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High-Speed Visualization of Two-Phase Flow inside a Transparent Fuel Injector

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Diminishing fossil fuel resources, ever-increasing energy cost, and the mounting concerns for environmental emissions have precipitated worldwide research on alternative fuels. In this study, a transparent fuel injector is utilized to investigate internal two-phase flow resulting from interactions between liquid and atomizing gas flows. The fuel injector replicates the flow-blurring concept, recently shown to yield much greater fuel surface area to volume ratio in continuous-flow systems as compared to conventional air-blast injectors. High-speed images of gas-liquid interactions inside the liquid supply tip and in the injector orifice are captured. The image sequence is analyzed to develop a fundamental understanding of the two-phase flow behavior in the flow-blurring concept and thus, to establish a framework for the development of predictive models.

1. Introduction

Recent increases in fuel costs, concerns for global warming, and limited supplies of fossil fuels have prompted widespread research on renewable liquid biofuels. Previous studies conducted in atmospheric pressure combustors have shown that NO_x (nitric oxides) and CO (carbon monoxide) emissions are determined mainly by fuel atomization and fuel/air mixing processes. The typical Air-Blast (AB) injector concept is widely used in current combustion systems. Shown in Figure 1, the AB injector effectively functions by introducing swirled high velocity atomizing air (AA), which generates shear layer instabilities as it interacts with the liquid jet, and disperses the fuel flow into droplets further downstream of the nozzle exit [2]. The AB atomizer effectively produces fine spray for low viscosity fuels. However, with a shift towards alternative fuels, there is a greater demand for biomass-based, higher viscosity fuels. Experimental studies show combustion of high viscosity fuels, such as vegetable oil (VO), in the AB injector leads to poor atomization and high NO_x and CO emissions [3]. High kinematic viscosity of the fuel restrains the instabilities of shear layer, thus limiting the atomization capability of the AB nozzle to produce fine spray for highly viscous liquids. Another type of fuel atomization concept, although less common, is effervescent atomization (EA). The working concept behind EA is that air is bubbled into the fuel line creating a bubbly two-fluid flow. Upon exiting the injector, the bubbles expand and “shatter” the fuel [10]. While EA results in small droplets, the concept itself requires high pressure drop and can lead to flow instabilities, thus rendering it less effective [9].

Recently, Gañán-Calvo (2005) put forward a concept of so-called flow-blurring (FB) injection providing “five to fifty times” more fuel surface area than a plain-jet AB atomizer [4]. The working principle of a FB injector is illustrated in Figure 2 [1]. An aerodynamic two-phase flow is created at the end of the inside liquid supply tube because of the surrounding air back flow penetrating into the liquid tube tip and bubbling into the liquid stream. The formation of the two-phase flow is mainly controlled by the two key requirements reported as: (1) The diameter of the injector orifice equal to the inside diameter (ID) of the fuel tubing, and (2) the gap, H, between the tube exit and the injector orifice, less than or equal to 0.25 ID. Through the injector orifice, this two-phase flow is exposed to a rapid pressure decrease, leading to bubble expansion and break up, yielding a spray with fine droplets. However, the detailed understanding of the FB mechanism and effects of operating parameter on air penetration, bubble formation and expansion, etc, is currently not available. Previous detailed Phase Doppler Particle Analyzer (PDPA) experiments show that the FB concept produces finer spray than the AB concept for the equivalent conditions. Compared to the AB injector, the FB injector requires lower energy input or lower pressure drop in the atomizing air line [5, 6]. For a given equivalence ratio, heat release rate, and atomizing air-to-liquid mass ratio (ALR), FB atomization in a swirl-stabilized combustor resulted in three to five times lower CO and NO_x emissions in diesel and kerosene flames, compared to those with AB atomization [7]. Straight vegetable oil (VO) and even glycerol, with more than two hundred times the kinematic viscosity of diesel, can be directly combusted in a FB injector mounted combustor with extremely low emissions at the exit [8, 9]. In addition, previous detailed measurement of the temperatures and emissions of diesel, biodiesel, VO, and glycerol flames inside the combustor indicated that mainly lean premixed combustion with extremely low emissions were achieved by implementing the FB injection, signifying that the FB injector is highly fuel-flexible [1, 9].

In this study, a transparent fuel injector is utilized to investigate internal two-phase flow resulting from interactions between liquid and atomizing gas flows. High-speed images of gas-liquid interactions inside the injector are captured analyzed to develop an understanding of the two-phase flow behavior in the FB concept which could help development of predictive models.

