
<td>0.30</td>
</tr>
</tbody>
</table>
5.2.2.4 Bottom Edge Trajectories and Correlations

Due to the difficulty of obtaining a clear visualization of the plume bottom edge in the high pressure rig, five test cases were eliminated. The amount of neat DF2 and water cases were limited due to lack of clear visibility near the spray side wall.

Figure 5.32 Bottom edge trajectories for emulsions, DF2, and water
Figure 5.33 Bottom edge trajectory correlation for emulsions, DF2, and water

Table 5.19 Bottom edge coefficients for emulsions, DF2, and water

<table>
<thead>
<tr>
<th></th>
<th>2-8 atm PITM Median</th>
<th>2-8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.33</td>
<td>0.29 - 0.37</td>
</tr>
<tr>
<td>b</td>
<td>0.63</td>
<td>0.62 - 0.65</td>
</tr>
<tr>
<td>c</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Figure 5.34 Bottom edge trajectory correlation for emulsions

Table 5.20 Bottom edge coefficients for emulsions

<table>
<thead>
<tr>
<th></th>
<th>2-8 atm PITM Median</th>
<th>2-8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.21</td>
<td>0.20 - 0.23</td>
</tr>
<tr>
<td>b</td>
<td>0.73</td>
<td>0.72 - 0.73</td>
</tr>
<tr>
<td>c</td>
<td>0.28</td>
<td>0.28 - 0.29</td>
</tr>
</tbody>
</table>
Figure 5.35 Bottom edge trajectory correlation for DF2 and water

Table 5.21 Bottom edge trajectory coefficients for DF2 and water

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>6.35</td>
<td>6.12 - 6.42</td>
</tr>
<tr>
<td>b=</td>
<td>0.03</td>
<td>0.03 - 0.04</td>
</tr>
<tr>
<td>c=</td>
<td>0.27</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Figure 5.36 Bottom edge trajectory correlation for DF2

Table 5.22 Bottom edge trajectory coefficients for DF2

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>8.29</td>
<td>7.91 - 8.55</td>
</tr>
<tr>
<td>b</td>
<td>-0.05</td>
<td>-0.06 - -0.04</td>
</tr>
<tr>
<td>c</td>
<td>0.31</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Compared to peak intensity and top edge trajectory correlations Figure 5.33 and Figure 5.35 demonstrate correlations for the bottom edge with a low $R^2$ value. When the correlations are looked at separately for emulsions, DF2, and water (Figure 5.34, Figure 5.36, and Figure 5.37) there is an increase in the $R^2$ value which may indicate the need for a bottom edge trajectory equation that takes into consideration liquid viscosity or emulsion quality. The optimized
coefficients of “a” and “b” between emulsions, DF2, and water were significantly different. Section 5.2.2.5 provides an illustration of this difference.

5.2.2.5 Bottom Edge Correlation Summary

Differences between the optimized bottom edge trajectories in Figure 5.38 point to a need for an emulsion unique bottom edge trajectory equation. Despite a lower $R^2$ than what was obtained for the top edge and peak edge, there are large differences in coefficients “a” and “b” that further lead to either a unique correlation or an additional emulsion quality or fluid viscosity parameter to equation 5.6 for bottom edge trajectories. Figure 5.38 demonstrates that the bottom edge of the emulsion plume is much closer to the spray wall than what is seen for the neat liquids. This may be due to the break up differences that have been previously noticed by past researchers between emulsions and pure liquids. Although these break up differences were not noticeable when observing the top edge of the jet-in-crossflow plume, they appear to be evident on the bottom edge. Fracture point differences were noticed between the emulsions and pure fluids and this bottom edge behavior may be the result of these differences.

$$\frac{y}{d} = a q^b \left( \frac{x}{d} \right)^c$$  \hspace{1cm} 5.6
Figure 5.38 Bottom edge trajectories for predicted $y/d$ calculated with optimized coefficients for $q=85$

