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Development and Characterization of Flow Independent Fuel Injectors

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DEVELOPMENT AND CHARACTERIZATION OF FLOW INDEPENDENT FUEL INJECTORS

by

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ABSTRACT

Jet-in-crossflow is an interaction between a fuel jet and air crossflow commonly found in jet engines. The crossflow is used to break up or atomize the fuel jet for downstream combustion. This interaction between fluids while at low speeds, is predictable, varies greatly at higher speeds. This investigation seeks to (1) create a mechanism for jet-in-crossflow, using mechanical pintles, that is independent of velocity to help increase the predictability and reliability of jet engines and (2) identify key design parameters that will lead to flow independence. Parameters investigated in this experiment include pintle height, angle, and percent of pintle coverage into the jet orifice. Pintles that covered 100 percent of the jet showed a strong deviation from the traditional interaction with no pintle. Relationships were also found between the angle, height, and penetration depth although none as ubiquitous as the jet coverage.

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INTRODUCTION

Jet design has always been limited by the weight of propellants required to operate. Jet propulsion systems take advantage of atmospheric oxygen using it to burn fuel. Thus, there is no need to store oxidizers onboard the aircraft and weight considerations become less strict. To achieve combustion, airflow is pushed through an inlet and met with the injection of a liquid fuel jet flowing orthogonal to the air [1]. The fuel jet will break up in various ways depending on different flight conditions and will combust further downstream if atomized properly. This mechanism is commonly referred to as liquid jet-in-crossflow. Jet engine propulsion has increased the range of jets for low altitude flight [2]. Further work is being conducted to increase the efficiency of this system, in turn creating more powerful and reliable jet engines.

This research will be focused on the mechanisms behind liquid jet-in-crossflow. The profile of any fuel jet will change depending on the different flight conditions which leads to uncertainty in the design of jets. The Navy is invested in developing technology for flow independent fuel injectors. Under this condition, regardless of incoming airflow, the liquid fuel jet would display similar fluid dynamic properties. Flow independence is a valuable condition for current propulsion systems. The development of flow independent fuel injectors will provide more stable combustion to current jets. Stability will increase the power and range and efficiency of these systems. Currently, the location of the column breakup point and atomization of the fuel are all primarily controlled by the speed of the incoming airflow contacting the jet [1]. This investigation will explore the possibility of achieving flow independence by using mechanical pintles to control the jet break-up and atomization.

To fully understand the breakup mechanisms in jet-in-crossflow, it is helpful to study the behavior of single droplet breakup. Hansen *et. al* [3] investigated the atomization of five different liquids to determine which properties of the fluid affected breakup. Unless the velocity of the air is greater than a critical value, the droplet will deform after initially interacting with the airflow for a sustained period. The deformation is referred to as a bag. This bag will continue to expand until the droplets reach a critical diameter. After this diameter is reached the bag will break and move downstream with the flow. In this experiment, breakup mechanisms were investigated in droplets of various sizes where the droplets were impacted with airflow of different velocities. Hansen concluded that breakup was dependent on surface tension which is consistent with past work regarding atomization of the liquid. For flow independence to be achieved, the breakup must also be independent of the surface tension of the jet.

The goal of using mechanical pintles is to try to achieve flow independence through impacting the fuel jet. Mechanisms involved in impact vary depending on the type of collision. One method that can help describe these mechanisms is jet impingement. There are multiple ways to impinge the fuel jet. The method used by Avulapati and Venkata [4] was air-assisted impinging jets. Introducing a gas jet would help further break up the fuel should the liquid impingement prove insufficient for atomization purposes. From the experiment, changing the impinging angle of the liquid jets, α, had very little effect on the breakup process. Increasing the velocity of the gas jet would universally improve the breakup of the fuel which leads to suggest that momentum parameters dominate the characteristics of the breakup rather than the collision. It is also important to note that the characteristics of the atomization were discovered to be dependent on viscosity as well as surface tension, similarly to the droplet investigation. This method stands only to provide insight into the breakup mechanisms at work as it was previously investigated by this group but required substantial pressures to drive atomization so it is not effective for the current experiment.