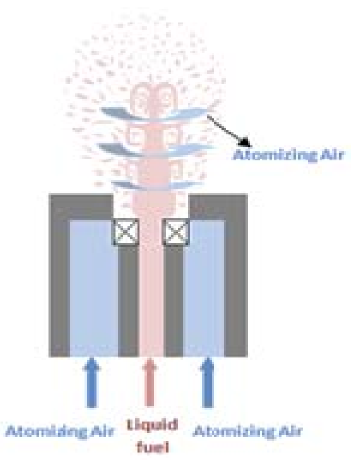

Figure 1. Principle of Air-Blast injector

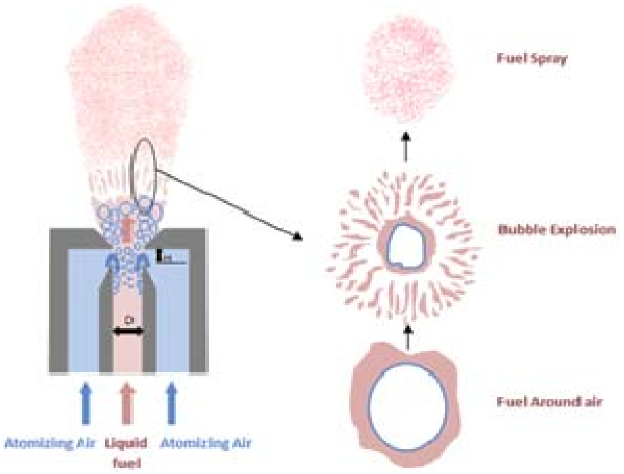

Figure 2. Principle of Flow-Blurring injector

2. Methods

Figure 3 shows an in-house built transparent FB injector head for visualizing the atomizing air penetration and bubble generation at the tip of the liquid supply tube. The schematic of this internal flow visualization experimental setup and the actual setup are illustrated in Figures 4 and

5, respectively. The inside diameter (ID) of the injector is 4 mm and H, the distance between the fuel tip exit and the injector orifice, is adjusted to 1 mm to generate the FB effect. Water is used as the working fluid and is pumped into the side of the injector holder by a Cole Parmer high performance peristaltic metering pump (Model 7523-40) with an accuracy of ± 0.25% of the reading. Water from above then flows down into the FB nozzle connected to the holder, shown in Fig. 4. Atomizing air (AA) is supplied from the upstream of the injector holder at a preset flow rate controlled by a needle valve and measured by an Aalborg mass flow meter (Model CFM47) with an accuracy of ± 1.5% of the reading. A high speed camera (MotionPro HS-4) attached with microscopic lens is utilized to focus on the field of view (FOV) with the dimension of 1 cm x 1 cm, yielding a spatial resolution of 20 μm per pixel. The FOV is illuminated by warm white LED light . In the present study, the effect of air-to-liquid mass flow ratio (ALR) on the FB effect, i.e. the interaction between the air back flow and the water flow, is investigated. ALR is controlled by keeping a constant water flow rate of 33 mL/min while varying the flow rate of the atomizing air. Specifically, the air flow rate increases from 17 standard liters per minute (slpm) to 56 slpm with the corresponding ALR ranging from 0.62 to 2.04, that is, from the start of bubble formation at the inside fuel tip to the state with an intense bubble generation zone to produce a fine spray. Digital images in the experiment were captured at 1000 frames per second (fps) with temporal resolution (exposure) held constant at 31 μs. Experimental trials were initiated at 33 mL/min of water flow rate and 0 slpm of air flow rate. The air flow rate was increased until it was noticeable that air bubbles were penetrating the tip of the liquid supply tube in the injector, as expected by the FB concept. Then, the air flow rate was increased from 20 slpm to 50 slpm in increments of 5 slpm. A final experiment at 56 slpm with an ALR of 2.04 was conducted to investigate the bubble dynamics. Approximately 2000 images were saved per trial, yielding an experimental duration of two seconds per trial.

Figure 3. The FB injector with a Transparent Injector Head.

