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Studies on Spray Behavior of a Pressure Swirl Atomizer in Transition Regime

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Hollow-cone sprays produced by pressure-swirl atomizers find application in a wide range of propulsive systems. During throttling and under low-thrust requirements, however, the spray pattern may change from a fully developed hollow cone to a solid (collapsed) spray resulting in an increase in pollutant emissions, thermal spikes, and decrease in efficiency. Also, the solid and developing cone regimes are susceptible to flow instabilities. The transition regime from a collapsed to a developing hollow-cone spray from a pressure-swirl atomizer has been investigated in this paper. The present atomizer uses a helical insert having a swirl number of 3.6. At low injection pressures (ΔP_{inj}) the spray cone angle did not change appreciably with increasing ΔP_{inj} as a result of the dominating surface tension forces. However, with increasing pressure, the conical sheet opens up. Under these conditions, the spray cone angle increases monotonically with injection pressure, finally leading to fully developed hollow-cone regime. Experiments were also carried out to determine spatial drop-size distribution and patternation. Average drop sizes were found to decrease from 150 to 100 μm for a twofold increase in injection pressure drop, along with a narrower drop-size spectrum with the transition from collapsed to developing cone regime. Increasing axial distance resulted in a narrower spray drop-size spectrum with slightly higher drop sizes. This could be attributed to the combined effect of coalescence, evaporation, and aerodynamic influences on drops. The drop size along the spray axis was found to be higher in comparison to the periphery for the collapsed spray regime, with a reversed trend in case of higher pressures. Mass distribution obtained using a mechanical patternator clearly reveals the flow features during the transition from collapsed regime to the developing cone regime.

Nomenclature

C_d	=	discharge coefficient
D	=	droplet size
D_s	=	swirler diameter
d_o	=	exit orifice diameter
Ls	=	swirler length
L_o	=	exit orifice length
l	=	depth of helical groove in swirler
N_s	=	swirl number
n	=	number of grooves in swirler
r, z	=	radial and axial distances
V_b, ν	=	bulk velocity and kinematic viscosity of test fluid
w	=	width of helical groove in swirler
X, q	=	Rosin–Rammler distribution parameters
$Y(D)$	=	fraction of total volume contained in drops of diameter =D
ΔP_{inj}	=	injection pressure, gauge
φ	=	swirler angle

I. Introduction

THE importance of atomization process for the effective operation of liquid-fueled combustors has long been recognized. Spray characteristics such as the drop size, drop-size spectrum, and distribution, cone angle, and patternation determine to a great extent the fuel–air mixing in the combustor and hence pollutant formation, life, and durability of the combustor, thermal spikes, and efficiency of gas turbine engines. Hollow-cone sprays produced by pressure-swirl (simplex) atomizers are used widely in gas turbine combustion chambers. Though many design variants of the same are available, they all depend upon the disintegration of the liquid sheet issuing out of the atomizer in the form of a hollow cone. It has been observed that sprays produced by simplex atomizers evolve from a collapsed regime (onion stage), developing cone (tulip stage), to finally a fine atomization regime with increasing pressure [1–3].

Hollow conical structure of the spray incurs appreciable exposure to the influence of the surrounding air. Normally, an increase in the spray cone angle increases the extent of this exposure, leading to improved atomization and better fuel–air mixing. Thus, spray cone angle is an important characteristic of swirl atomizers. Chen et al [4] found that the spray cone angle increases continuously at low injection pressures and reaches a maximum asymptotically at high injection pressures in the range studied (0.34–1.72 MPa). Ramamurthi and Tharakan [5] found that increasing swirl number results in an increase in the spray cone angle with higher swirl number atomizers producing cone angles almost independent of injection pressures.

Another parameter of consequence in combustion applications with regard to combustion efficiency and pollutant formation is the mass distribution (spray patternation) of fuel achieved by the atomizers. Spray patternation studies are useful in the identification of spray nonuniformities and thus combustor nonidealities. Santolaya et al. [6] and Cohen and Rosfjord [7] studied the spray patternation resulting from pressure-swirl atomizers and concluded that the regime of spray evolution dictates the mass distribution. It was found that under low-flow conditions, the spray indicated a collapsed single, coarse jet with the mass flux being maximum at the center. At higher flow rates, the spray produced indicated a well-developed and symmetric hollow-cone structure. In another study, Santolaya et al. [8] found a sharp rise in the profile of axial volumetric flux along the radial direction, indicating liquid distribution in an annular zone (fully developed hollow cone). The maximum axial flux was found to decrease with increasing pressure due to progressive spatial distribution of the liquid droplets.

