On the Effect of Central Jet in Solid Cone Pressure-Swirl Atomizers

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ABSTRACT

Studies on swirl spray have received considerable attention due to its importance in numerous applications. The present study investigates the characteristics of sprays emanating from solid cone pressure swirl atomizers. Several atomizers with different exit orifice diameter were investigated using water at room temperature as the working fluid. The investigation reveals that the jet emanates from the central port significantly modifies the resulting sprays, particularly for atomizers with smaller exit orifice diameter. It is also found that a reduction in exit orifice diameter results in a significant increase in discharge coefficient and an almost linear increase in air core diameter. A semi-empirical correlation is also proposed to predict the axial velocity in terms of the main atomizer dimensions.

Keywords: *pressure swirl atomizer, discharge coefficient, swirl spray.*

Introduction

Liquid atomization is a transformation of bulk liquid into droplets or spray [1]. The device by which the process is achieved is known as atomizer. The process of liquid atomization of a fully-developed swirl spray can be divided into two stages, i) a primary break up in which the liquid is transformed into a combination of small ligaments and droplets, and ii) secondary break up where larger droplets further break into smaller droplets [2].

In the former region, liquid sheet break up into ligaments due to the Kelvin–Helmholtz instability [3], which is mainly affected by internal forces

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such as turbulence, inertial effects, changes in velocity (flow relaxation or bursting effect), and surface tension[4]. The diameter of the ligaments depends on its break up wavelength. The ligaments are then break up into droplets.

Further downstream, droplets atomize due to the deformation or aerodynamic forces exerted on it, in addition to the aforementioned forces. This deformation was resisted by the surface tension tending to restore the drop to a spherical shape. The Weber number *We*, defined as the ratio of the disrupting aerodynamic forces to the restorative surface tension forces, describes the mechanisms of secondary atomization such as bag break up, bag-and-stamen break up, vibrational break up and sheet stripping [5]. A larger *We* indicates a higher tendency towards atomization [6].

Droplet size, its distribution, spray cone angle, liquid file break up length, Euler number and Sauter Mean Diameter (SMD) are among the important atomizer performance characteristics [7], [8]. The characteristics are influenced by various parameters including types of liquid, liquid physical properties, operating parameters, and atomizer geometries [9].

Liu *et al.* [10] compared the discharge coefficient of liquid nitrogen and water in solid-cone pressure swirl atomizer. An increase of injection pressure increases the discharge coefficient of liquid nitrogen. Contrarily, a slight decreasing trend was observed for water.

The study related to the influence of swirl atomizer geometry on spray characteristics were conducted by Payri *et al.* [11], Hamid *et al.* [12] Ghaffar *et al.* [13]. Their investigations reach a conclusion that spray tip penetration and spray cone angle were dependent to the atomizer geometry. Ochowiak *et al.* [14] introduced gas bubbles to the existing atomizer in order to examine the effect of liquid aeration on the atomization process. The modification leads to decrease of the mean droplet diameter.

However, in the literature, the effect of an axial stream from a central port on the atomization characteristic has not been greatly studied. Furthermore, despite the fact that the exit orifice diameter is one of the most crucial geometrical parameters in determining spray structure and discharge coefficient [15], studies related to it are rather scarce. The present investigation seeks to better understand the role of central jet stream in modifying the spray characteristics of a solid cone pressure swirl atomizer with various exit orifice diameter.

Methodology

All atomizers were tested using water to define the discharge coefficient and other spray characteristics. These atomizers produce either hollow or solid cone shape spray. In the former spray, the concentration of droplets is at the outer edge of the spray with little or no droplet in the centre (typical spray pattern is shown in Figure 1), while in the latter spray, the distribution of droplets is fairly uniform across the cross section of the spray.

Figure 1: Typical spray pattern for hollow cone atomizer.

A solid cone spray is produced when high pressure liquid is fed to the atomizer partly through a central cylindrical port which provides a pure axial type entry and partly through side inlet slots which imparts swirl to the liquid, while a hollow cone spray is produced when the liquid is supplied only through the side slots only. The geometry and notation for the atomizer is depicted in Figure 2, while its specification is summarized in Table 1.

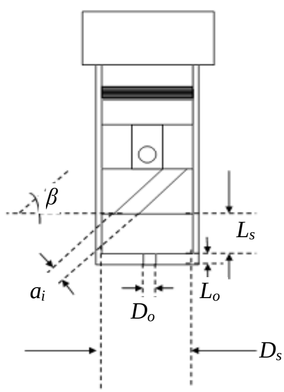

Figure 2: Geometry and notation for a pressure swirl atomizer.