Table 5.24 Summary of coefficients for bottom edge correlations

<table>
<thead>
<tr>
<th></th>
<th>Median</th>
<th>Error Range Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emulsions</td>
<td>DF2</td>
</tr>
<tr>
<td>$a$</td>
<td>0.21</td>
<td>8.29</td>
</tr>
<tr>
<td>$b$</td>
<td>0.73</td>
<td>-0.05</td>
</tr>
<tr>
<td>$c$</td>
<td>0.28</td>
<td>0.31</td>
</tr>
<tr>
<td>$a$</td>
<td>0.20 - 0.23</td>
<td>7.91 - 8.55</td>
</tr>
<tr>
<td>$b$</td>
<td>0.72 - 0.73</td>
<td>-0.06 - 0.05</td>
</tr>
<tr>
<td>$c$</td>
<td>0.28 - 0.29</td>
<td>0.31</td>
</tr>
</tbody>
</table>
5.2.2.6 Width Trajectories and Correlations

Subtracting the bottom edge trajectories from top edge trajectories provided us with width trajectories of the plumes. In comparison to the bottom edge correlations, higher $R^2$ values were obtained. As with the bottom edge results, the optimized coefficients between the emulsion cases and neat DF2 and water were also different for the width trajectories. The impact of this difference on the optimized trajectories is described in section 5.2.2.7.

![Width trajectories for emulsions, DF2, and water](image)

Figure 5.39 Width trajectories for emulsions, DF2, and water
Figure 5.40 Width trajectory correlation for emulsions, DF2, and water

Table 5.25 Width coefficients for emulsions, DF2, and water

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>2.43</td>
<td>2.34 - 2.44</td>
</tr>
<tr>
<td>b=</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>c=</td>
<td>0.36</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Figure 5.41 Width trajectory correlation for emulsions

Table 5.26 Width coefficients for emulsions

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>2.20</td>
<td>2.09 - 2.25</td>
</tr>
<tr>
<td>b=</td>
<td>0.35</td>
<td>0.35 - 0.36</td>
</tr>
<tr>
<td>c=</td>
<td>0.37</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Figure 5.42 Width trajectory correlation for DF2 and water

Table 5.27 Width coefficients for DF2 and water

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.60</td>
<td>1.43 - 1.60</td>
</tr>
<tr>
<td>b</td>
<td>0.41</td>
<td>0.44</td>
</tr>
<tr>
<td>c</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Figure 5.43 Width trajectory correlation for DF2

Table 5.28 Width coefficients for DF2

<table>
<thead>
<tr>
<th></th>
<th>2 -8 atm PITM Median</th>
<th>2 -8 atm PITM Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=</td>
<td>1.53</td>
<td>1.53 - 1.81</td>
</tr>
<tr>
<td>b=</td>
<td>0.43</td>
<td>0.44</td>
</tr>
<tr>
<td>c=</td>
<td>0.33</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Similar to the conclusion from the bottom edge correlations, Figure 5.45 points to a need for an emulsion unique equation to predict width trajectory behavior. The differences in predicted width trajectories below are consistent to the predicted bottom edge trajectories. The emulsion cases have wider plumes due to the bottom edge being closer to the wall as
demonstrated in Figure 5.38. What is interesting is that even though the bottom edge trajectory for emulsions is closer to the spray wall, the top edge and relative peak intensity trajectories stay the same. This points to droplets coming off the jet fracture point penetrating much closer to the spray wall for emulsion cases. The major differences are once again seen in the “a” and “b” coefficients.

