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Research paper

Roles of Atomizing Gas in Swirl Effervescent Atomization

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Abstract

Issues of propellant atomizing, mixing and viscous loss become increasingly more important as the thrust chamber are reduced in size. The present investigation examines the behavior of resulting sprays emanating from swirl effervescent atomizers at various gas-to-liquid ratios (GLRs) and aeration tube configurations. A series of cold flow test has been conducted, where water and nitrogen were used as simulation fluids. Results show that the injection of atomizing gas tends to reduce the spray angle and the discharge coefficient. Results also indicate narrower spray angle and lower discharge coefficient at higher GLRs. A smaller total aeration hole size also leads to a narrower spray angle and a higher pressure drop for the gas injection. Interestingly, a smaller total aeration hole size produces higher discharge coefficient. In general, the atomizing gas has shown to significantly alter the resulting sprays of a swirl effervescent atomizer even at a relatively low GLR.

Keywords: *Swirl; Effervescent; Atomizer; Discharge Coefficient; Spray Angle.*

1. Introduction

Liquid atomization is a transformation of bulk liquid into droplets or spray through a device known as atomizer [1]. Studies on spray atomization have been a topic of interest to the propulsion community, particularly from the standpoint of propellant atomizer design for liquid rocket engine [2]. A principal function of an atomizer is to introduce and meter liquid propellant to a combustion chamber.

Atomizer design is crucial since small differences in its configuration or geometrical dimensions can result in dramatically different performance. A smaller combustion chamber is possible for smaller droplets of propellant, where a flame front close to the injector head is established. However, a good distribution of droplet size is also important to produce efficient and quiet combustion [3].

There are various types of atomizers available, and the selection depends on their suitability for particular applications. A commonly used atomizer in gas turbine and liquid-propellant rocket engine is a pressure swirl atomizer [4], where a circular outlet orifice is preceded by swirl chamber into which liquids flows through several tangential holes or slots. The swirling liquid creates a core of air or gas that extends from the discharge orifice to the rear of the swirl chamber. The liquid emerges from the discharge orifice as an annular sheet, which spreads radially outward to form a hollow conical spray.

The main task of a pressure swirl atomizer is to produce and diffuse droplets, which is achieved through a primary and secondary break ups. In primary break up, liquid is transformed into a combination of small ligaments and droplets, while in secondary break up, larger droplets from the primary break up further break into smaller droplets [5].

Ligaments are formed due to the Kelvin–Helmholtz instability [6], which is mainly affected by internal forces such as turbulence, inertial effects, changes in velocity and surface tension [7]. The break up wavelength determine the diameter of the ligaments. Once droplets are formed, they atomize due to the deformation or aerodynamic forces exerted on it, in addition to the aforementioned forces.

Discharge coefficient and spray angle are examples of parameters used to characterize the performance of spray atomization. Ballester *et al.* [8] have investigated the effect of injection pressure on the discharge coefficient and spray of a small pressure swirl atomizer. They found that discharge coefficient and spray angle increased with increasing injection pressure. The increase of discharge coefficient is almost linearly with the injection pressure within the investigated range. In the higher range of injection pressure, however, the discharge coefficient is almost uninfluenced by the pressure drop [9]. More recently, Liu *et al*. [10] compared the discharge coefficient of liquid nitrogen and water in solid-cone pressure swirl atomizer. They observed that discharge coefficient increased with an increase of injection pressure for liquid nitrogen, while contrarily a slight decreasing trend was observed for water. Chen *et al.* [11] have considered the effect of ambient pressure on the resulting spray characteristics. They reported that higher ambient pressure leads to a narrower spray angle and higher discharge coefficient, and that the effect is more prominent at low injection pressures.