Two parameters will be used to help characterize the liquid jet-in-crossflow in this experiment. The first is the Weber number,

$$\mathrm{We} = \rho U^2 D / \sigma \tag{1}$$

where ρ is the density of the crossflow, U is the velocity of the crossflow, D is the diameter of the fuel injector, and σ is the surface tension of the fuel. The second parameter is the momentum flux ratio [1].

$$q = \frac{\rho_{fuel} U_{fuel}^2}{\rho_{air} U_{air}^2} \tag{2}$$

Previous work has determined that changing the values of these parameters has profound effects on the profile of the liquid jet. In an examination of the effects of the Weber number and momentum flux ratio conducted by Lubarsky *et. al* [1], the breakup of liquid jets is better understood. When a liquid jet meets crossflow, the jet breaks up in a way similar to the droplets mentioned earlier. It is important to note that the liquid column of the jet remains unaltered until a breakup point. Where this point is located was found to vary with the momentum flux ratio. As this point varies, the profile, or penetration, of the

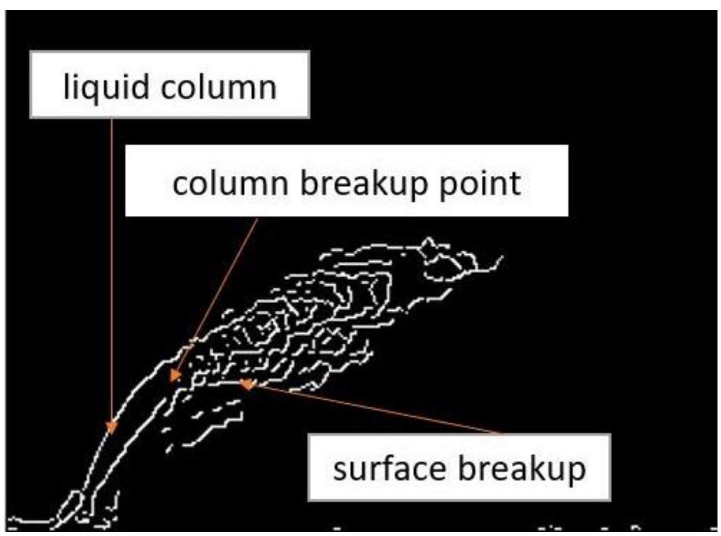

Figure 1: Typical Spray Profile of Fuel Jet-In-Crossflow Injector

jet will change as well After this point, the breakup will occur as shown in the previous investigation on droplet breakup. The column will start to break into droplets and those droplets will experience bag break up once separated from the jet. Another breakup mode would occur depending on the test conditions. The dominating breakup mechanism transitions from bag breakup to shear breakup as the Weber number increases past 200[1]. In shear breakup, the droplets are sheared off of the column by the force of the airflow. The most relevant conclusion in this study was the discovery that between We = 400-1600, penetration was flow independent as shear breakup became the only breakup mode acting on the column. Experimental studies help characterize the jet-in-crossflow beyond the use of nondimensionalized parameters. Jet penetration and breakup have been shown to vary with jet diameter [6]. Additionally, an investigation conducted by Wu et al., through the use of pulsed shadowgraphy, discovered breakup is driven by column waves and acceleration waves. Primary breakup occurs due to the column waves and secondary breakup, the breakup of droplets occurring after the original column breaks up, is dominated by the acceleration waves. Alongside these observations, correlations were provided to predict the behavior of the liquid jet. The column breakup point can be located with the following correlation:

$$\frac{y_b}{d} = C_y\sqrt{q} \tag{3}$$

where y_b is the y coordinate of the column breakup point, d is the jet orifice diameter and C_y is the proportionality constant. Their measurements suggested a more specific fit of:

