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Influence of Convergence Angle on Hollow Cone Spray Characteristics

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Abstract **-** Simplex atomizer (Pressure swirl atomizer) is widely used in liquid rocket engines and gas turbines because of its enhanced atomization characteristics. In a simplex atomizer, swirling motion is imparted to the liquid by the tangential entry of the fuel. In turn, a hollow cone fuel spray is produced from the orifice under the action of centrifugal force. Liquid properties, injection flow conditions and atomizer geometry govern the performance of an atomizer. Thus, it is very important to study the effects of these parameters, for optimizing the spray characteristics in terms of the drop sizes and spray cone angle. The swirl chamber convergence angle (θ_C) is one of the most important parameters which affects the injector performance. Very few researchers have focused on this aspect. In this paper, an experimental parametric analysis is performed to investigate the effect of swirl chamber convergence angle on the performance of simplex atomizer and the characteristics of the hollow conical liquid jet exiting the nozzle. Four different simplex atomizers with varying convergence angle (30°, 45°, 60° and 75°) are used for the experimental study. All other geometrical parameters are kept the same. The atomization behaviour which includes spray cone angle, co-efficient of discharge, Sauter mean diameter (SMD) and drop size distribution is analyzed at various radial locations by using a high-speed camera and Phase Doppler Interferometer (PDI). Experiments are carried out at different pressures ranging from 0 to 7 bar to characterize the atomizer performance at different operating conditions.

Keywords**:** Simplex atomizer, Convergence angle, Spray, Sauter mean diameter, Drop size distribution, PDI.

1. Introduction

The process of atomization includes the formation of fine droplets from bulk liquid. A simplex atomizer, shown in Figure 1 (a), is widely used in gas turbines and liquid rocket engines since it offers enhanced atomization quality. In a simplex atomizer, swirling motion is imparted to the fuel through tangential ports leading it under the action of centrifugal force to spread out in the form of a hollow cone as soon as it leaves the exit orifice. The hollow cone then becomes unstable and breaks to form ligaments, which further break to form droplets as shown in Figure 1 (b). A central air core is formed which decides the partial area of the orifice available for liquid discharge, which in turn, affects the co-efficient of discharge and other spray characteristics.

It is evident that the liquid properties, injection flow conditions, and the atomizer geometry govern the performance of the atomizer (Lefebvre [1]). Thus, it is very important to study the effect of these parameters on the spray to optimize the performance of the atomizer i.e. mean droplet size (Sauter mean diameter), spray cone angle and drop size distribution.

Spray cone angle and mean droplet size are the two important performance parameters in a high-pressure swirl atomizer. The spray cone angle (θ) is determined by:

$$\theta = 2\tan^{-1}\left(\frac{\overline{\mathrm{W}}}{\overline{\overline{\mathrm{U}}}}\right) \tag{1}$$

where $\overline{\mathrm{W}}$ and $\overline{\mathrm{U}}$ represent the average swirl and axial velocities respectively at the orifice exit.

The Sauter mean diameter (SMD) is defined by:

$$\mathrm{SMD} = \frac{\sum \mathrm{N_i D_i^3}}{\sum \mathrm{N_i D_i^2}} \tag{2}$$

where N_i represents the number of droplets in i^{th} range and D_i represents the mean diameter of the droplets in i^{th} range.