Zaremba et al. [12] found that liquid breakup mechanism of an improved design of effervescent atomizer can be divided into two separated processes: i) breakup in the spray core and ii) breakup at the edges which give different droplet diameter respectively. Lin et al. [13] found that in aerated liquid jet/effervescent atomization, rapid expansion of the two-phase spray creates a huge decrease in density, leading to a decrease in the average momentum flux in the spray region. Włodarczak et al. [14] summarized that a decrease of atomizer discharge orifice diameter, decrease of discharge orifice diameter to length ratio and outlet profiling cause the spray angle to increase and Sauter mean diameter to decrease for swirl effervescent atomizer.

Despite all the efforts to gain a better understanding of spray behaviour, in-depth analysis of the effect of atomizing gas on the overall spray characteristics and the break up mechanisms of effervescent swirl atomizer is not well understood. The present investigation aims to assess the roles of atomizing gas in swirl effervescent atomization at various GLRs and at two different total aeration hole sizes. Atomizers are tested by means of cold flow test. This is an alternative method for static firing test in investigating atomizer performance. This approach provides clear visualization on atomization and break up process, which could not be obtained from a firing test.

2. Methodology

The methodology used in the present investigation is presented in this section. In section 2.1, the experimental setup and the atomizer geometry is presented. The method for spray angle measurement is presented in section 2.2.

2.1. Experimental Setup

A series of cold flow test were conducted, where water is used as working fluid and nitrogen as atomizing gas. Both fluids were at room temperature. A pulseless pump (marked (1) in Fig. 1) was used to deliver water from a water supply tank through a high-pressure hose to the injector. Water strainer was installed at the outlet of the water supply tank and at the inlet of water flow meter to avoid unwanted debris passes through the meter and into the atomizer. The rate of water flow was controlled by a ball valve installed between the pump and a pressure gauge. Nitrogen gas was supplied directly from a high-pressure nitrogen tank (marked (2) in Fig. 1), where a pressure regulator controls its flowrate. The pressure and flow rate of both fluids were measured by digital pressure gauges (marked (3) and (4) in Fig. 1) and digital flow meters. The injector (marked (5) in Fig. 1) was set in a vertical downward position, and the water was sprayed into a collection tank (marked (6) in Fig. 1).

A high-speed complementary metal-oxide semiconductor (CMOS) sensors camera (marked (7) in Fig. 1) with maximum resolutions of 800x600 pixels was utilized to capture sequence of images at a rate of 1000 frame per second (fps) and 5μs shutter speed. The attached lens with 50mm focal length was adjusted to a maximum aperture f1.8. The resultant sprays were recorded using shadowgraph technique (i.e. floodlight pointed towards the camera aperture).

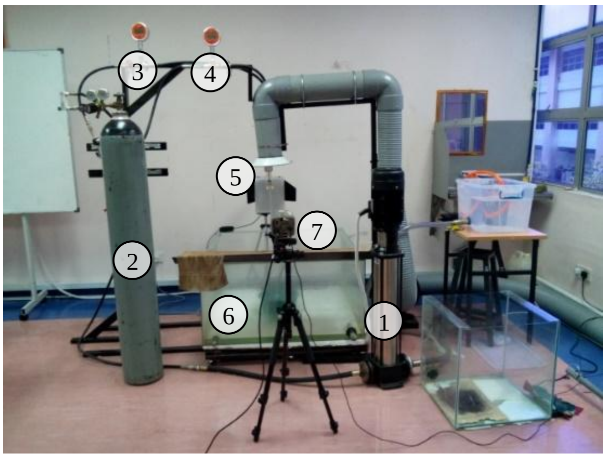

Fig. 1: Experiment test rig for atomizer cold flow test

The atomizer, which was developed as reported in [15], consists of three major parts, which are inlet ports, swirl chamber and discharge orifice (as shown in Fig. 2). An aeration tube is inserted in the mixing chamber, where nitrogen gas is injected at various pressures. The dimensions of the atomizer are summarized in Table 1.