$$\frac{y_b}{d} = 3.07q^{0.53} \tag{4}$$

slightly altering the power of the momentum flux ratio used in the correlation. The x-coordinate of the column breakup point was experimentally found to be constant using the following relation:

$$\frac{x_b}{d} = 8.06 \tag{5}$$

The aforementioned correlations and observations are used for traditional liquid jet-in-crossflow and help explain the interaction between the liquid fuel jet and the gaseous crossflow. However, to understand the spray and splash dynamics at the jet-pintle interface, more information is needed. The Coanda effect may explain the results of this investigation. This effect describes the tendency of a fluid to deflect along a surface close to the outlet [7]. In this investigation, the pintles will be located immediately after the injection orifice, to break up the fuel jet before it is subjected to aerodynamic shear. This effect is sensitive to the geometry of the surface located after the orifice with steeper steps causing the flow to separate [8]. The success of the different pintles will depend on how the Coanda effect drives fluid flow on the pintle. Curved edges and sharp edges will lead to different surface interactions. It is reasonable to assume that should flow independence be achieved, that there will be a breakup mode unlike those displayed by previous investigations.

METHODOLOGY

This research was conducted in the Propulsion and Energy Research Lab – Center for Advanced Turbomachinery and Energy Research (CATER) at the University of Central Florida. The objectives were to (1) develop fuel independent fuel injectors concepts, (2) investigate the fuel independent injector concepts at relevant flight conditions, and (3) explore the interaction and control of the fuel jet flow to drive the spray atomization and combustion.

The injector concepts were developed based on an in-depth literature review. The first variable of interest was the breakup point. If the jet were to break up before the momentum forces of the gas began to dominate the interaction, the fuel jet profile may start to become more independent of the crossflow. The set of pintles that test this hypothesis have varying angles from the base of the injection orifice. The higher the angle, the further upstream of the jet the y-coordinate of the column breakup point will be. Similarly, the x-coordinate will also be varied with these concepts by altering the length of the pintle. Longer pintles will cover more of the injection orifice and may affect the spray profile. Also, the pintle surfaces will be flipped to see if the other surface has any effect on the flow parameters as well. All the pintle concepts used in this investigation, shown in Figure 2, were created using an AnyCubic Photon S resin SLA printer, with an XY resolution of 47um, a layer height of 25 um, and a layer resolution of 1.25 um.