![Figure 5.45 Width trajectories for predicted y/d calculated with optimized coefficients for q= 85](image)

**Table 5.30 Summary of coefficients for width correlations**

<table>
<thead>
<tr>
<th></th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emulsions</td>
</tr>
<tr>
<td>a</td>
<td>2.20</td>
</tr>
<tr>
<td>b</td>
<td>0.35</td>
</tr>
<tr>
<td>c</td>
<td>0.37</td>
</tr>
</tbody>
</table>
5.3 Dual-PLIF Water-to-Oil Concentration for Emulsion-in-Crossflow

To investigate the composition of an emulsion spray in a jet-in-cross flow injection strategy, the Dual-PLIF method depicted in Figure 4.33 was utilized. Being that it was the first time this experiment was performed, special care was taken in insuring the fluorescence out of both liquids. In this section, fluorescence images are presented on the same scale for both neat and emulsion sprays. The test matrix for this experiment is displayed in Table 5.31. All images have been processed and registered so that they can be viewed normal to the laser sheet. The fuel injector is oriented in the top right position with the cross flow of air traveling downward. Although the main interest of this study is the fuel and water dispersion within the spray plume, results presented also demonstrate differences in the spray penetration with respect to the momentum flux ratio for each case. In the images presented it is evident that larger momentum flux ratio values lead to greater jet penetration except for the behavior seen at 1 atm cases. The 1 atm cases do not follow the same pattern due to the inability to accurately measure liquid and air pressure drops at this atmospheric pressure condition. Liquid pressure drop measurement error came from the low pressure drop values falling within the range of error for the pressure transducer used. Difficulty in pressure drop measurement for the air came from the inability to detect any noticeable pressure drop measurement from the mercury manometer at such low air flow rates. Not being able to detect the air pressure drop across the test section led to the inability to calculate the effective area for these atmospheric cases and therefore may have caused some error in our momentum flux ratio calculations. In these figures, the liquid injector is located to

<table>
<thead>
<tr>
<th></th>
<th>Emulsions</th>
<th>DF2</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.09 - 2.25</td>
<td>1.53 - 1.81</td>
<td>0.73 - 1.00</td>
</tr>
<tr>
<td>b</td>
<td>0.35 - 0.36</td>
<td>0.40 - 0.43</td>
<td>0.48 - 0.55</td>
</tr>
<tr>
<td>c</td>
<td>0.37</td>
<td>0.33</td>
<td>0.35</td>
</tr>
</tbody>
</table>
the right of the images. The images have been registered to account for the angle between the camera and the laser sheets. As a result, the images reflect what would be observed from directly above the test section. The slices shown in these images represent results from the laser sheet 40 mm below the point of injection. Throughout this section, water will be displayed on the left and DF2 on the right. Each figure is presented with its corresponding optical filter used F (water or DF2), ambient pressure P, liquid composition or mass fraction \( \Phi \), and momentum flux ratio \( q \).

Figure 5.46 and Figure 5.47 demonstrates the coordinates used to describe Dual-PLIF results illustrating as an example plume slice illuminated by a laser sheet.

<table>
<thead>
<tr>
<th>Table 5.31 Dual-PLIF test matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Pressure (atm)</td>
</tr>
<tr>
<td>Intensity Scale (counts)</td>
</tr>
<tr>
<td>Fuel Injection Nozzle [Type: Diameter (mm)]</td>
</tr>
<tr>
<td>Crossflow Air Velocity (m/s)</td>
</tr>
<tr>
<td>Crossflow Mass Flow (kg/min)</td>
</tr>
<tr>
<td>Liquid Velocity (m/s)</td>
</tr>
<tr>
<td>Liquid Mass Flow (kg/min)</td>
</tr>
<tr>
<td>Emulsion Water Mass Fraction (( \Phi=W/(O+W) ))</td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Comparison Momentum Flux Ratio (q)</td>
</tr>
<tr>
<td>Liquid Injection Pressure (MPa)</td>
</tr>
</tbody>
</table>

Figure 5.46 Coordinate system used in Dual-PLIF experiment illustrating laser sheet through spray plume
5.3.1 Neat Liquids