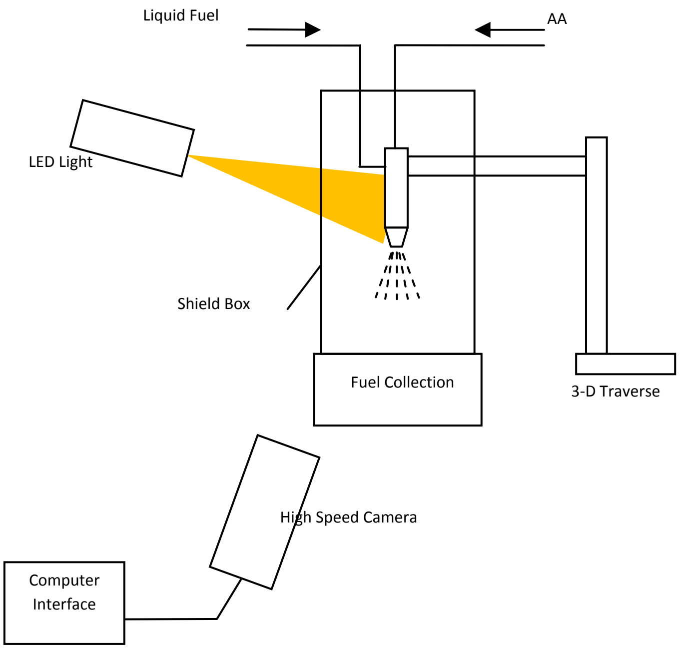

Figure 4. Schematic of FB Injector Set-up.