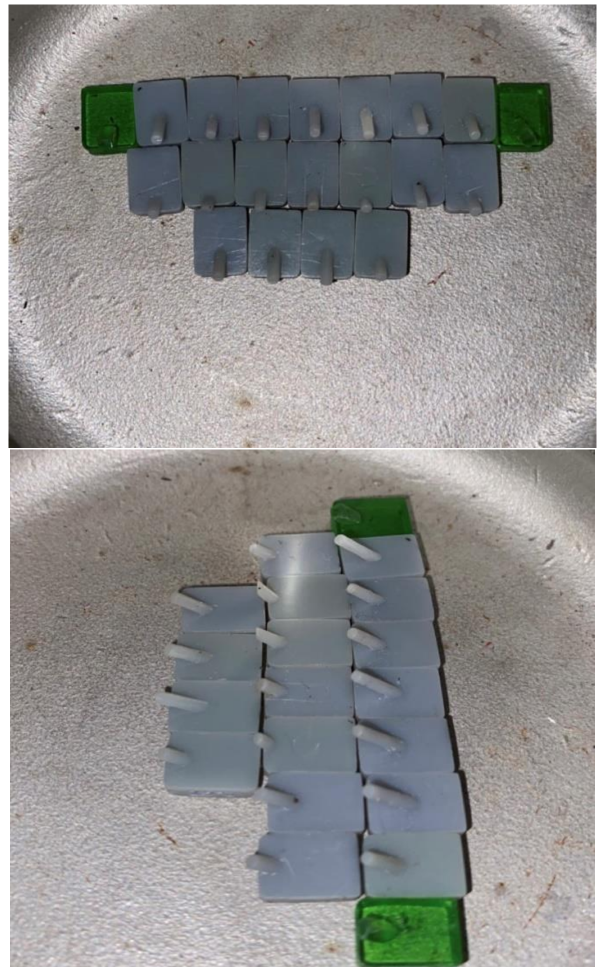

Figure 2: Pintle Injector Concepts

To test the pintles at the desired conditions, a blowdown wind tunnel, as shown in Figure 3, was used. They were tested in non-reacting conditions with varying Weber numbers and momentum flux ratios to evaluate flow independence. The following conditions will be investigated in this experiment:

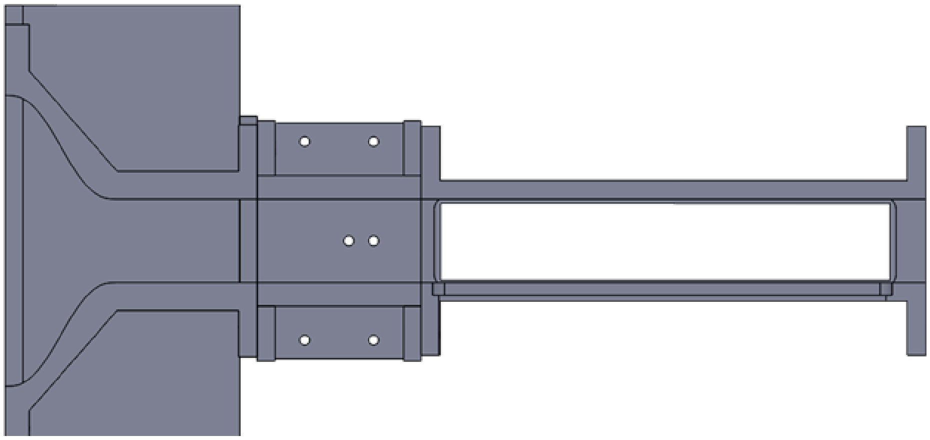

Figure 3: Wind Tunnel Facility

Table 1: Test Cases for Pintle Concepts

Test Case	Jet Velocity (m/s)	Air Velocity (m/s)	Crossflow Weber Number	Jet Weber Number	Momentum Flux Ratio
1	1.9	40	21	10	1.9
2	3.8	40	21	44	8.3
3	8.8	40	21	176	33
4	6.5	80	85	115	5.42
5	18.7	80	85	963	29

Every pintle concept was tested under the 5 different test cases. The jet fluid used in this investigation is water. To obtain accurate exit velocities, control valves will be calibrated to control the speed of the crossflow. The measured venturi meter velocity was compared to the pitot tube velocity downstream to ensure that the concepts are being tested at the correct values. LABVIEW controls were used for timing purposes as well as to verify velocity readings. Uncertainty in the airflow velocity is predicted to be about 5% of the reading. For the liquid jet, a tank will be pressurized at a tested pressure to ensure that it is outputting the correct mass flow rate. Two Photron SA1 cameras captured the images at 10000 frames per second with a shutter speed of 1/104000s and at a resolution of 1024x512 pixels. These images were processed using MATLAB. First, a mean image for each experimental run was calculated. Then in this mean image, the windward edge, leeward edge, and jet centerline were detected. Finally, the image would be processed with the 3 lines detected. Through this collection of data, the promising concepts were identified and can be improved to be retested.

Once the most promising concepts have been refined, injectors will be tested again over a more expansive range of Weber numbers and momentum flux ratios. They will also be exposed to both non-reacting and reacting flow. The goal of these tests will be to characterize the physics behind fuel independence. The analysis will take place using Phase Doppler Particle Analysis (PDPA). Through this technique, penetration and atomization can be examined and quantified. Using the data collected, theories can be developed on the breakup mechanisms behind flow independence. Their performance will also be quantified at this time. Finally, fuel injectors will be tested to learn how to control the atomization characteristics. This test will also be conducted through reacting flow and through the use of chemiluminescence data, models will be developed to predict the behavior of flow independent fuel injection.