Dual-PLIF results for the neat (i.e., pure) liquids are presented in Figure 5.48 through Figure 5.51 for pressures of 1-5 atm. The results for the pure liquids provide a foundation for observing the patternation characteristics for emulsion jet-in-cross flow type fuel injection. The neat fuel images are presented in order of low to high pressures and demonstrate the appropriate response from the Dual-PLIF diagnostic since both water and DF2 image are observed to have higher intensities with the increase in pressure. The increase of intensity at greater pressures is due to higher liquid mass flow rates necessary in obtaining the sought out momentum flux ratios at elevated pressures. There are some noticeable differences between the neat water and neat DF2 images presented below. The water appears to be circular and round while the DF2 appears to be more oval and elongated in the z-direction.
Momentum flux is subject to relatively large uncertainty.
5.3.2 Emulsions $\Phi = 0.23$, W/O$= 0.30$

Results are shown in Figure 5.52 through Figure 5.57 for emulsions with a water fraction of 0.23. For emulsions, differences in the shape of the spray cross section between the water and DF2 are evident. The DF2 appears to disperse more widely in the $z$-direction as was evident in the neat cases and the water appears to lose its round shape from the neat cases and appears to elongate in the $y$-direction. Both water and oil intensities increase with increasing pressure, but the DF2 has higher overall intensity since by volume there is more fuel than water for this case. Note that the behavior of each liquid in the emulsion differs from that of the individual liquid when injected as a pure liquid shown in Section 5.3.1.

lux is subject to relatively large uncertainty
Figure 5.52: \( F = W, P = 1.01 \text{ atm}, \Phi = 0.20, q = 50^\circ \)

Figure 5.53: \( F = DF_2, P = 1.01 \text{ atm}, \Phi = 0.22, q = 45^\circ \)

Figure 5.54: \( F = W, P = 1.99 \text{ atm}, \Phi = 0.28, q = 109.02^\circ \)

Figure 5.55: \( F = DF_2, P = 1.98 \text{ atm}, \Phi = 0.25, q = 120.53^\circ \)
5.3.3 Emulsions $\Phi = 0.38, W/O = 0.60$

In Figure 5.58 through Figure 5.63 the water continues to demonstrate an elongated oval expansion in the $y$-direction and the DF2 in the $z$-direction. The water becomes brighter and the DF2 dimmer for the $\Phi = 0.38$ cases which is expected based on an increased presence of water and decreased presence of DF2. One more observation when comparing the DF2 concentration position for the $\Phi = 0.23$ and $\Phi = 0.38$ cases is that in increasing emulsion water content results in the DF2 concentration position to move forward in the $y$-direction. Intuitively this may be explained by the water elongating in in the $z$-direction.
Figure 5.58 F= W, P= 1.01 atm, Φ= 0.22, q= 50