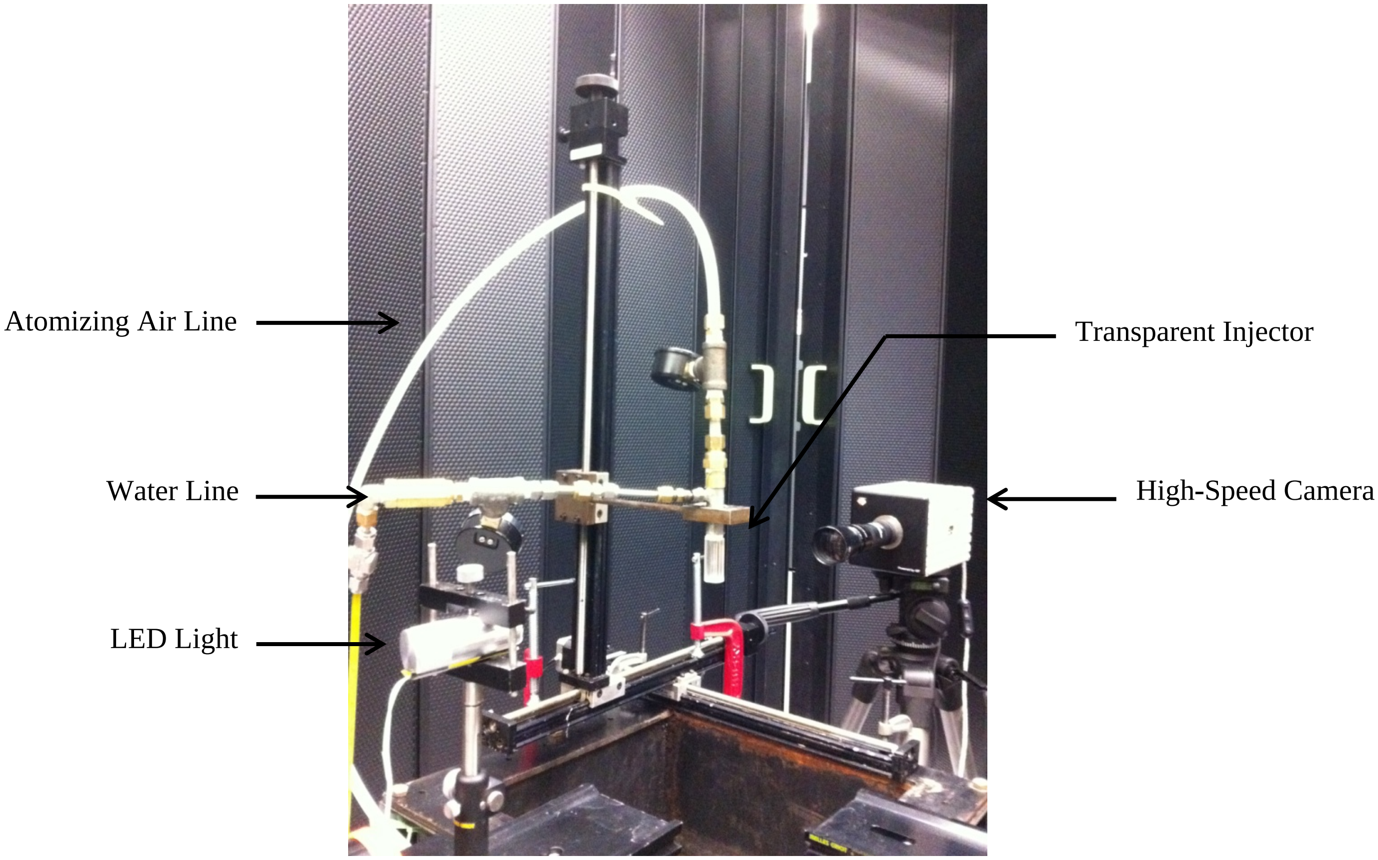

Figure 5. Photograph of Experimental Setup.

3. Results and Discussions

Experimental trials show that a host of changes take place with the increase in atomizing air flow rate through the injector. The first phenomenon that is visible is air bubble penetration into the central liquid supply line of the injector. As expected, there is no penetration of air into the liquid line tip when the ALR is zero. Additionally, this penetration remains nonexistent until the air flow reaches a minimum 17 slpm (0.62 ALR). At 17 slpm, minor penetration of air into the liquid line of less than 1 mm occurs, and a noticeable spray is formed, albeit of poor quality. Figures 6 – 11 illustrate the change in penetration depth and air bubble concentration with respect to atomizing air flow rate, with air ranging from 0 slpm to 50 slpm, or ALR ranging from 0 to 1.8.