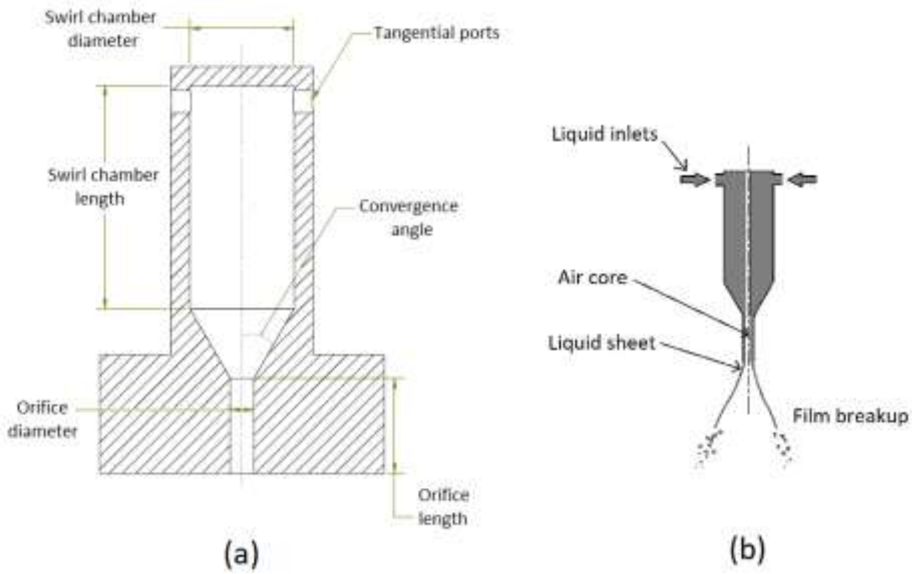

Fig. 1: (a) Schematic view of the simplex atomizer, (b) Liquid flow and breakup process for the simplex atomizer.

Xue et al. [2] numerically investigated the effect of geometry of simplex atomizer on its performance. The atomizer performance was investigated in terms of dimensionless film thickness, spray cone angle and discharge co-efficient. Arun Vijay et al. [3] summarized the research of several studies and presented a review on the performance of simplex atomizer. The paper provided physical insight into the physics of the atomization process for the simplex atomizer. Moon et al. [4] proposed an optimized design of a new gasoline direct swirl injector. The optimum sizes of the orifice length, cone angle, swirl angle, orifice diameter and needle lift were obtained by analyzing numerical results. Rashad et al. [5] performed an experimental study to inspect the effect of variation of three geometric ratios on spray cone angle and SMD in pressure swirl atomizers using 12 different atomizers. The geometric ratios include geometric parameters like swirl chamber diameter, length of swirl chamber, orifice diameter and length of the orifice. Rashid et al. [6] reported the effect of inlet slot number on the spray cone angle and co-efficient of discharge at different injection pressures varied in the range of 2 to 8 bar. Firdaus et al. [7] have performed an experimental investigation to study the effect of length and diameter of discharge orifice on the air core diameter. It was finally concluded that atomizer with a larger orifice diameter and shorter orifice length gives larger air core inside the swirl chamber. Yeh et al. [8] established a numerical model to study the flow in plain orifice atomizers with chamfered or rounded orifice inlets. It was concluded that atomizer with a rounded orifice inlet is beneficial for better atomization.

Halder et al. [9] experimentally investigated the effect of geometry of simplex atomizer on the size of the air core. It was observed that as swirl chamber convergence angle increases, the air core diameter in the swirl chamber marginally increased. Xue et al. [10] numerically investigated the performance of a simplex atomizer in terms of spray cone angle, co-efficient of discharge and sheet thickness at the orifice exit by changing the convergence angle through 45° to 90°, keeping all other geometrical parameters constant. Convergence angle is measured from the longitudinal axis of the atomizer (similar to the definition used in this paper). Spray cone angle was found to be decreasing with increase in the convergence angle, whereas co-efficient of discharge and sheet thickness were found to be increasing with an increase in the convergence angle. Rezaeimoghaddam et al. [11] considered four simplex atomizers with convergence angle ranging from 30° to 50° and performed computational analysis to compare their performance. Here, convergence angle is measured from the traverse axis of the atomizer. With the increase in convergence angle (as per defined in this paper), spray cone angle increases whereas co-efficient of discharge decreases.

Only very few researchers have so far performed studies on the effect of convergence angle. The analyses available in literature cover parameters like spray cone angle, co-efficient of discharge and sheet thickness. The other spray characteristics like Sauter mean diameter and drop size distribution, which are important characteristics of spray, have not been dealt with in detail. On the effects of convergence angle, the available studies also contradict each other to some extent.

2. Methodology

The atomization characteristics are greatly affected by a slight change in convergence angle. To understand the influence of the variation of convergence angle on the performance of spray, an experimental parametric analysis is performed. Four different simplex atomizers with varying convergence angle (30°, 45°, 60°, 75°) are used for the experimental study, keeping all other internal dimensions of an atomizer same. Other important atomizer dimensions are selected based on the studies available in the literature. Important internal dimensions of the atomizers used in the present study are tabulated in Table 1. Experiments are carried out at different pressures ranging from 1 to 7 bar to check the operability of atomizer at different operating conditions. The atomization behaviour is studied in terms of the spray cone angle, co-efficient of discharge, Sauter mean diameter (SMD) and drop size distribution.

Table 1: Geometric details of simplex atomizers used in the present study.