In Figure 2, D_o and D_s are the exit orifice diameter and swirl chamber diameter, respectively, L_o and L_s are the exit orifice length and swirl chamber length, respectively, a_i is the inlet slot width and β is the inlet slot angle.

Table 1 Specifications of tested atomizers (all length dimensions are in mm)

Atomizer	D_s	L_s	**β (º)**	D_0	L_0	a_i
A1	11	1.5	20	1.5	1.5	1
A2	11	1.5	20	2.0	1.5	1
A3	11	1.5	20	2.5	1.5	1
A4	11	1.5	20	3.0	1.5	1

The experimental set-up comprises of a compressed air tank, a water tank, feed lines fitted with flow control valves, a pressure gauge and a flow meter. The atomizer is mounted downward on a vertical plane, so that the water spray is injected directly into a collecting basin at the ambient condition. Figure 3 shows overall test setup.

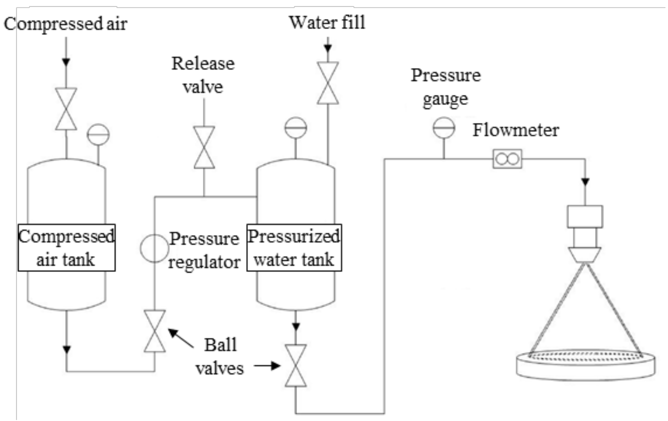

Figure 3: Line diagram of the experimental setup.

Results and discussion

Estimation of air core diameter

This section presents the estimation of the air core diameter at the exit of the orifice. The model is based on the theory of the inner flow proposed by Lefebvre *et al*. [16] for the pressure swirl atomizers. The theory suggests that the discharge coefficient is a function of air core area and orifice area, i.e.

$$C_D = 1.17\left[\frac{(1-X)^3}{1+X}\right]^{0.5}, \quad (1)$$

with

$$X = \left(\frac{D_a}{D_o}\right)^2, \quad (2)$$

where C_D is discharge coefficient and X is the ratio of air core area to the orifice area. The value of X is determined by solving the implicit equation (i.e. Equation (1)) with known value of C_D obtained from the experiment. The air core diameter is then estimated by solving Equation (2) for D_o. Figure 4 depicts the relationship between the normalised air core diameter (i.e. the ratio of air core diameter of a solid cone atomizer to the respective air core diameter of a hollow cone atomizer, $D_{a,\mathrm{solid}}$ / $D_{a,\mathrm{hollow}}$).

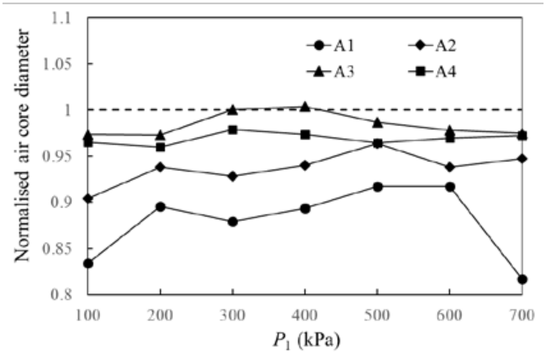

Figure 4: Normalised air core diameter plotted against injection pressure P_1 for atomizers as indicated. Dashed line represents $D_{a,\mathrm{solid}}$ / $D_{a,\mathrm{hollow}}$ = 1.

It is observed from Figure 4 that solid cone atomizers produced smaller air core than hollow cone counterparts. This observation is attributed to the fact that the flow from the central port tends to weaken the centrifugal component of velocity of the swirling flow in the swirl chamber, and thus increasing the thickness of the liquid film. It is also interesting to note that the effect of the central stream is more prominent for a smaller exit orifice. The reason for this observation is that for a small exit orifice, the air core diameter is small (as shown in Figure 5). Thus, there is a relatively strong interaction between the central stream and the swirling flow at the orifice, which results in a big difference in the air core diamteter between the solid cone and hollow cone atomizers.