RESULTS AND DISCUSSION

To evaluate flow independence, mean images will be examined for each of the different pintle variations. A baseline image was taken without a pintle for each Weber number and momentum flux ratio for comparison. Also, the default angle for the pintle was 45 degrees and at this angle, most of the data points were taken.

VARIATION IN COVERAGE AND HEIGHT

Coverage in this investigation is defined to be the percentage of the jet orifice that the tip of the pintle covered. Height is the vertical distance from the injection orifice to the tip of the pintle. At heights of 0.05in, 0.10in, and 0.15in, coverages of 50, 75, and 100 percent were tested for various crossflow Weber number and momentum flux ratios. A few key observations about the variation in coverage were noted. At all weber numbers and momentum flux ratio cases, 50 and 75 percent coverage behaved similarly to the baseline case. The most exaggerated example of this happens at a height of 0.15in. At a high Weber number and low momentum flux ratio, the liquid jet seems to deflect away from the pintle before it can interact with the surface. The aerodynamic forces appear to dominate the liquid jet and the breakup modes which explains why these cases behave similarly to the baseline case. Even in the cases where the flow did not immediately deflect away from the pintle, the aerodynamic

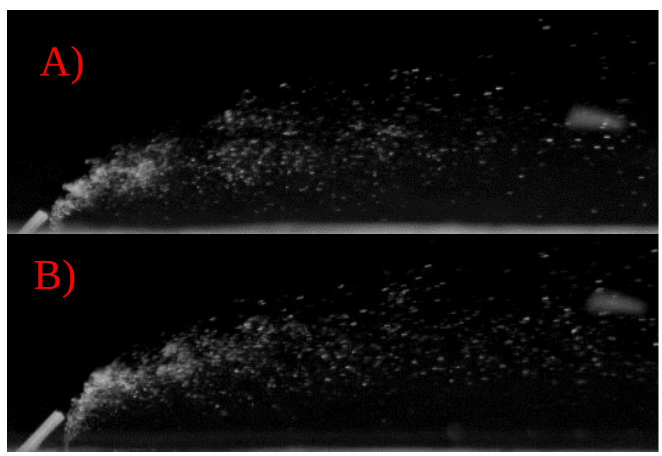

Figure 4: Liquid Jet Deflection at Test Case 4 for A) 50% Coverage B) 75% Coverage

forces seem to still dominate the breakup mechanisms creating a similar penetration and atomization process to that of the baseline.

At We = 85 and q = 29 (test case 5), the maximum value for both parameters in this investigation, the breakup is fairly similar between coverages 50 and 75 percent. This is most clearly displayed at a pintle height of 0.05in. Test case 5 represents the high extreme of the test case and as a result, it seems the aerodynamic forces have more control over the pintle at this condition rather than the surface interaction forces. However, the 100 percent coverage test cases showed a significant decrease in penetration. Across the data set, at 100 percent coverage penetration profiles would diverge from the baseline case. Except for test case 5, the jet at 100 percent coverage would behave in contrast to the other pintle cases at all 3 pintle heights. There must be another breakup mechanism involved in the interactions that occur at the maximum coverage. With this