Geometric parameter	Atomizer			
	A1	A2	A3	A4
Orifice diameter (mm)	1	1	1	1
Swirl chamber diameter (mm)	4.4	4.4	4.4	4.4
Tangential port diameter (mm)	0.8	0.8	0.8	0.8
Number of tangential ports	3	3	3	3
Swirl chamber convergence angle	30°	45°	60°	75°

Water is used as a working fluid in all the experiments. Pressurized air is used to pressurize water, which is then injected into an open test section through a simplex atomizer. PCO Dimax HS1 (1 Megapixel, 7000 fps) camera is used to take high-speed images of the spray. Backlight and diffuser plate are also used to provide proper illumination for the experiments as shown in Figure 2. Image processing techniques using Matlab and ImageJ software are used to process raw images obtained by the camera for the sake of measuring spray cone angle.

Further, Phase Doppler Interferometry (Artium PDI) is used to measure drop size distribution at different radial locations, at a particular axial location of 70 mm downstream of the orifice exit for an injection pressure of 5 bar (Figure 3). PDI has a solid-state laser which emits radiation at a wavelength of 532 nm (green). It uses two coherent laser beams which intersect each other to form a probe volume. The light scattered because of the droplets passing through the probe volume is collected by a receiver placed across the test section. The phase difference recorded by the receiver is used by the software to calculate the diameter of droplets.

Sauter mean diameter values at different radial locations are then compiled and compared. The axial location of 70 mm is selected to ensure the tracking of droplets only and not ligaments, assuming a proper atomization of droplets has occurred. Furthermore, Root Mean Square (RMS) error for every measurement is also calculated and is defined as the root of square of variance of measured value with respect to average value observed at the same conditions.

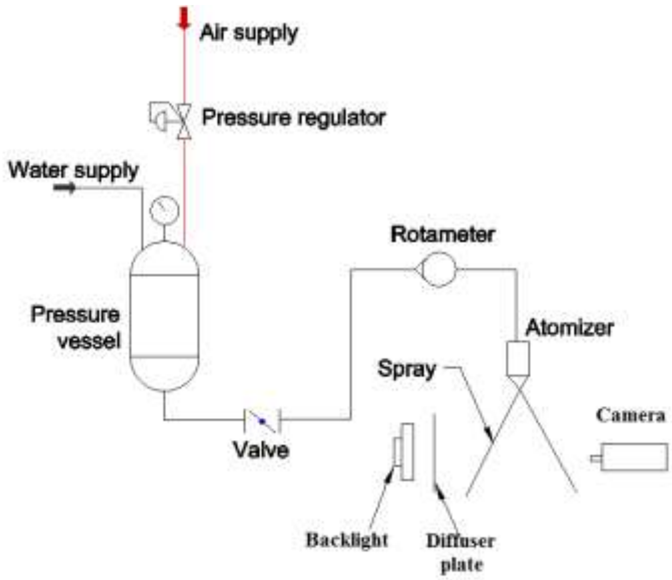

Fig. 2: Schematic of Experimental setup.

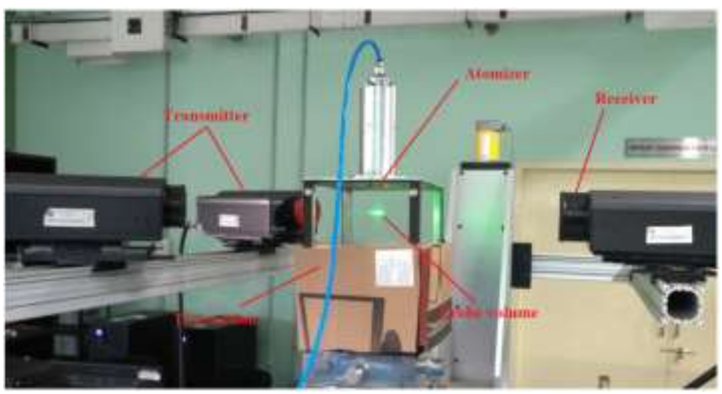

Fig. 3: Phase Doppler Interferometry.