The variation of Sauter mean diameter (SMD) with injection pressure and the spatial evolution of sprays have been reported by some authors [8–15]. In most of the cases, an increase in drop size has

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been observed with increasing axial distance. This phenomena has been attributed to droplet coalescence and evaporation. However, in contradiction, Dodge and Biaglow [13] found that the SMD along the centerline decreases with axial distance. Rizk and Lefebvre [14] determined that SMD initially decreases with axial distance and then increases continuously. This initial drop in droplet size was attributed to the over-representation of lower drop sizes due to their lower velocities as a result of aerodynamic forces. They suggested that the SMD measurements should be made at least 150 mm downstream of the exit orifice. Further downstream, it was found that the drop-size spectrum was narrower with increasing axial distance. Under fine atomization regimes, it has been observed that SMD increases with radial distance indicating the presence of smaller drops at the center and larger ones at the edge of the spray; the prominence of the trend increasing with increasing axial distance, a phenomenon attributed to the entrainment of smaller drops into the air core. Santolaya et al. [8] evaluated the near-field spray structure and found a change in sheet breakup mechanism from perforations in the sheet to the development of surface waves, with increasing the latter yielding finer droplets. This was attributed to the process of generation of satellite droplets by high inertia collision phenomena. The authors also reported a increase in SMD in the near field (9–18 mm). However, the atomizer in most of these studies were operated under stable operating conditions (constant C_d and cone angle).

Review of the preceding literature reveals that most of the data pertaining to swirl atomizers have been obtained at higher injection pressures and under hollow-cone regime. However, during throttling and idling, these atomizers may undergo a transition into collapsed regime. The behavior of sprays under this regime has not been quantified in detail. The present study thus examines the performance of swirl atomizers under the collapsed and developing cone flow regimes at low injection pressures in terms of spray cone angle, patternation, SMD, and its spatial distribution.

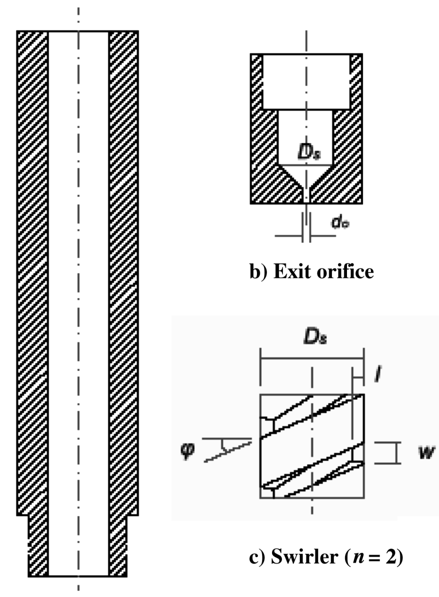
II. Experimental Procedure

The pressure-swirl atomizer (Fig. 1) used in the present work had a discharge orifice diameter d_o of 0.8 mm and an exit length to diameter ratio L_o/d_o of 1.25. A helical insert with diameter D_s and length L_s both of 5 mm was used in the present study to impart swirl motion to the liquid flow. The swirler has two ($n = 2$) ports having a cross-sectional area of 0.65 mm^2 ($w \times l$) and a turn angle φ of 23 deg. The tangential velocity component imparted to the liquid to be atomized depends on the dimensions of the helical insert as well as the exit orifice and the mean axial velocity. The swirl number [4] N_s which accounts for this effect is defined as

$$N_s = \frac{\pi d_o D_s \cos\varphi}{4nwl} \qquad (1)$$

All experiments were done with water as the test fluid. The experimental setup developed for SMD measurement is shown in Fig. 2. Water pressurized to 860 kPa passed through a series of valves before being discharged through the swirl atomizer. The spray cone angle was measured with the aid of a laser sheet produced using a 100 mW laser and a charge-coupled device (CCD) camera (SONY DCR PC350E). A mechanical patternator was used to obtain the mass distribution of spray at an axial distance of 150 mm. Axial and radial distributions of average drop sizes were obtained with the Malvern's Spraytec analyzer. The instrument, based on line-of-sight measurement, uses a 5 mW laser beam at a wavelength of 670 nm, a beam diameter of 5 mm, and a 200 mm focal length lens, and has a measurable drop-size range of 1–400 μm (based on the median of the drop-size range). For ensuring accurate measurements, data with higher transmission levels of laser power (>50%) only have been considered for the present study. In all cases, each data point is an average of at least three readings. The drop-size spectrum is represented by the Rosin–Rammler distribution function, which is a two-parameter equation and given by