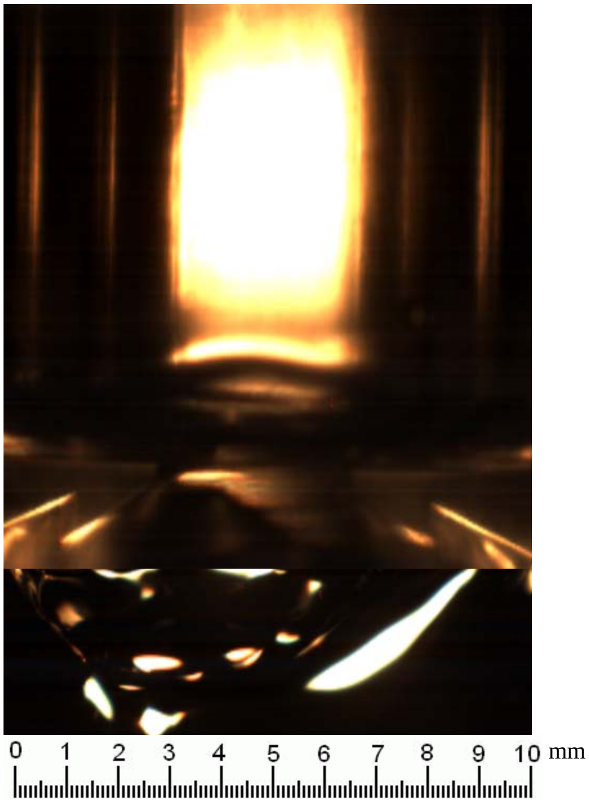

Figure 6. ALR = 0

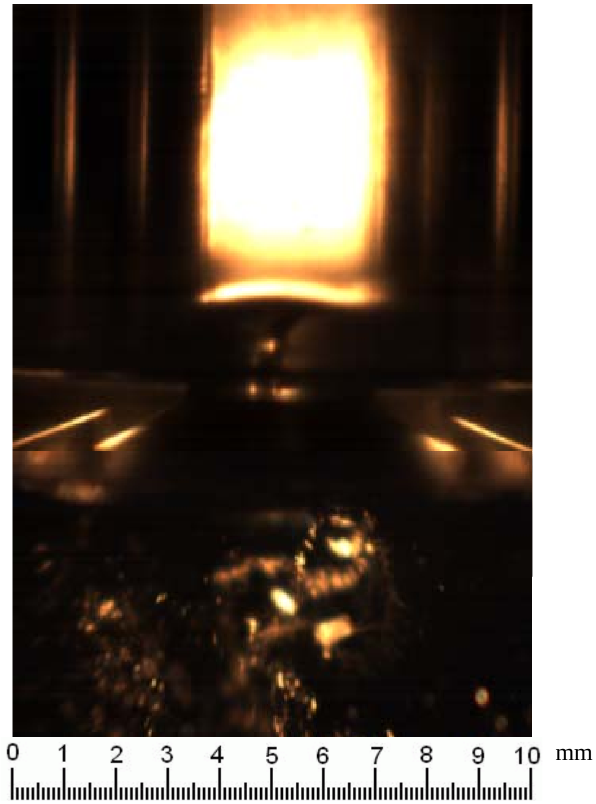

Figure 7. ALR = 0.62

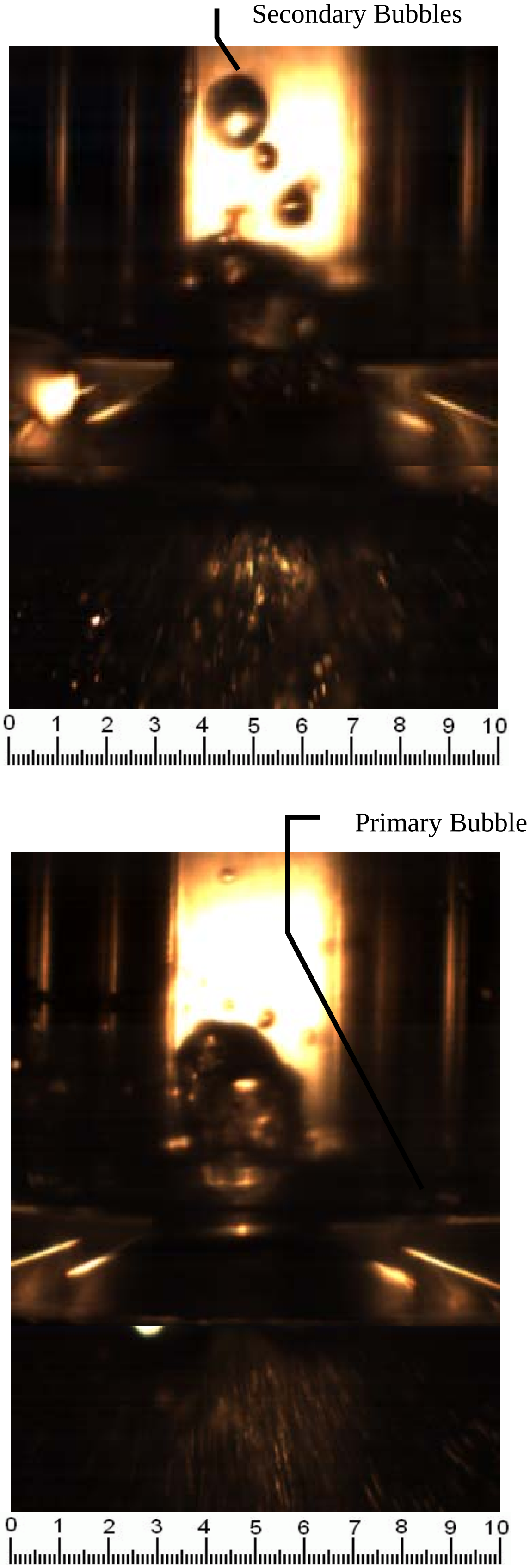

Figure 10. ALR = 1.46

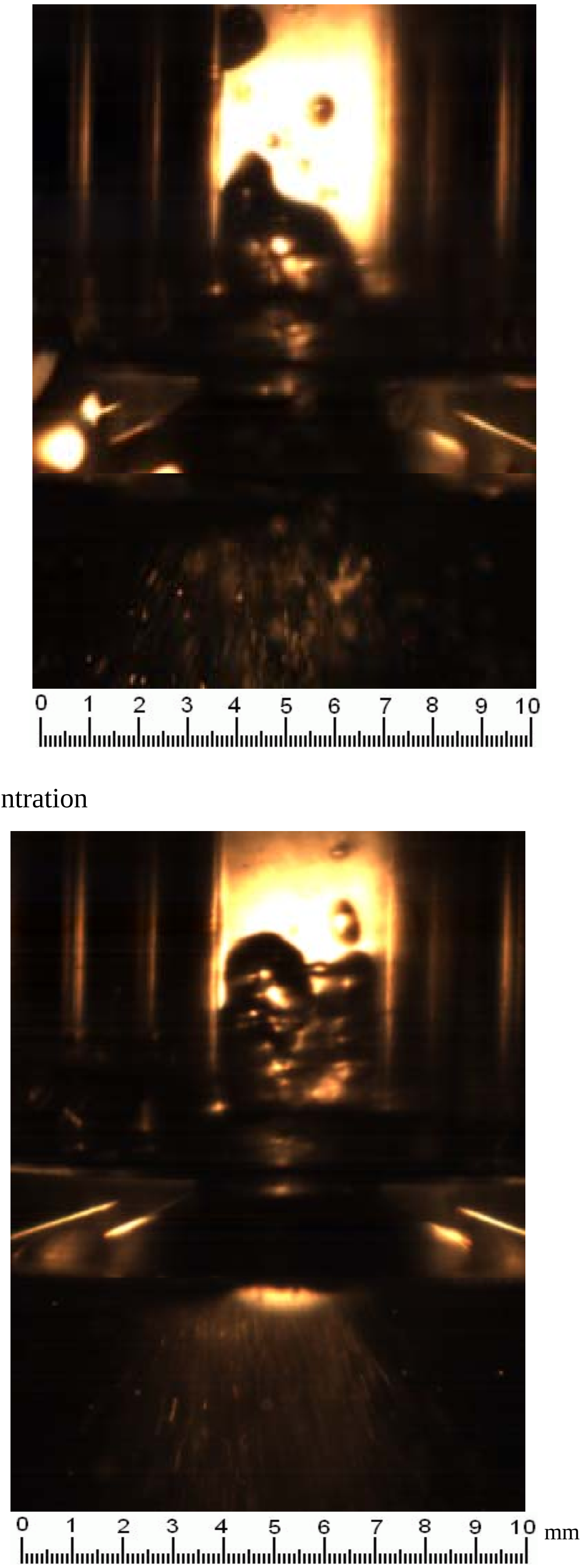

Figure 11. ALR = 1.82

It is evident that with constant water flow rate and an increase in atomizing air flow rate, the concentration of air bubbles and depth of penetration in the liquid line tip both escalate. From 0 slpm to 16 slpm air, as stated previously, there is no penetration of atomizing air into the liquid supply line. At approximately 17 slpm of atomizing air, minor penetration of less than 1 mm occurs, and from this point forward the penetration grows incrementally with increase in atomizing air flow rate. “Penetration” is considered to be the depth of the primary concentration of air bubbles in the liquid supply tube. Notice that, in Figures 8-11, very fine bubbles are released from the primary concentration of air bubbles and flow much farther upstream into the liquid supply tube than the primary bubble concentration does. The frequency with which those minute air bubbles are released also increases with increase in the atomizing air flow rate. For air flow rates between 0 and 50 slpm, the penetration of air bubbles peaked at approximately 4.5 mm within the liquid supply line. Figure 12 shows a plot of the penetration depth with respect to ALRs.