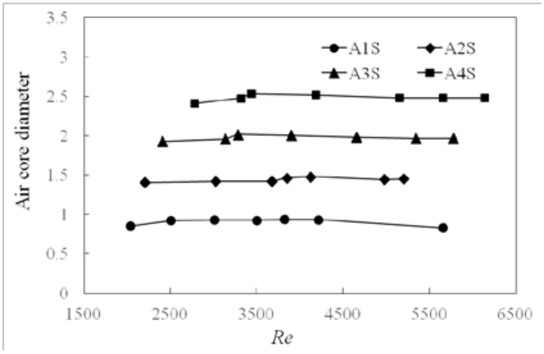

Figure 5: Air core diameter plotted against Reynolds number for solid cone atomizers as indicated.

In Figure 5, the Reynolds number *Re* is calculated using

$$\mathrm{Re} = \frac{2\rho\dot{V}}{\mu\pi R_s}, \tag{3}$$

where μ and ρ are the water viscosity and density, which are taken to be 0.000799 kg/ms and 996 kg/m^3, respectively, $\dot{V}$ is the volume flow rate and R_s is the radius of swirl chamber. It is also noted from Figure 5 that the air core diameter is almost uninfluenced by the Reynolds number. This is likely due to the fact that the effects of swirl and the adverse frictional resistance counterbalance each other and result in almist constant values of air core diameter [17].

Semi-empirical model for spray axial velocity

This section details the derivation of the semi-empirical model that predicts the axial velocity of liquid film at the exit of the orifice. The total velocity of the flow through the inlet slots is estimated by solving the continuity equation,

$$\frac{\dot{m}_1}{\rho} = A_i V_i + A_c V_c , \tag{4}$$

and the energy equation,

$$\frac{2P_1}{\rho} = V_i^2 + V_c^2 \,, \tag{5}$$

to give

$$V_i = 1/2k\left[\frac{2A_i\dot{m}_i}{\rho A_c^2} \pm \sqrt{\left(\frac{2A_i\dot{m}_i}{\rho A_c^2}\right)^2 - 4k\left[\left(\frac{\dot{m}_i}{\rho A_c}\right)^2 - \frac{2P_1}{\rho}\right]}\right], \tag{6}$$

where

$$k = \left(\frac{A_i}{A_c}\right)^2 + 1 \,. \tag{7}$$

Here, $\dot{m}_1$ is the total mass flow rate, A_i and A_c are the total area of inlet slots (in the present investigation, there are two inlet slots with square cross-section of side length a_i = 1mm) and the cross-section area of central port, and V_i and V_c are the stream velocities in the inlet slot and central port, respeectively. It is important to note that the fluid friction and the effect due to difference in elevation are neglected, and it is assumed that the flow is uniformly distributed over both the inlet and outlet areas. The total mass flow rate through the inlet slot $\dot{m}_i$ can then be determined through

$$\dot{m}_i = \rho A_i V_i \,. \tag{8}$$

This is the mass flow rate of the swirling flow within the swirl chamber. The axial velocity component of this flow u at the exit orifice is determined through

$$u = \frac{\dot{m}_i}{\rho A_{\text{eff}}} \cos\theta \,, \tag{9}$$

where $\theta = \beta/2$ is the half spray cone angle, which can be determined either from experiment or from published empirical correlations, e.g. by Rizk and Lefebvre [18]:

$$\theta = 3\,K^{-0.15}\left(\frac{\Delta P\,D_o^2\rho}{\mu^2}\right)^{0.11} \,, \tag{10}$$

where $K = A_i / (D_o D_s)$ is the atomizer constant, $\Delta P = P_1$ is the pressure drop across the atomizer and A_{eff} is the effective area of the flow, which is given by

$$A_{\text{eff}} = \int_{r_a}^{r_o} 2\pi r \,\mathrm{d}r = \frac{\pi}{4}\left(D_o^2 - D_a^2\right). \tag{11}$$

The plot of spray axial velocity against Reynolds number is presented in Figure 6. It can be seen from this figure that high Reynolds number (i.e. high injection pressure) leads to high axial velocity of the spray at the exit orifice. This is expected since the effective area of the flow at the exit orifice is almost uninfluenced by the Reynolds number (as shown in Figure 5), and that the Reynolds number is proportional to the mass flow rate (as defined in Equation (3)), thus the conservation of mass dictates that the velocity must increased with increasing Reynolds number.