3. Results and Discussion

3. 1. Effect on co-efficient of Discharge

Co-efficient of discharge (C_d) is the ratio of actual mass flow rate to the theoretical mass flow rate of a fluid. The actual mass flow rate is calculated using a Rotameter employed in the experimental setup whereas, the theoretical mass flow rate and C_d are calculated using Eqn. 3.

$$C_d = \frac{\dot{M}_a}{\dot{M}_t} = \frac{\dot{M}_a}{A_0\sqrt{2\rho_l \Delta P_l}} \tag{3}$$

Figure 4 shows the variation of C_d for four different atomizers (A1, A2, A3 and A4) at various injection pressures. The co-efficient of discharge is found to be decreasing with increase in pressure (maximum change = 9.27 %). For different atomizers, at the same pressure, co-efficient of discharge is found to be decreasing with increase in the convergence angle with a maximum change of 9.49 %. It can be attributed to the change in air core diameter values for different atomizers. Halder et al. [10] also presented the effect of convergence angle (θ_C) on air core diameter. Air core diameter increases with the increase in θ_C, was reported. The increment in air core diameter limits the amount of liquid emanating from the atomizer, thereby decreasing the overall C_d.

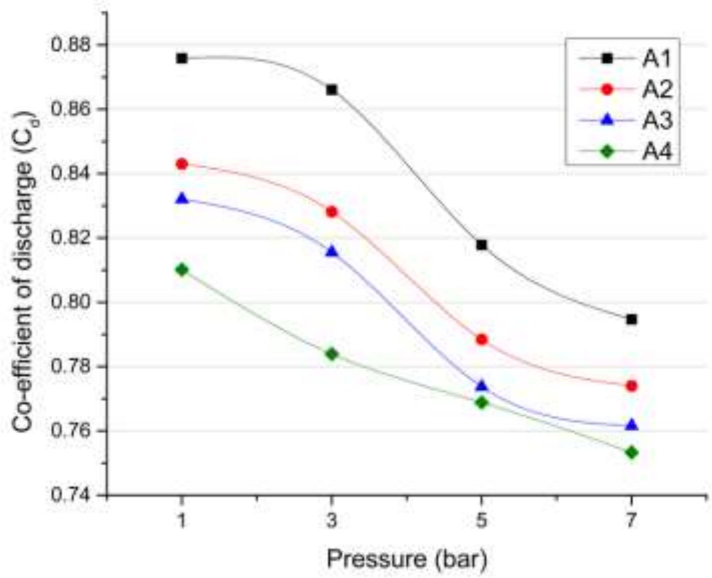

Fig. 4: Effect of swirl chamber convergence angle on co-efficient of discharge. (RMS error: 3.5 %).

3. 2. Measurement and comparison of Spray cone angle

The instantaneous images captured by the camera are processed to get the final spray image using Matlab for the calculation of spray cone angle. Operations like subtracting an image from the background image, thresholding and noise reductions are performed and the final image is obtained as shown in Figure 5.

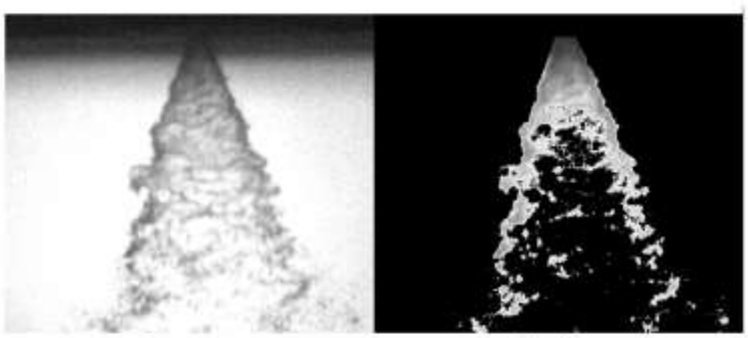

Fig. 5: Captured raw image and the final image.

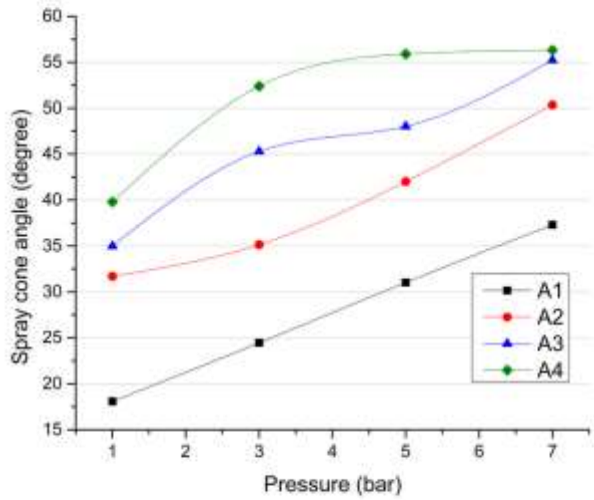

Fig. 6: Effect of swirl chamber convergence angle on spray cone angle. (RMS error: 7 %).