$$Y(D) = 1 - \exp[-(D/X)^q] \qquad (2)$$



a) Inlet tube

Fig. 1 Schematic of the swirl atomizer.

where the parameter X is a representative diameter such that 63.2% of the total liquid volume is in drops of smaller diameter. A measure of the spread of droplet size is given by q, with large values representing monodisperse sprays. For most sprays, the value of q lies between 1.5 and 4 [1]. The Rosin–Rammler parameters in the present study were obtained through curve fitting using MATLAB with a 95% confidence interval.

III. Results and Discussion

A. Discharge Coefficient

Pressure-swirl atomizers have low discharge coefficients (~0.3–0.5) due to the presence of an air core that results in a reduction of the effective flow area in the discharge orifice [1]. It has been demonstrated by several authors [16,17] that at low Reynolds number, $Re = V_b d_o/\upsilon \leq 2000$, the discharge coefficient ($C_d = V_b/\sqrt{2\Delta P_{\mathrm{inj}}/\rho}$) decreases with increasing Reynolds number, and at higher Reynolds number (>2000), it is almost independent of the Reynolds number. Figure 3 shows the variation of discharge coefficient with Reynolds number for the atomizer studied. It can be observed that C_d almost remains constant for Reynolds number in the range of 4000–10,000, consistent with the observations of Chung and Presser [15]. The flow number ($\dot{m}/\sqrt{\Delta P.\rho}$) for the present nozzle was 2.48×10^{-7} m^2.

B. Effect of Injection Pressure on Cone Angle

Swirl atomizers have profound advantages over pressure atomizers as well as aerated atomizers, as far as the fuel distribution is concerned, as evident from higher cone angles achieved. Figure 4 is a plot of the initial divergence angle θ of the spray as emerging from the exit orifice against the pressure differential across the atomizer. These data were obtained from images of the liquid conical sheet illuminated by a thin laser sheet. Time-averaged images were processed by determining the spray edges using Sobel's algorithm available in MATLAB's image processing toolbox. At low injection pressures, the cone angle did not change appreciably. This regime is dominated by surface tension forces. As the applied pressure (centrifugal force) is not sufficient enough to overcome the surface tension, the conical sheet collapses after emerging from the atomizer. However, with increasing pressure, the conical sheet opens up and the centrifugal forces start dominating. Under these conditions, the spray cone angle increases monotonically with injection pressure.