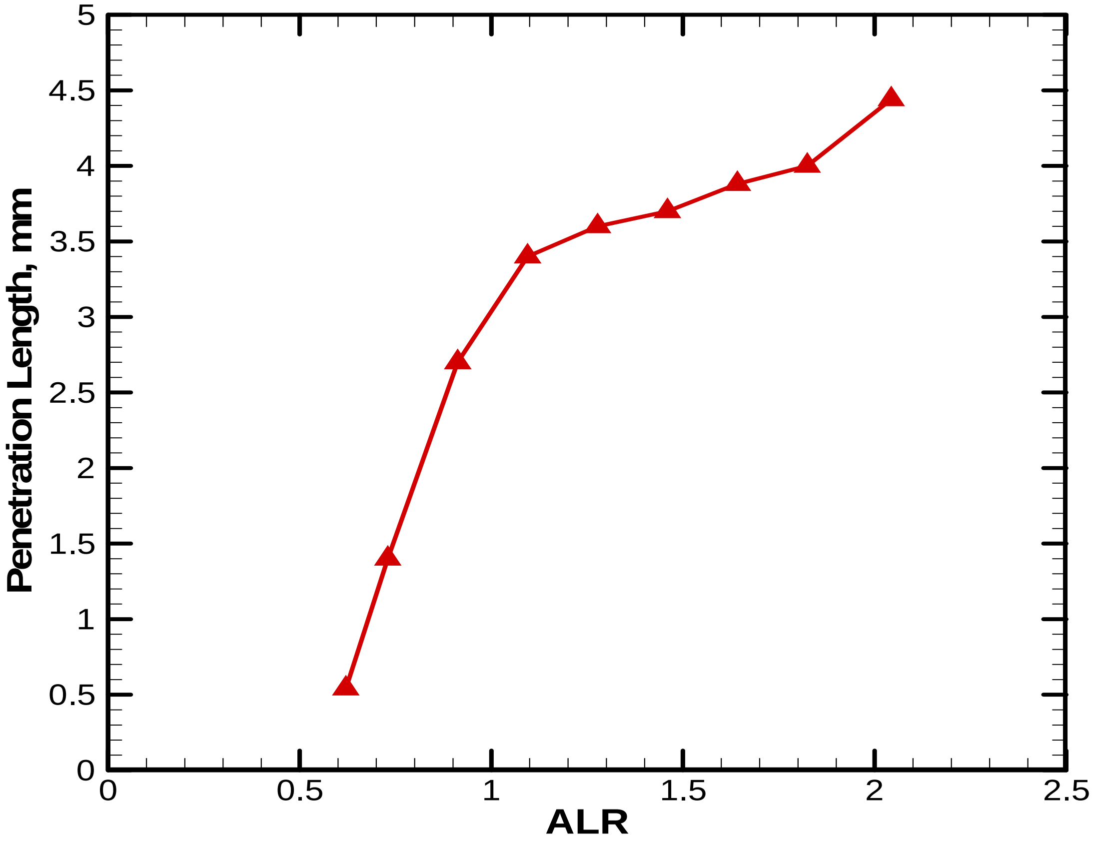

Figure 12. Penetration Length vs. ALR

Measurements taken with a spatial resolution of 20 µm show that the maximum penetration into liquid supply tube varies from 0.5 mm to 4.5 mm as ALR is varied from 0.6 to about 2.0. Interestingly, the penetration depth increased rapidly between ALR of 0.6 and 1.1; however, after reaching ALR = 1.1, or 30 slpm air flow, the rate of change decreased, reaching a maximum penetration of 4.4 mm for ALR = 2.04, which also resulted in the finest spray, as seen in Figure 11.

In addition to increasing liquid supply line penetration, bubble dynamics are also transformed during the transition from low air flow rate to high air flow rate. For low air flow rates (20-25 slpm), a poor quality spray is obtained, as illustrated in Figure 13. The air penetration ranges from 1 to 2 mm. The air, in the outer channel around the center fuel tube, meets the water in the 1 mm gap and penetrates into the fuel tip to create the two phase flow consisting of bubbles at the liquid supply line exit. The bubbles then explode due to the pressure drop at the injector orifice and break-up the surrounding water into droplets. Because the air flow rate is low, consequently, the air pressure is low inside the orifice. The lower the air pressure is, the lower will be the expansion of air bubbles, and thus the less effective is the atomization of liquid. The two-phase flow at low flow rates is concentrated inside the orifice as illustrated in the Figure 13.

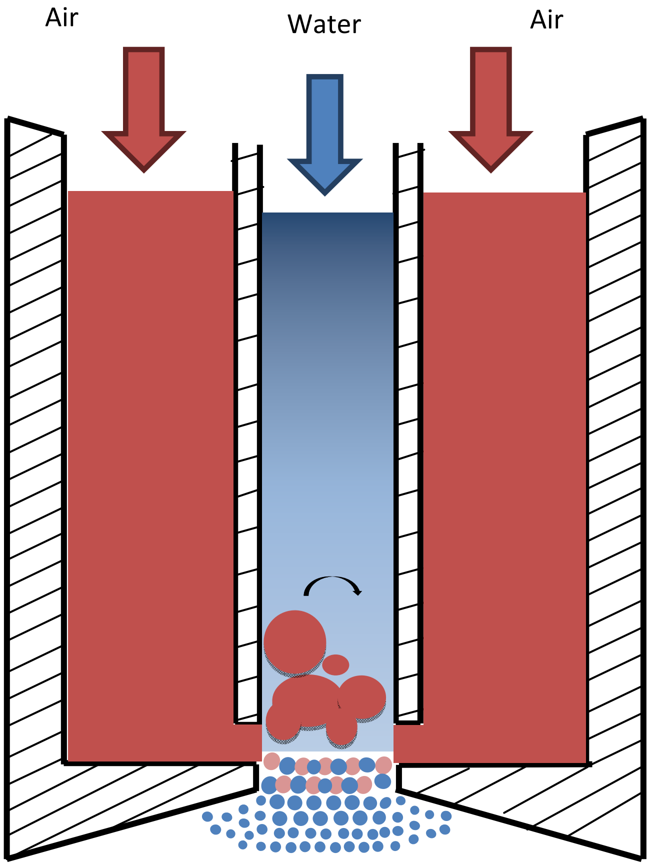

Figure 13. Distribution of bubbles inside injector, low atomizing air flow rate.