Figure 5.59 F= DF2, P= 1.01 atm, Φ= 0.34, q= 50

Figure 5.60 F= W, P= 2.05 atm, Φ= 0.39, q= 97.25

Figure 5.61 F= DF2, P= 1.95 atm, Φ= 0.39, q= 102.28
5.3.4 Dual-PLIF Summary

The neat fluids demonstrate a proof of concept of the Dual-PLIF technique at high pressure conditions. In the neat fluid images, fluorescence intensity of both DF2 and water is seen to increase with ambient pressure which corresponds to higher liquid mass flow rates. In the emulsion cases higher intensities for higher flow rates are again observed in addition to the confirmation that the DF2 and water are being optically separated. For emulsions of a water-to-oil ratio 0.3 and 0.6 the DF2 fluorescence is much more intense at 0.3 than at 0.6 due to higher DF2 concentration at 0.3 than 0.6. The inverse is observed with the dyed water, where there is less fluorescence intensity at 0.3 than at 0.6 because there is higher water concentration at 0.6. In addition to this proof of concept, the above results allow us to qualitatively observe the spray penetration with varying momentum flux ratios (with the exception of the one atm cases—these cases have low injection pressures and are thus subject to considerable uncertainty).
The previous Dual-PLIF testing at atmospheric conditions focused on the ability to optically separate oil and water dispersion in a section of a cone spray in a quiescent environment as well as cone sprays and plain jets injected into a crossflow. Quantitative results from the previous experiment demonstrated that the fluorescence intensity out of both water and DF2 are directly proportional to the surface area of the spray droplets. A quantitative comparison of the current Dual-PLIF experiments with the previous is not possible since it is a different experiment using different lasers and injection strategy. From the above results it is concluded that the fluorescence intensity of the fluids is proportional (although the proportionality ratio has not been quantified) to the spray surface area since the images with higher intensity pertain to higher mass flow rates (with increasing pressure). Similarly the above results demonstrate that the spray penetration matches well with what is expected based on momentum flux ratios with the exception of the one atmosphere cases for reasons described section 5.3. In addition to a proof of concept and a proportional relationship (yet to be quantified for this experiment) between fluorescence intensity and fluid concentrations, some behavior differences between water and DF2 were observed with the Dual-PLIF experiments. For emulsion experiments the shape of the water slice was observed to elongate in the y-direction. This observation may indicate that the bottom edge behavior for emulsion sprays observed in section 5.2.2.5 is due to this change and elongation of the water in the horizontal direction. Emulsions appeared to have bottom edge trajectories closer to the spray wall, but it is not certain from these images if this behavior is due to water droplets, diesel droplets, or both shedding off the fracture point sooner than they would as a neat fluid. From looking at the distances from right to left in Figure 5.64 (with the exception of images 136 and 137 where window wetting was present) the DF2 is present farther from the spray wall than the water in the emulsion cases, but this may also be due
to the differences in momentum flux ratio between the emulsion cases. In addition to momentum flux ratio differences there may be some differences in the fluorescence intensities from both the DF2 and water that have not yet quantified yet to make the conclusion that either DF2 or water droplets are present closer to the wall.

<table>
<thead>
<tr>
<th>Image #</th>
<th>Fluid</th>
<th>Water to Oil Ratio by Mass Measured</th>
<th>Ambient Pressure (atm)</th>
<th>MFR</th>
<th>Distance Right to Left (Pixels)</th>
<th>Distance Right to Left (mm)</th>
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Figure 5.64 Dual-PLIF matrix with distance of plume from the right to left as a reference comparison
6 Summary, Conclusions, and Future Work

6.1 Summary

Experiments for the investigation of emulsion jet-in-crossflow spray behavior were conducted at elevated pressures for the first time. A total of 53 experiments were completed varying the following parameters: ambient pressure 2 – 8 atm, momentum flux ratios 40 – 170, emulsion water concentrations of \( \Phi = 0.00, 0.23, 0.38 \) and 1.00 and nozzles diameters of 0.57 mm and 0.72 mm. Diagnostics were used to investigate the top edge penetration, peak intensity, bottom edge, and width trajectories in addition to the in-situ oil and water dispersion of these sprays. Various parameters were varied throughout the testing including the injector diameters, emulsion quality, momentum flux ratios and ambient pressure. Emulsion experiments were conducted at applicable gas turbine conditions for the first time in this research area. The Dual-PLIF diagnostic was also conducted as a first time occurrence at these elevated pressure gas turbine conditions. Below is a summary of the results and findings of this research.

6.2 Conclusions

- Optical separation of oil and water within an emulsion spray demonstrated that water distribution is elongated in the direction perpendicular to the spray wall.