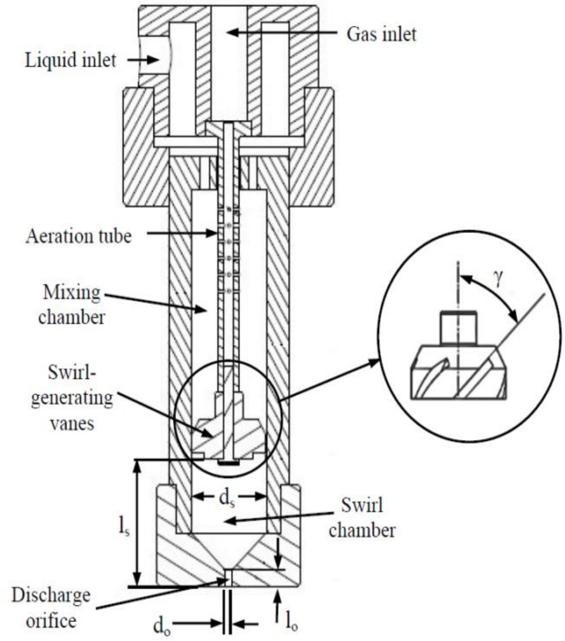

Fig. 2: Schematic of swirl effervescent atomizer

Table 1: Atomizer geometrical dimensions (in mm)

Parameter	Designed	Actual
d_o	2	1.850
d_s	2.5	2.520
l_o	0.8	0.770
l_s	4.2	4.085
Vane angle (^{o})	60	62.50

There are two configurations of the aeration tube; Tube A consists of 12 holes with diameter of 1mm and Tube B consists of 24 holes with 1 mm diameter. This yields a total hole area of Tube B is twice of the Tube A. The specifications of these tubes are summarized in Table 2.

Table 2: Specifications of aeration tubes

Atomizer	Aeration tube	Number of holes	Aeration hole diameter (mm)	Total area of aeration holes (mm^2)
I	A	12	1	9.425
II	B	24	1	18.850

2.2. Measurement of Spray Angle

Videos recorded in high speed camera were converted into sequence of images. The images were then analyzed using an image processing software.

The image was processed to detect edges by using Canny Edge Detection algorithm. In this process, gradient magnitudes and directions are calculated at every single point in the image. Edges are then defined at a point with a high gradient magnitude. In defining the edges, two threshold values were set to remove small pixels noises on the assumption that edges are long lines. The measurement of the spray angle is determined by two straight lines drawn on the edge of the spray, which is defined from the exit orifice to the point where the liquid sheet breaks, as shown in Fig. 3. A total of 90 images were post-processed for each spray angle measurement and the averages were reported for each case. The standard deviations were also reported in the form of error bars in the plots.

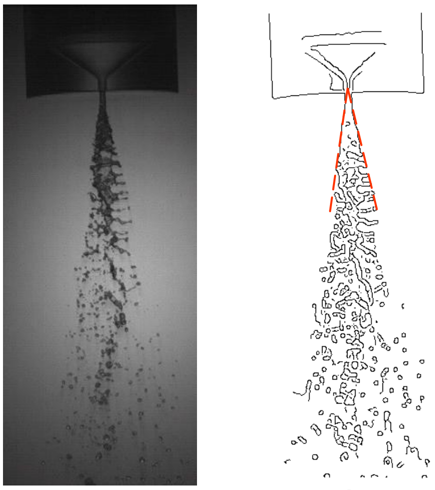

Fig. 3: Typical swirl spray for measurement of spray angle. (a) original image and (b) spray edges using Canny Edge Detection algorithm.

3. Results and Discussion

In this section, the effects of total area of aeration hole on the spray angle and discharge coefficient are presented.

3.1. Spray Angle

The variation of spray angle with GLR and total aeration hole area is presented in Fig. 4. The total area of aeration holes for Tube A ($9.425mm^2$) is half of Tube B ($18.850mm^2$), given the fact that the number of aeration holes in Tube B is twice of Tube A and that the size of an aeration hole is the same for both tubes.