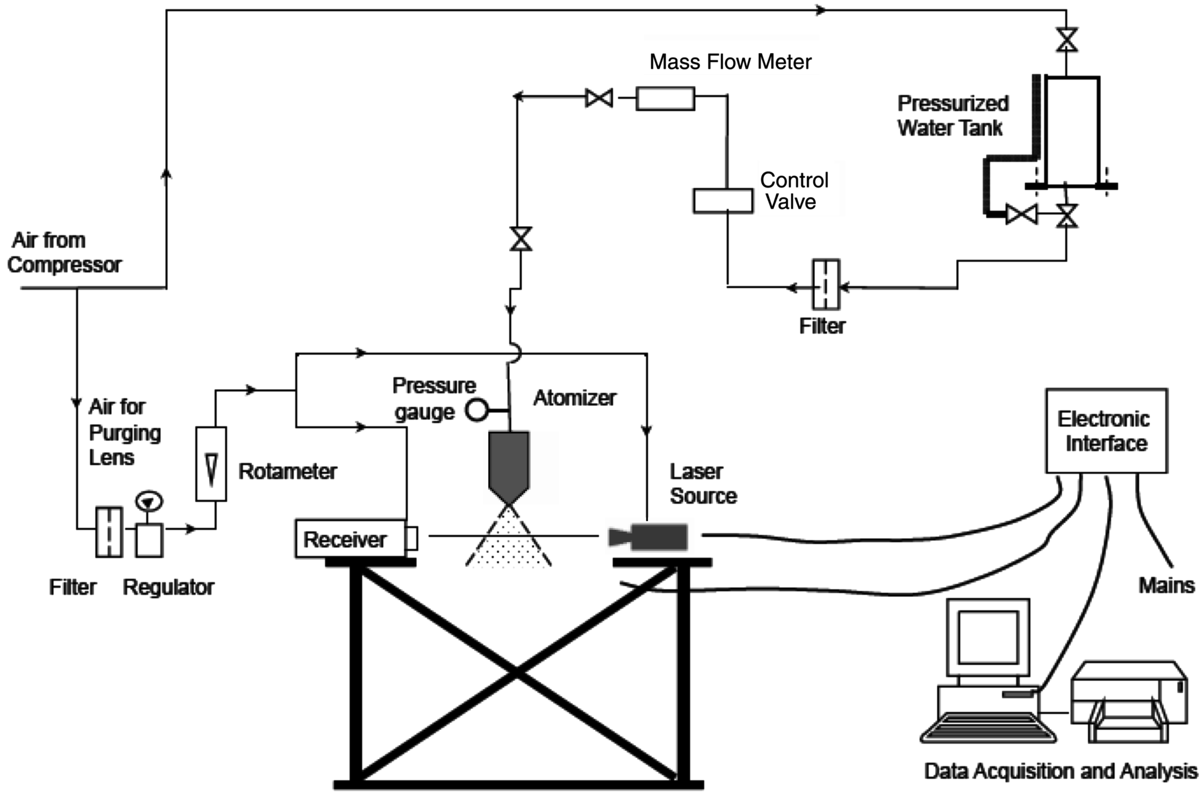


Fig. 2 Experimental setup for atomization studies (for SMD measurement).

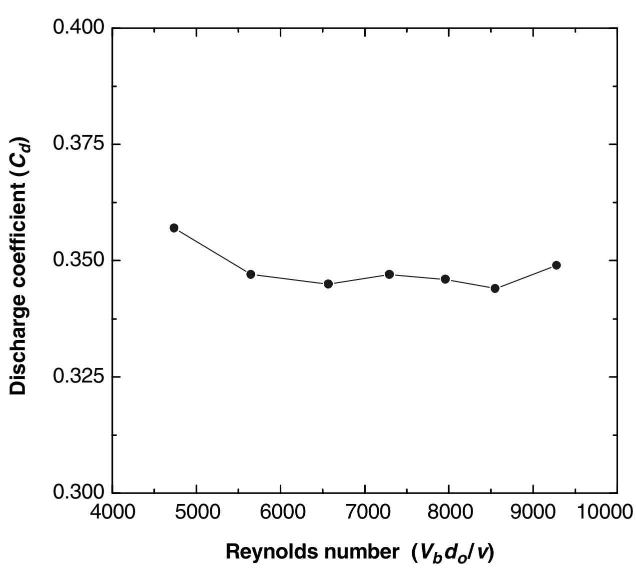


Fig. 3 Variation of discharge coefficient with Reynolds number.

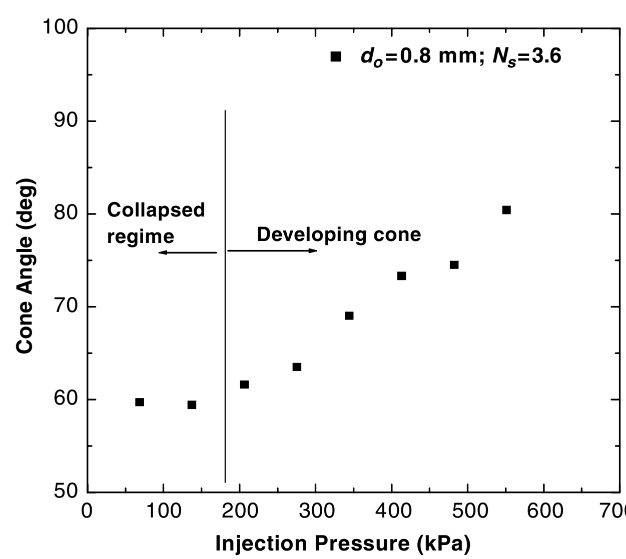


Fig. 4 Effect of injection pressure on spray cone angle.