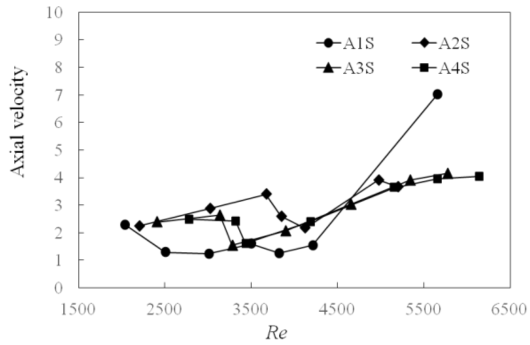

Figure 6: Spray axial velocity plotted against Reynolds number for solid cone atomizers as indicated.

Spray discharge coefficient

Figure 7 compares the discharge coefficient of atomizers with different exit orifice diameter. The discharge coefficient is calculated using the relation

$$C_D = \frac{\dot{m}}{A_o\sqrt{2\rho\Delta P}}, \tag{12}$$

where A_o is the orifice area. The discharge coefficient for all atomizers was almost constant within the tested range of Reynolds number. Datta and Som [17] reported similar observation for higher flow rate regime. This observation can be explained as follows: in the high Reynolds number regime, the flow through both the central port and the inlet slots increases.

This causes an increase in both the average axial and tangential velocities at the inlet, which gives rise to the counterbalancing effects of increased strength of swirl and its subsequent decay due to friction in the injector. This in turn results in almost constant values of discharge coefficient with Reynolds number.

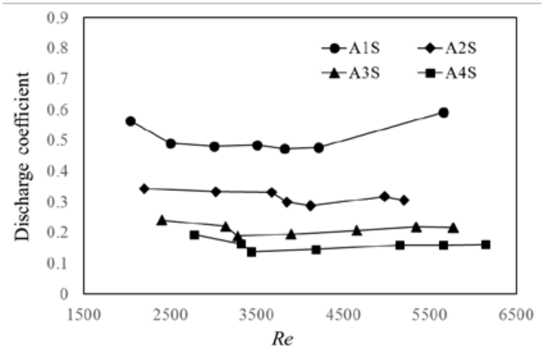

Figure 7: Effect of Reynolds number on discharge coefficient for solid cone atomizers as indicated

The average values of discharge coefficient over the tested range of Reynolds number for all atomizers are depicted in Figure 8. In general, larger orifice diameter leads to lower discharge coefficient, which confirms the previous observations by Yule and Widger [15] and our previous work [19] on hollow cone swirl atomizer. This is because larger orifice diameter increases the swirling motion inside the swirl chamber and hence the diameter of the air core (as evidenced in Figure 5), which finally results in low discharge coefficient.

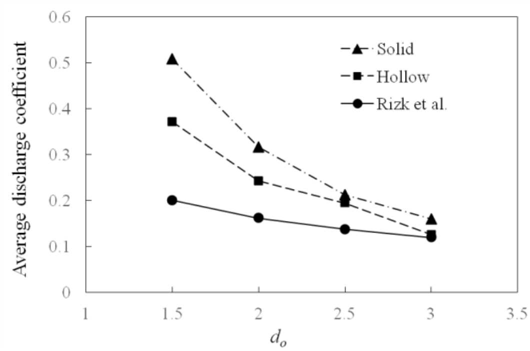

Figure 8: Average discharge coefficient plotted against orifice diameter.

Furthermore, solid cone atomizer produces higher discharge coefficient than its hollow cone counterparts. The reason is clear: for a given pressure drop, the central port of the solid cone atomizer imparts a significant axial velocity component in the swirl chamber, thus reducing the flow resistance and increasing the discharge coefficient. Like the air core diameter, the effect of the stream from the central port is more prominent for a smaller exit orifice.

Figure 8 also contains the data points generated from the correlation proposed by Rizk and Lefebvre [18], i.e.

$$C_D = 0.35\,K^{0.5}\left(\frac{D_s}{D_o}\right)^{0.25}. \tag{13}$$

It is noted that the present C_D is relatively higher since the correlation is proposed for a simplex atomizer, where the liquid is fed into a swirl chamber through tangential ports that give the liquid a high angular velocity. In the present investigation, however, the liquid is fed into the swirl chamber at an angle, imparting both tangential and axial components of velocity to the liquid, which result in less friction to the flow and thus higher discharge coefficient. Nevertheless, the general trend agrees: increasing exit orifice diameter leads to lower discharge coefficient.