Optical separation of water and oil within an emulsion jet-in-crossflow was obtained using the Dual-PLIF technique. Optically separating the two fluids allowed for the investigation of the differences in the two fluids as they were being atomized downstream of the injection point. Emulsion spray patterns demonstrate unique behavior with respect to plume shapes, sizes, distributions and orientations in comparison to neat fuel patterns. These differences were evident
qualitatively from looking at the different plume shapes, sizes, distributions and orientations. From looking at the Dual-PLIF results the water plume for emulsion cases was observed to elongate in the horizontal direction. There may be some indications of water and DF2 droplet shedding being affected by the emulsion but it is difficult discern at the moment which liquid is present closer to the spray wall due to momentum flux ratio fluctuations and lack of quantification of fluorescence intensity from both liquids. Future improvements of the Dual-PLIF experiment may give more clarity on specific component distribution relative to the spray wall.

- **Momentum ratio captures the windward edge trajectory behavior for the conditions studied. Emulsion quality or some independent effect of emulsification does not impact the trajectory in any special way.**

Measured trajectories of water, DF2, and emulsions at elevated pressures were plotted and visually demonstrated that the momentum flux ratio dominates the top edge trajectory behavior based on the averaged images of each case. These measured trajectories were then used to optimize a trajectory correlation for emulsions at elevated pressures and through a linear regression numerical analysis it was established that the momentum flux ratio is the dominating factor. Coefficients for these elevated pressures were optimized and did not vary significantly from 2 atm, 5 atm, and 8 atm ambient pressure conditions, allowing us to conclude that an additional penetration correlation that includes the impact of pressure or emulsion quality is not necessary to predict the top edge penetration behavior as demonstrated below in Figure 6.1. Coefficients optimized for top edge trajectory correlations using Edge Trace Method and were validated with Pixel Intensity Trace Method further establishing the conclusion that momentum flux ratio dominates top edge trajectory behavior rather than ambient pressure or emulsion quality.
Emulsion sprays exhibit much wider spray plumes in comparison to neat fuel and water sprays indicating the need for a unique correlation to predict the width and bottom edge trajectories of emulsion sprays.

Using the Pixel Intensity Trace Method bottom edge, plume width, and peak intensity correlations were developed for emulsions. Similar to what was concluded for the top edge penetration behavior, differences in the peak intensity for the emulsions and neat fluids were negligible and the peak intensity results do not point to a need for a unique emulsion correlation. However, bottom edge and width trajectory results point to a need for a unique emulsion correlation. Emulsion cases demonstrated a bottom edge trajectory closer to the spray wall in comparison to neat liquid cases leading to a larger plume width as presented in Figure 6.2.
Future Work

The experimental approach and analysis of this work was fairly new bringing about much insight on future work opportunities. Some of the major experimental challenges were window wetting, fluid pumping difficulties, fluorescence intensity calibration, and crossflow velocity metering. Future improvements on these issues will allow for further emulsion jet-in-crossflow exploration in addition to a confirmation of the most current findings. The following are some future work opportunities:

- Complete quantitative analysis of Dual-PLIF images
- Investigate instantaneous emulsion spray plume behavior at break up regimes
• Investigate combustion behavior of emulsions utilizing spray penetration correlations

• Improve Pixel Intensity Trace Method in order to expand the available data on bottom edge and width trajectories to further confirm that a unique bottom edge and width correlation is needed for emulsions

• Complement emulsion bottom edge trajectory findings with Dual-PLIF analysis on specific component location relative to spray wall
References


Appendix A: Test Matrices

Table 7.1 Jet-in-crossflow test matrix for 0.57 mm orifice
Table 7.2 Jet-in-crossflow test matrix for 0.72 mm orifice

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<th>Value 3</th>
<th>Value 4</th>
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</table>

Note: Each column represents a different parameter with multiple values for each condition.
Table 7.3 Jet-in-crossflow test matrix for Dual-PLIF experiment (0.57 mm orifice)
Appendix B: Jet-in-crossflow observations

Figure 7.1 Water, DF2, and emulsion streak line comparison (noticeable difference in fracture points)
Figure 7.2 Some differences observed in jet break up regimes between emulsions and pure DF2
Appendix C: MATLAB codes