In general, injection of gas bubbles tends to produce narrower sprays compared to the case of no effervescent. This observation can be explained as follows: the gas bubbles disturb the angular momentum of the swirled liquid and convert most of the input energy into the axially oriented motion at the exit orifice. These explanations can be clearly seen in Fig. 5. Initially, the swirling liquid sheet is issuing from the exit orifice at t = 0s, as shown in Fig. 5(a). At t = 0.003s, the liquid sheet progresses downstream and thinning. At the same instance, a high-pressure bubble squeezing through the exit orifice. Conservation of mass requires that the axial component of liquid velocity in the orifice be increased, which in turn reducing the tangential component of liquid velocity, and thus the spray angle.

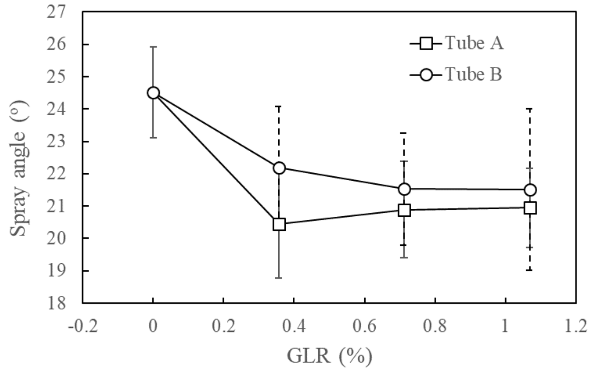

Fig. 4: Average spray angle plotted against GLR for aeration tubes as indicated. Error bars represent standard deviations of the mean spray angle.

After 0.002s, the liquid sheet breaks into a ligament as it swirls and stretches (this is a primary break up, as shown in Fig. 5(c)). The ligament will further break up into droplets due to varicose instability. Concurrently, the bubble expands rapidly once exits the orifice, causing liquid sheet to break (marked in circle). It is important to note that the mechanism of this break up is different to that of the primary break up. In the latter, the droplets are formed due to the aerodynamic destabilization of the thinning liquid annular sheet emanating from the exit orifice and further destabilization of the liquid sheet. On the other hand, in the former, the formation of droplets is caused by the rapid expansion of high-pressure gas bubbles.