Conclusions

The spray characteristics of pressure swirl atomizers with varying ext orifice diameter have been investigated. It was found that the central jet played a significant role in modifying the spray characteristics, for example solid cone atomizers produced smaller air core and higher discharge coefficient than its hollow cone counterparts. The effect is more striking for a smaller exit orifice. Furthermore, it was found that the air core diameter and the discharge coefficient were almost uninfluenced by the Reynolds number. However, it was predicted that the axial component of spray velocity increased with increasing Reynolds number. An analysis of discharge coefficient for various exit orifice diameter revealed a significant increase in discharge coefficient and an almost linear increase in air core diameter occurred for reduction in exit orifice diameter. A semi-empirical model predicting the axial velocity of sprays from a pressure swirl atomizer was proposed. Further works are required to verify this model.

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References

[1] E. Babinsky and P. E. Sojka, "Modeling drop size distributions," *Prog. Energy Combust. Sci.*, vol. 28, no. 4, pp. 303–329, 2002.
[2] T. G. Shepard, "Bubble size effect on effervescent atomization," University of Minnesota, 2011.
[3] N. Dombrowski and W. R. Johns, "The aerodynamic instability and disintegration of viscous liquid sheets," *Chem. Eng. Sci.*, vol. 18, no. 3, pp. 203–214, 1963.
[4] H. Liu, *Science and Engineering of Droplets:: Fundamentals and Applications*. New York: Noyes Publications, 2000.
[5] H. F. Liu, X. Gong, W. F. Li, F. C. Wang, and Z. H. Yu, "Prediction of droplet size distribution in sprays of prefilming air-blast atomizers," *Chem. Eng. Sci.*, vol. 61, no. 6, pp. 1741–1747, 2006.
[6] D. R. Guildenbecher, C. López-Rivera, and P. E. Sojka, "Secondary atomization," *Exp. Fluids*, vol. 46, no. 3, p. 371, 2009.
[7] Y. I. Khavkin, *Theory and practice of swirl atomizers*. New York: Taylor & Francis, 2004.
[8] A. Ibrahim, "Comprehensive study of internal flow field and linear and nonlinear instability of an annular liquid sheet emanating from an atomizer," University of Cincinnati, 2006.
[9] M. Rahman, "Scaling of effervescent atomization and industrial two-phase flow." University of Alberta, 2010.
[10] X. Liu, R. Xue, Y. Ruan, L. Chen, X. Zhang, and Y. Hou, "Flow characteristics of liquid nitrogen through solid-cone pressure swirl nozzles," *Appl. Therm. Eng.*, vol. 110, pp. 290–297, 2017.
[11] R. Payri, J. P. Viera, V. Gopalakrishnan, and P. G. Szymkowicz, "The effect of nozzle geometry over the evaporative spray formation for three different fuels," *Fuel*, vol. 188, pp. 645–660, 2017.
[12] A. H. A. Hamid, "Spray cone angle and air core diameter of hollow cone swirl rocket injector," *IIUM Eng. J.*, vol. 12, no. 3, 2011.
[13] Z. A. Ghaffar, S. Kasolang, A. Hussein, A. Hamid, O. C. Sheng, and M. A. A. Bakar, "Effect of geometrical parameters interaction on swirl effervescent atomizer spray angle," *J. Teknol.*, vol. 76, no. 9, pp. 63–67, 2015.
[14] M. Ochowiak and M. Matuszak, "The effect of additional aeration of liquid on the atomization process for a pneumatic nebulizer," *Eur. J.*

Pharm. Sci., vol. 97, pp. 99–105, 2017.
[15] A. J. Yule and I. R. Widger, “Swirl atomizers operating at high water pressure,” *Int. J. Mech. Sci.*, vol. 38, no. 8, pp. 981–999, 1996.
[16] A. H. Lefebvre, “Atomization and Sprays, Hemisphere Pub,” *Corp., New York*, vol. 1989, 1989.
[17] A. Datta and S. K. Som, “Numerical prediction of air core diameter, coefficient of discharge and spray cone angle of a swirl spray pressure nozzle,” *Int. J. heat fluid flow*, vol. 21, no. 4, pp. 412–419, 2000.
[18] N. K. Rizk and A. H. Lefebvre, “Internal flow characteristics of simplex swirl atomizers,” *J. Propuls. Power*, vol. 1, no. 3, pp. 193–199, 1985.
[19] A. H. A. Hamid, M. H. M. Noh, H. Rashid, A. H. Abdullah, W. Wisnoe, and S. Kasolang, “Characteristics of hollow cone swirl spray at various nozzle orifice diameters,” *J. Teknol.*, vol. 58, pp. 1–4, 2012.