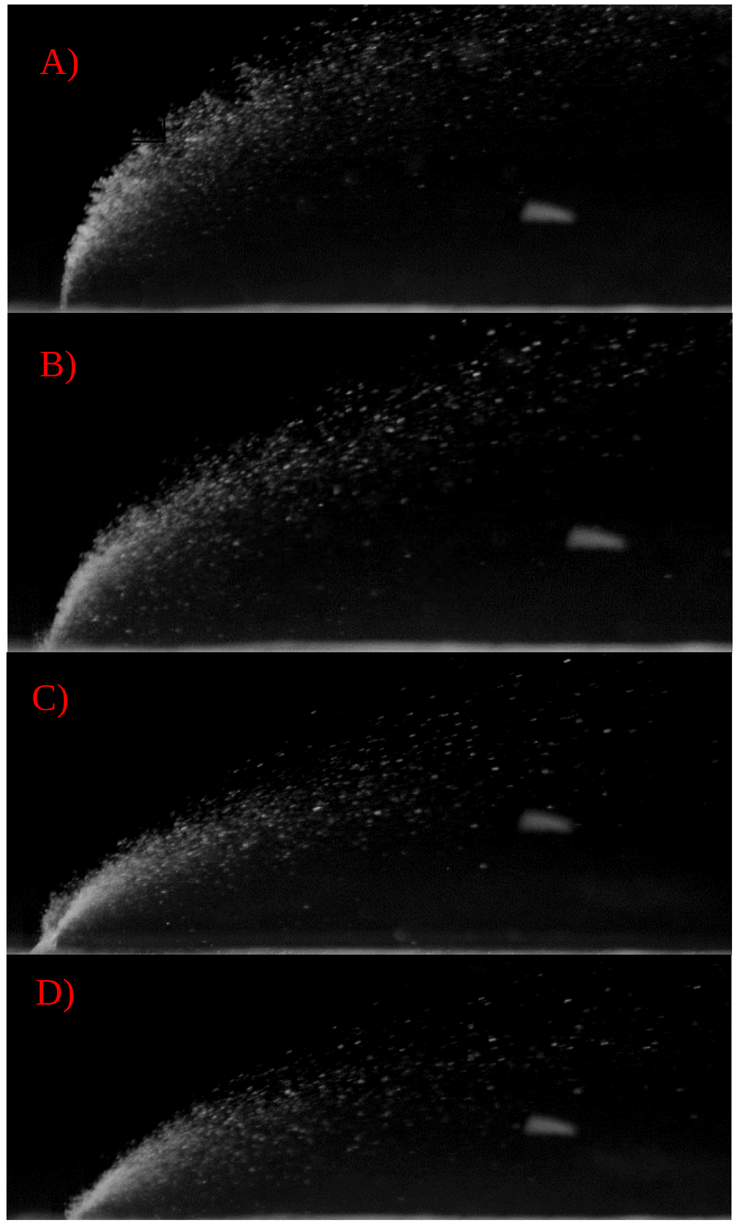

Figure 5: Liquid Jet Profile at Test Case 5 for A) Baseline (no pintle) B) 50% Coverage C) 75% Coverage D) 100% Coverage

coverage, the jet cannot deflect away from the pintle even at high crossflow velocities, so the surface forces play a role in how the jet interacts with the crossflow. Also, the surface of the pintle will be a lot closer to the orifice of the jet at the maximum coverage than at the other coverage cases. These conditions paired with a slow injection velocity are favorable for the Coanda effect to play a considerable role in jet penetration. Even at a height of 0.15in, the furthest a pintle will be from the jet in this investigation, and with high liquid jet velocities, the tendency for the liquid jet to follow the surface located immediately after the surface is evident. The Coanda effect leads to lower penetration depth across all test cases, although it is more prevalent in cases with lower jet velocity. While it can be seen sparingly at 75 percent coverage, it has a profound effect at 100 percent coverage.