The variation of spray cone angle with injection pressure for four different atomizers is shown in Figure 6. The spray cone angle is found to be increasing with increase in convergence angle. For atomizer with higher convergence angle, liquid recirculates inside the simplex atomizer, due to the restriction of fluid flow in axial direction whereas the tangential component of flow remains unchanged. This changes the velocity distribution at the orifice exit, making tangential component of the velocity as the dominant one. The obstruction of fluid flow inside the simplex atomizer also increases the residence time of fluid inside the atomizer. For the same geometry, with an increase in pressure, the tangential component of velocity increases, thereby increasing the resulting spray cone angle.

3. 3. Comparison of Sauter mean diameter (SMD)

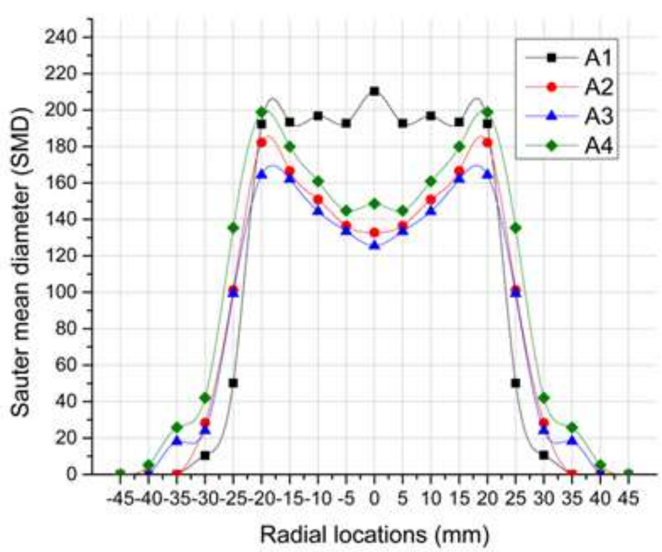

Fig. 7: Variation of SMD at different radial locations at an axial location of 70 mm. (RMS error: 6 %).

Sauter mean diameter values at different radial locations ranging from -55 mm to 55 mm at the axial location of 70mm downstream of the discharge orifice, are measured and plotted (shown in Figure 7). The liquid injection pressure is kept constant at 5 bar. The value of SMD at the centre of the spray is decreasing for atomizers A1 (convergence angle: 30°) to A3 (convergence angle: 60°) and then it increases for atomizer A4 (convergence angle: 75°). For atomizer A1 (convergence angle: 30°), the value of SMD at the centre of the spray is larger than the SMD at the periphery. On the other hand, for atomizers A2, A3 and A4, SMD is decreasing when traversed from the periphery towards the centre of the spray. Thus it can be inferred that the atomizer A1 operates in solid cone spray mode whereas other atomizers are operating in hollow cone spray mode. In general, as convergence angle increases, tangential velocity component dominates which helps to open up the spray from tulip structure at low pressure. But, on the other hand, greater obstruction of the flow occurs when atomizer with very high convergence angle values are used. In our experiments, atomizer A3 with a convergence angle of 60° is found to be optimum when compared with other atomizers (A1, A2 and A4), in the context of optimal atomization.

3. 4. Drop size distribution

Drop size distributions for four different atomizers at an axial location of 70 mm are plotted in Figure 8. It is observed that the curve shifts towards left indicating the dominance of fine droplets as convergence angle is increased from atomizer A1 to A3. Further, drop size distribution for atomizer A4 with largest convergence angle deviates slightly from that of atomizer A3. It indicates the better performance of atomizer A3 over the other atomizers (A1, A2 and A4) as percentage volume of small-sized droplets is highest for atomizer A3.