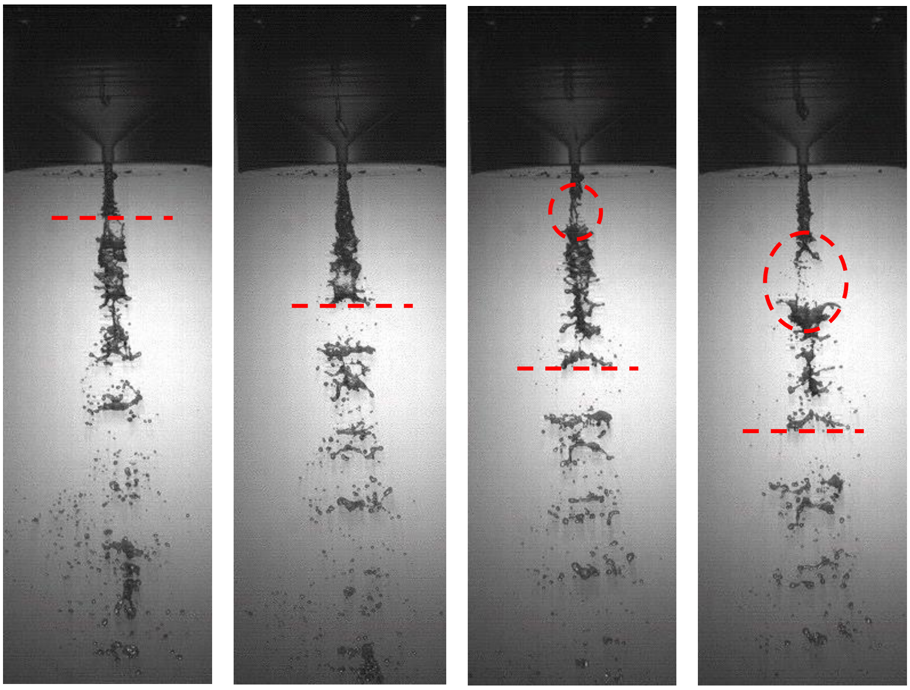

Fig. 5: Development of typical swirl effervescent atomization. Photos were taken for atomizer I at GLR = 0.36%. Dashed lines represent the front-end of the liquid sheet, indicating progression of flow with time.

In Fig. 5(d), the liquid sheet is completely disintegrated (marked in circle), causing a discontinuity in the spray propagation at a distance closer to the exit orifice than the primary break up. It is important to note that the spray angle is measured based on the edge of the liquid annular sheet. Although the introduction of gas bubbles into the mixing chamber leads to a narrower spray angle, the violent action of bursting bubble results in broader dispersion of liquid droplets as compared to the non-effervescent case (as can be seen in Fig. 5(d).

It is also interesting to observe that more numbers of aeration hole (while the diameters are constant) leads to a wider spray angle. This is attributed to the fact that for the same GLR, the injection pressure of atomizing gas for atomizer I (with less number of aeration hole than atomizer II) is higher than for atomizer II (as shown if Fig. 6). Consequently, gas is introduced at higher velocities, reducing the angular momentum of the swirling liquid and thus narrowing the spray angle. It is noted that the pressure drop for the liquid gas injection is larger than for gas injection. This is likely due to the large pressure drop in the swirler section of the atomizer as the flow accelerates passing through the vanes.

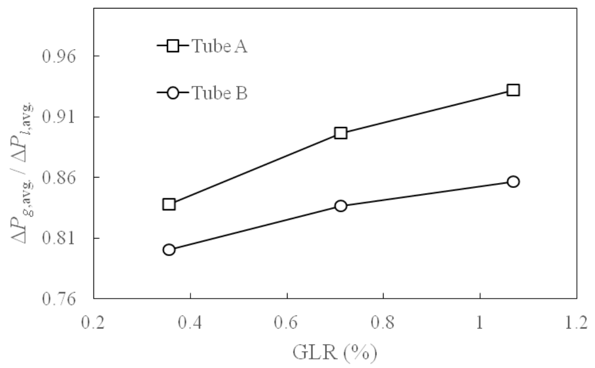

Fig. 6: Average normalized gas injection pressure plotted against GLR for tubes as indicated.

3.2. Discharge coefficient

Discharge coefficient is one of crucial parameters in the design of an atomizer. The discharge coefficient is calculated using the relation

$$C_D = \frac{\dot{m}}{A_o\sqrt{2\rho\Delta P}} \quad (1)$$

where A_o is the orifice area, $\dot{m}$ and ρ are mass flow rate and density of water, respectively, and ΔP is the gauge injection pressure of water. The variation of discharge coefficient with GLR and numbers of aeration hole is presented in Fig. 7.

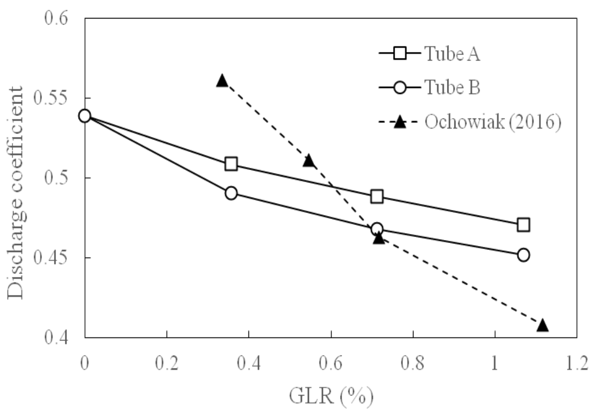

Fig. 7: Discharge coefficient plotted against GLR for aeration tubes as indicated.