%% This m file was used to determine the outline of a spray in order to
%% determine the top edge trajectory
%% This code averages videos into singe edge filtered image
%% Close all previously open files
%% This code was put together by Justin Legg and modified by Guillermo Gomez
%% Matlab reads the avi files into the software (both Edge Sobel and direct
%% shadowgraph image)

clear
clc
for j=78:81;
    I=num2str(j);
    filename1=['HJ_0.72_','I','_T.avi'];
    filename2=['HJ_0.72_','I','_TES.avi'];

    sprayES = aviread(filename2);
    spray = aviread(filename1);

    % The following portion was found online, and gives a way to find
    % average frame of the avi file. The movie generated, 'sprayES',
    % is a structure array, with each element defining one frame.
    % Within each element are 2 further elements, called 'cdata'
    % and 'colormap'; 'cdata' is the actual bitmap image, and this needs
    % to be extracted.
    % First the number of frames are defined.

    [jigES framesES] = size(sprayES);
    [jig frames] = size(spray);

    % Using a for loop, extraction of each individual frame, invert it
    % (because of the Edge Sobel process), and then convert it to a
    % double array to be averaged. Also in this block, the images are
    % converted to black and white

    for i = 1:framesES;
        x = sprayES(i).cdata;
        xi = im2double(x);
        level = graythresh(x);
        %imagesES(:,:,i) = xi;
imagesES_bw(:,:,i) = im2bw(x, level);
%T(j,i)=level;
end

%% With the frames now extracted, the can be averaged

x_avg = mean(imagesES, 3);
figure, imshow(x_avg);
k=num2str(level);
x_bw_avg = mean(imagesES_bw, 3);
figure, imshow(x_bw_avg);
filename3=['J_0.55_close_','I',',','k','_AvgES.tif'];

filename4=['HJ_0.72_close_','I','_ES.tif'];
imwrite(x_bw_avg,filename4,'TIF')
imwrite(x_avg,filename4,'TIF')

**********************************************************
********************
clear
clc
% Programmer: Guillermo A Gomez
% Contact: gag@apep.uci.edu
% Created: 3-16-12
% Purpose of this file is to trace the top edge of a spray plume in a
% Jet-in-crossflow set up. The code initially converts the averaged spray
% image into a binary image and from there uses a sub code to trace the
% edge

for j=17;
    I=num2str(j);
    filename1= ['HJ_0.72_close_','I','_ES.TIF'];
%%% Image Input
%%% %image = imread(filename1);
%%% %figure,imshow(image)
%%% %Creates a binary image
%%% level=graythresh(image)
%%% BW = im2bw(image,0);
%%% figure,imshow(BW);

%%% Eliminates spots with connectivity of less than 800 pixels
BW2 = bwareaopen(BW,200);
figure,imshow(BW2);
filename10=['HJ_0.72_close_' I,'TRACE_200.TIF'];
%imwrite(BW2,filename10);

% Run Plume Edge code to trace the top edge of the spray plume
d=plumeedge(BW2);
filename3=['HJ_0.72_close_' I,'_TRACE_200.xls'];
xlswrite(filename3, d);

End

*************************************************************************
% Sub code plumeedge (d)
function d=plumeedge2(BW2)
g=1;
for m=1:512
  for n=1:512
    if BW2(n,m)==1
      Q(g,1)=m;
      Q(g,2)=n;
      g=g+1;
    end
  end
end
figure
plot(Q(:,1),512-Q(:,2),'.')

s=size(Q);
for h=1:s(1)
  x=min(Q(:,1));
  x_max=max(Q(:,1));
  e=1;
  while x<=x_max
b=1;
for k=1:s(1)
    if Q(k,1)==x
        A(b)=512-Q(k,2);
        b=b+1;
    end
end
d(e,1)=x;
d(e,2)=max(A);
x=x+1;
e=e+1;
end

hold on
plot(d(:,1),d(:,2),'r')

hold off