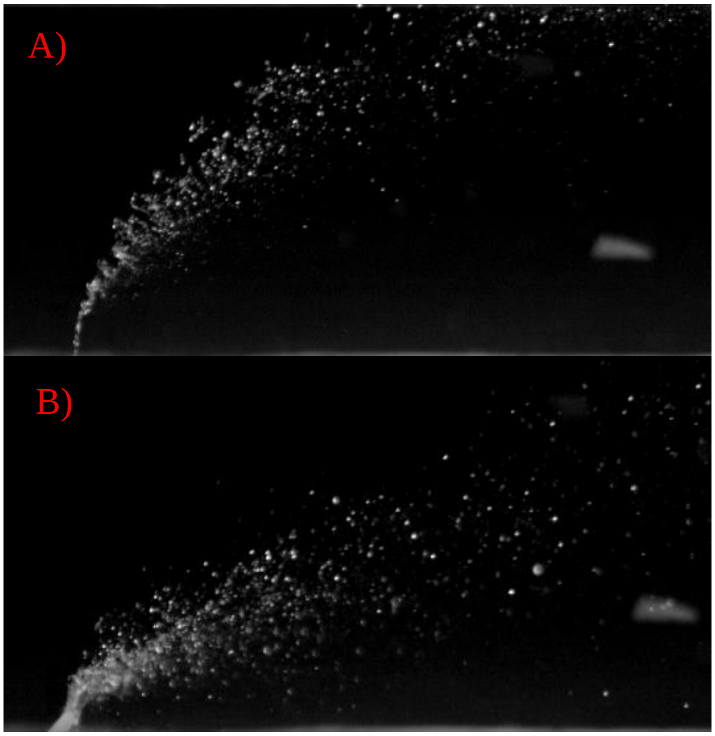

Figure 6: Penetration of jet at Test Case 4 – A) Baseline Case B) 0.15in Pintle at 100 percent Coverage

VARIATION IN ANGLE

The default angle in this investigation was considered to be 45 degrees. However, pintles were designed at 30 degrees and 60 degrees to see if the variation of angle offers control over the penetration and breakup. In the previous section, coverage and height were varied to see if either variable affected all while keeping a constant pintle angle of 45 degrees.

Deviation from 45 degrees in either direction would only affect the lower Weber number cases. At higher test cases, the liquid jet would behave similarly between the 3 different angles. Figure 7 shows very similar jet profiles compared to the baseline and it becomes apparent that the aerodynamic drag becomes more important than the angle of the pintle at higher angles.

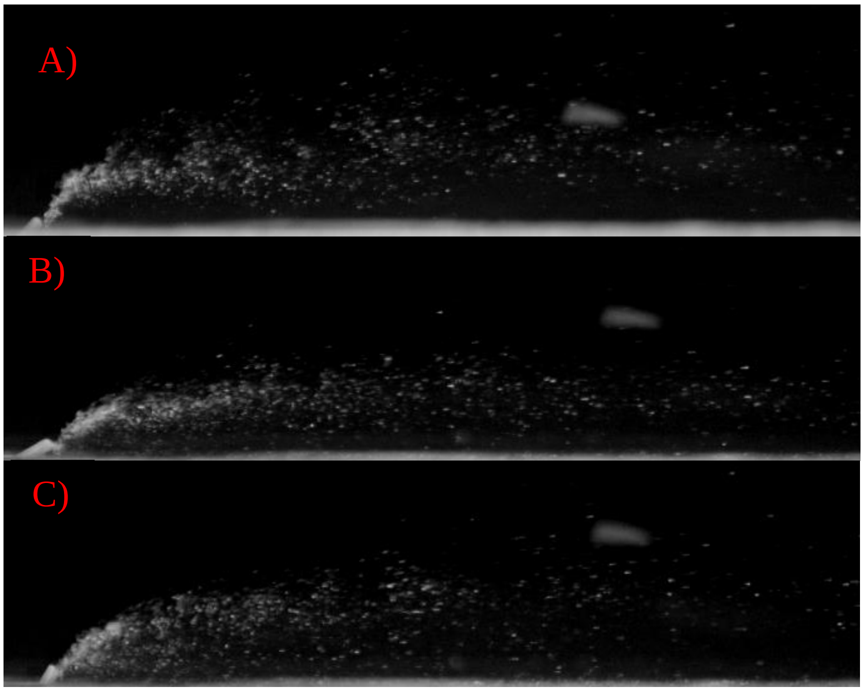

Figure 7: Effect of Angle Variation at Test Case 4 for A) Baseline (45 degrees) B) 30 Degrees C) 60 Degrees

To see what happens when the angle of the pintle is varied, test case 2 can be referred to. At low crossflow velocities, the jet penetration will directly correlate with the penetration angle. The jet column breakup point is wherever it contacts the pintle and this location will move up and down following the change in angle.