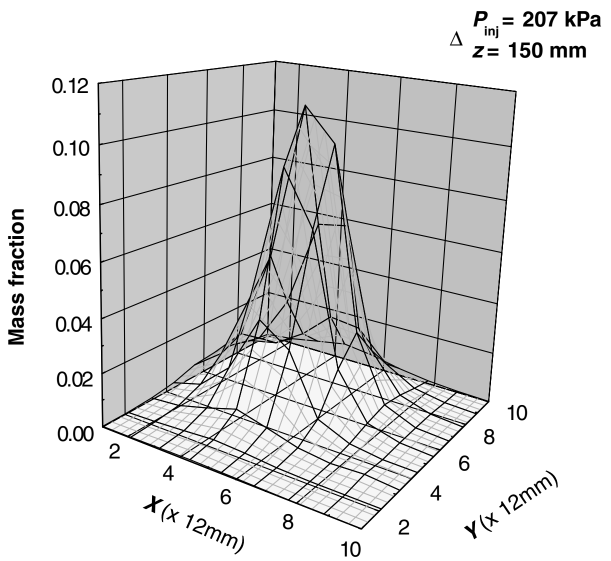
C. Spray Patternation

To further substantiate the transition from collapsed to developing cone regime, the liquid mass distribution was determined for two pressures at $z = 150$ mm using a mechanical patternator (9×9 square cells, each having a linear dimension of $\sim$12 mm). Spray was collected for a duration of 60 s and the mass fraction in each cell was obtained by dividing the individual masses by the total liquid collected, with the data presented averaged from three readings. The collection efficiency in the present case was around 65%. As is evident from Fig. 5a, at low injection pressures after a certain distance, the collapsing of the hollow conical sheet results in higher mass flux at the center. However, higher pressures result in the development of a hollow cone with lower mass fraction at the center than periphery, as is evident from Fig. 5b. The two cases represent the transition of the flow regime from collapsed spray to developing hollow-cone spray and are consistent with the observations of Cohen and Rosfjord [7].

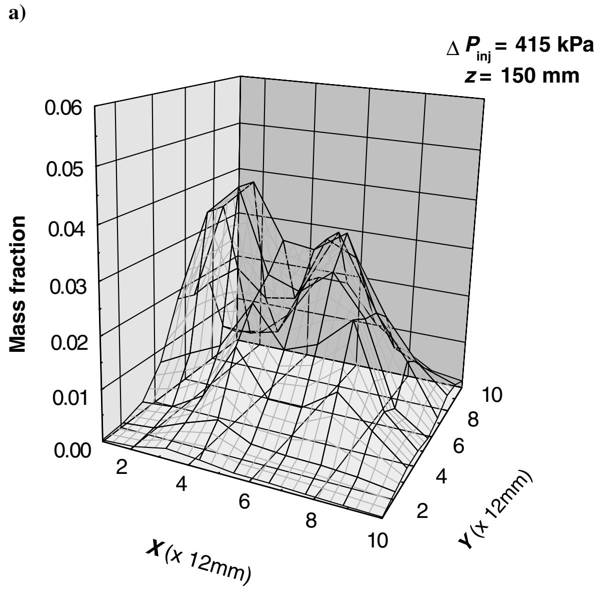
D. Drop-Size Distribution

1. Effect of Injection Pressure on Sauter Mean Diameter

Drop-size measurement was carried out as explained in the previous section. Figure 6 shows the variation of SMD with injection pressure. These measurements were made at an axial distance of 150 mm from the exit orifice along the atomizer spray axis. It can be seen from Fig. 6a that the drop size decreases rapidly with increasing pressure initially, but the influence of injection pressure gradually decreases at higher ΔP_{inj} values, as evident from the later part of the