Notice that the majority of bubbles remain within the 4-mm diameter of the orifice and no bubbles back flow into the atomizing air channel. Additionally, bubble sizes leaving the orifice are relatively large. These two phenomena of bubble distribution and average bubble size differ greatly in comparison to higher flow rates (50-56 slpm), as depicted in Figure 14.

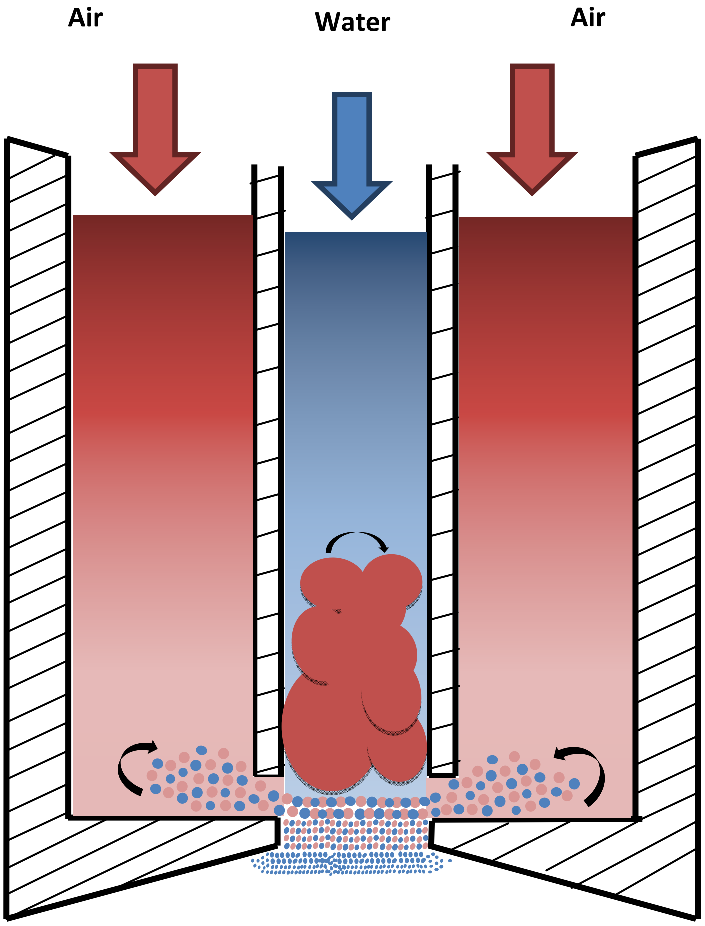

Figure 14. Distribution of bubbles inside injector, high atomizing air flow rate

For higher atomizing air flow rates, the concentration of bubbles inside the liquid supply line dramatically increases, in addition to penetration depth. Figure 14 shows that for high air flow rates, the two-phase flow is not only contained in the orifice region, but also seeped into the surrounding air channel before recirculating and exiting through the orifice. The result is a more desirable, finer quality spray.

The final imaging experiments were performed with an air flow rate of 56 slpm, yielding an ALR of 2.04. The image sequence in Figure 15 depicts the dynamics of the bubbles over a time interval of 12 ms (1 ms per image acquired at frame rate of 1000 fps). The images illustrate the dynamics of two-phase flow. It can be seen that small bubbles are released from the primary concentration of air bubbles and flow farther upstream into the liquid supply line prior to being forced to rejoin the primary bubble concentration. This process is recurring and results in repeatable dynamic flow behavior inside the liquid supply line.

Figure 15. Bubble Dynamics illustrated by images taken 1 ms apart, ALR = 2.04

4. Conclusion

In this study, the internal two-phase flow of a flow blurring injector is visualized using a transparent model. The inner injector and spray images were produced for multiple experimental conditions, with low to high atomizing air flow rates and constant water flow rate. The images produced show that air bubbles reach penetration lengths of up to 4.5 mm inside the liquid supply line. Atomizing air penetration depth and the fineness of the resulting spray increase with increasing ALR. This result is indicative of a relationship among the ALR, air penetration depth and spray quality. The spatial resolution and temporal resolution of the images were satisfactory for the imaging purposes. In future developments, higher quality images at higher flow rates will be produced with greater frame rates. Upon those developments, we expect to determine optimum conditions for operation with the flow-blurring concept. The data collected in this study will provide useful insight and validation information for the development of phenomenological and numerical models of the flow-blurring injector.

Acknowledgements

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