It is shown that the discharge coefficient decreased with an increasing value of GLR, due to the cross-sectional area of exit orifice being occupied by the gas and liquid. Ochowiak et al. [16] reported a similar finding, where the discharge coefficient of swirl effervescent atomizer decreases with increasing GLR (their results are co-plotted in Fig. 7). The values of discharge coefficient are, however, differ from the present data. This is expected since the atomizer geometrical dimensions and the swirl mechanism are different for both cases. The ratios of orifice length to its diameter (a significant parameter that governs the discharge coefficient of an atomizer) are 0.4 and 1.01, respectively, for the present atomizer and the one reported in Ochowiak et al. [16], respectively. Furthermore, in the present investigation, the swirling motion of the liquid is generated via a swirl-generating vanes angled at 60°, while Ochowiak et al. [16] used a simplex atomizer (i.e. liquid enters the swirl chamber in tangential direction).

It is also observed that the discharge coefficient varies almost linearly with GLR. This is expected since the discharge coefficient is inversely proportional to the GLR. However, it was reported that the discharge coefficient of a swirl effervescent atomizer decreases asymptotically to a value of approximately 0.15 with GLR. Their observation can be attributed to the fact that the range of GLR is much wider than one reported here (i.e. 0.2% < GLR < 12%). At a higher GLR, (i.e. higher injection pressure), gas is compressed and thus its blockage effect at the exit orifice becomes less prominent.

It is also noted that Tube A produces higher discharge coefficient than Tube B for all GLRs. This is likely due to the fact that Tube B, with more numbers of aeration hole, produces a higher resistance towards liquid flow in the mixing chamber. As a result, a higher liquid injection pressure is required for the same GLR, which leads to a lower value of discharge coefficient.

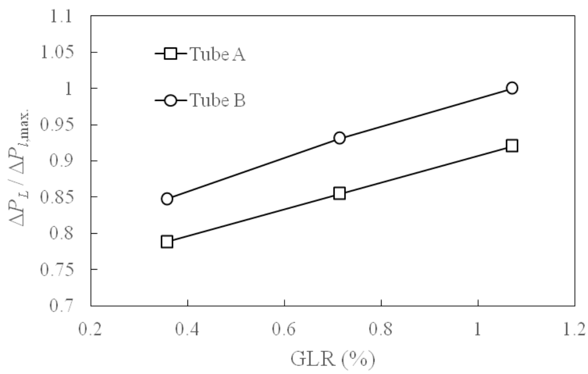

Fig. 8: Normalized liquid pressure drop plotted against GLR for aeration tubes as indicated.

The pressure drop of liquid is approximately 7.5% to 9% for Tube B than Tube A. A high pressure drop indicates high requirement of feed energy and low atomization efficiency. Energy considerations in atomization process are not the topic of interest in this paper. However, this would be an interesting avenue for future study and one can refer to Jedelsky et a. [17] for further details.

4. Conclusion

The present study has investigated the spray angle and discharge coefficient of swirl effervescent atomizers. Two different types of aeration tubes were fitted in the mixing chamber to investigate the effect of total aeration hole size on the resulting spray characteristics. Two mechanisms of droplets formation were observed, namely, due to the aerodynamic destabilization of the thinning liquid annular sheet and due to bursting of high-pressure gas bubbles. In general, the injection of atomizing gas into the liquid stream upstream of the discharge orifice leads to a narrower spray angle and lower discharge coefficient. Similar effects were observed for increasing GLR. Furthermore, a larger total aeration hole size leads to a wider spray angle and lower discharge coefficient. It is anticipated that injection of gas bubbles into swirl atomizer can lead to a rapid atomization of propellant prior to the mixing and combustion, and thus a shorter combustor is possible.

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