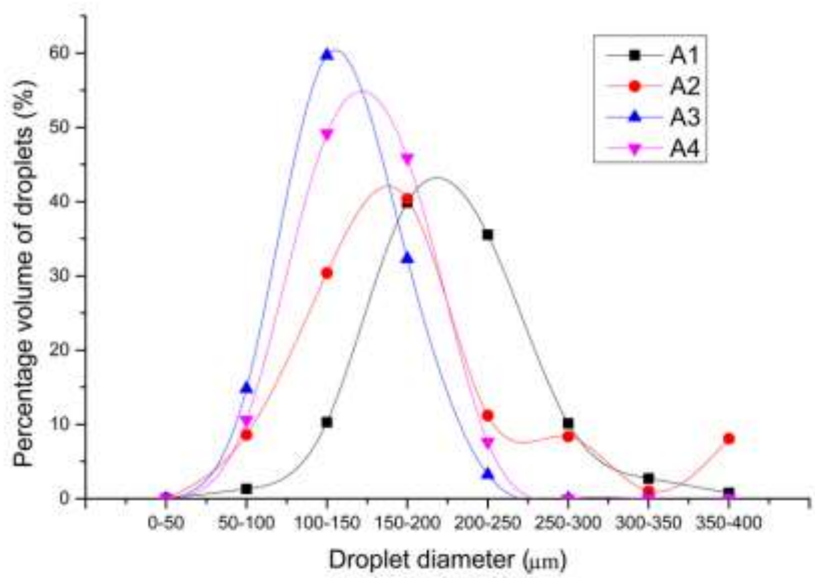

Fig. 8: Drop size distribution at an axial location of 70 mm and centre of the spray for different atomizers. (RMS error: 4.7 %).

4. Conclusion

An experimental investigation is conducted to study the effect of different swirl chamber convergence angles. The investigation is carried out at different injection pressures, ranging from 1 to 7 bar.

Increment in θ_C increases the air core diameter, which in turn reduces the co-efficient of discharge. Increase in θ_C changes the velocity distribution at orifice exit, making tangential component to be dominant, which increases spray cone angle. The variation in θ_C changes SMD drastically. In our experiments, atomizer with convergence angle of 60° is found to be optimum since it facilitates fine atomization (lower SMD and drop size distribution leaning towards fine droplets) when compared with other atomizers having convergence angle of 30°, 45° and 75°.

Acknowledgements

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References

[1] A. H. Lefebvre and V. G. McDonell, *Atomization and sprays*. Cambridge, MA: MIT Press, 1986.
[2] J. Xue, M. A. Jog, S. M. Jeng, E. Steinthorsson and M. A. Benjamin, "Influence of Geometry on the Performance of Simplex Nozzles under Constant Pressure Drop," in *Proceedings of the 15th Annual Conference on Liquid Atomization and Spray Systems*, Madison, WI, May 2002.
[3] G. A. Vijay, N. S. V. Moorthi and A. Manivannan, "Internal and external flow characteristics of swirl atomizers: a review," *Atomization Sprays*, vol. 25, no. 2, 2015.
[4] S. Y. Moon, S. H. Bae and C. W. Lee, "Optimized design of a new gasoline direct swirl injector," *Numer. Heat Transfer, Part A*, vol. 40, no. 2, pp. 157-167, 2001.
[5] M. Rashad, H. Yong and Z. Zekun, "Effect of geometric parameters on spray characteristics of pressure swirl atomizers," *Int. J. Hydrogen Energy*, vol. 41, no. 35, pp. 15790-15799, 2016.
[6] M. S. F. M. Rashid, A. H. A. Hamid, O. C. Sheng and Z. A. Ghaffar, "Effect of inlet slot number on the spray cone angle and discharge coefficient of swirl atomizer," *Procedia Eng.*, vol. 41, pp. 1781-1786, 2012.
[7] M. S. F. M. Rashid, A. H. A. Hamid, C. S. Ow and Z. A. Ghaffar, "An Experimental Investigation on the Effect of Various Swirl Atomizer Orifice Geometries on the Air Core Diameter," *Applied Mechanics and Materials*, vol. 225, pp. 32-37, 2012.
[8] C. L. Yeh, "Turbulent flow simulation of liquid jet emanating from pressure-swirl atomizer," *Heat Mass Transfer*, vol. 44, no. 3, pp. 275, 2008.
[9] M. R. Halder, S. K. Dash and S. K. Som, "Initiation of air core in a simplex nozzle and the effects of operating and geometrical parameters on its shape and size," *Exp. Therm Fluid Sci.*, vol. 26, no. 8, pp. 871-878, 2002.
[10] J. Xue, M. A. Jog, S. M. Jeng, E. Steinthorsson and M. A. Benjamin, "Effect of geometric parameters on simplex atomizer performance," *AIAA J.*, vol. 42, no. 12, pp. 2408-2415, 2004.
[11] M. Razaeimoghaddam, H. Moin, S. M. R. Modarres Razavi, M. Passandideh Fard and R. Elahi, "Optimization of a High Pressure Swirl Injector by Using Volume-of-Fluid (VOF) Method," in *ASME 10th Biennial Conference on Engineering Systems Design and Analysis ESDA*, Istanbul, Turkey, 2010.