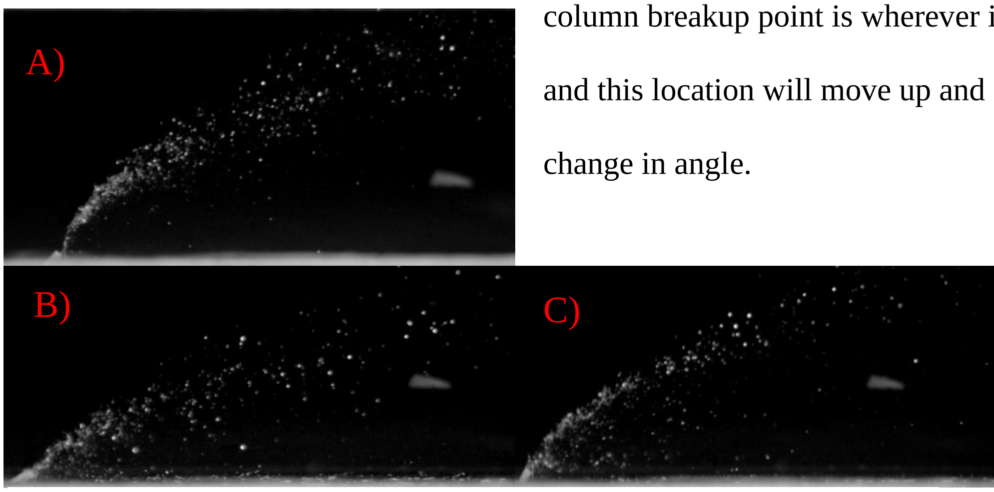

Figure 8: Variation in Penetration at Test Case 2 for A) Baseline (45 Degrees) B) 30 Degrees and C) 60 Degrees

CONCLUSIONS

The effect of different pintle designs in liquid jet-in-crossflow has been experimentally observed and analyzed. The goal of this investigation was to gain an understanding of how different pintle parameters would change the liquid jet interaction with the crossflow. The height and angle of the pintle were varied as well as the percent coverage of the pintle into the liquid jet. The pintles that had the greatest control over the penetration and breakup of the jet over the widest range of Weber numbers and momentum flux ratios. were those at 100 percent jet orifice coverage. The surface forces that were present because the pintle was close to the injection orifice caused the liquid jet profile to be considerably lower than all other test cases. At lower heights, the surface effects become more dominant and are noticeable in the 75 percent coverage cases. Steeper heights at low coverages lead to the liquid jet deflecting from the pintle before it can make significant contact. Another relationship was found, albeit over a more limited range of test cases, was the angle that the pintle made with the injection surface. At low crossflow velocities, the penetration depth is directly correlated to the angle of the pintle.

RECOMMENDATIONS

To develop pintles that will become independent of the crossflow conditions, the surface forces will need to be utilized. At high coverages, the surface effects create a jet profile that behaves differently than that of the baseline case with no pintle. This suggests that there is some control granted by higher coverages. The most flow independent pintles will have low heights and provide a large percent coverage of the jet orifice. This way, there will be more of the surface located close to the jet orifice which will allow the liquid jet to interact with it before the aerodynamic drag forces start to dominate the interaction. Additionally, for applications in jets, pintles must be tested both over a wider range of Weber numbers and momentum flux rations but also with more relevant liquid jets. Jet fuels with different liquid properties will change how the surface forces affect penetration depth and breakup modes. This investigation will also have to explore this interaction relevant flight conditions such as ambient pressure at elevated heights. Finally, reacting fuel jet-in-crossflow must also be explored to gain insight into what effect the pintles have on the downstream combustion.

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