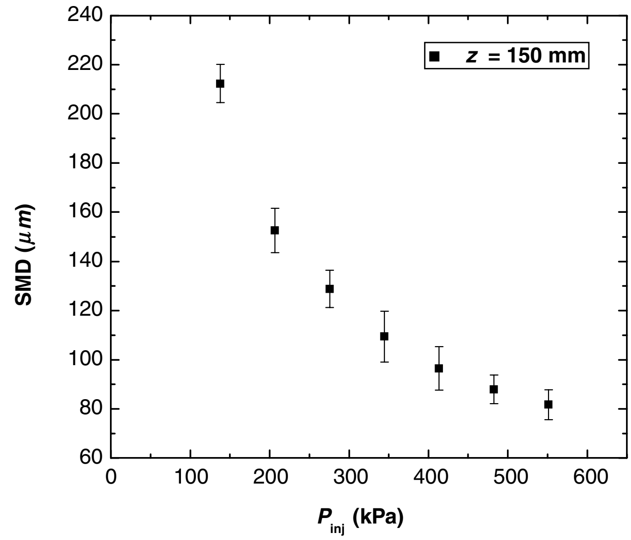


a)

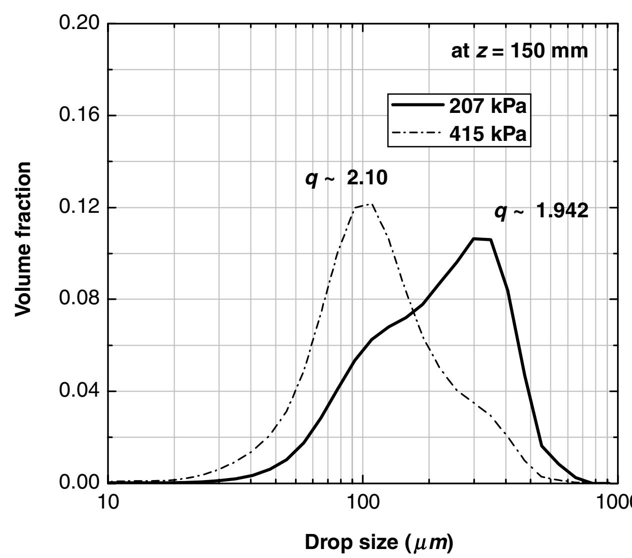


b)

Fig. 5 Mass distribution at a) low injection pressures (collapsed spray) and b) higher injection pressure (developing hollow cone).



a)



b)

Fig. 6 Effect of injection pressure on a) SMD and b) droplet size distribution.

graph. Also, with increasing pressure, the drop-size spectrum gets narrower (Fig. 6b). This is due to the fact that at low injection pressures, the conical sheet collapses and is characterized by a large degree of coalescence. With increasing pressure, the liquid sheet diverges and the sheet breakup is controlled more by the surface waves due to increased aerodynamic drag resulting in finer atomization.

2. *Spatial Distribution of Drop Size*

The radial evolution of the drop sizes were determined for two injection pressures, 207 and 415 kPa, and three axial distances, $z = 100$, 150, and 200 mm. As can be seen from Fig. 7a for the case of $\Delta P_{\text{inj}} = 207$ kPa, the drop-size distribution is slightly unsymmetrical. This was observed in all cases studied in this work and may be attributed to the surface finish of the helical swirler and frictional and viscous effects. Increasing axial distance resulted in a slight increase in SMD with spatial evolution indicating a more uniform spray. The drop size was found to be higher at the center, a behavior different from that reported in literature [10–12], the main reason being the collapse of the liquid conical sheet due to the dominant surface tension forces, resulting in a spray characterized with a large degree of coalescence. Figure 7b indicates that the spray droplet size spectrum gets broader with increasing axial distance. Also, the edge of the spray has a slightly smaller drop-size distribution compared with the center (Fig. 7c). This is a result of a decrease in the mass flux of the spray with increasing axial distance. These observations are in agreement with the results obtained by Rizk and Lefebvre [14].

However, this trend changes with increasing injection pressure, as is evident from Figs. 8a–8c. With the liquid conical sheet spreading and being exposed more to the aerodynamic drag at higher pressures, the drop sizes decrease. When the spray forms at the outlet of a pressure-swirl atomizer, it first expands radially before finally assuming a fully axial direction. The larger drops penetrate farther radially than the smaller droplets due to inertia. This could be one of the reasons for the drops to be distributed radially from smaller drops at the center of the spray to larger drops at the edge. Another possible reason for the observed radial SMD distribution is the strong ambient gas flow induced by the spray action itself. This ambient gas flow moves directly across and through the spray surface from the outside of the spray in toward the spray axis, transporting the smaller drops with the gas flow. As observed in the previous case, the SMD increases with increasing axial distance mainly due to drop

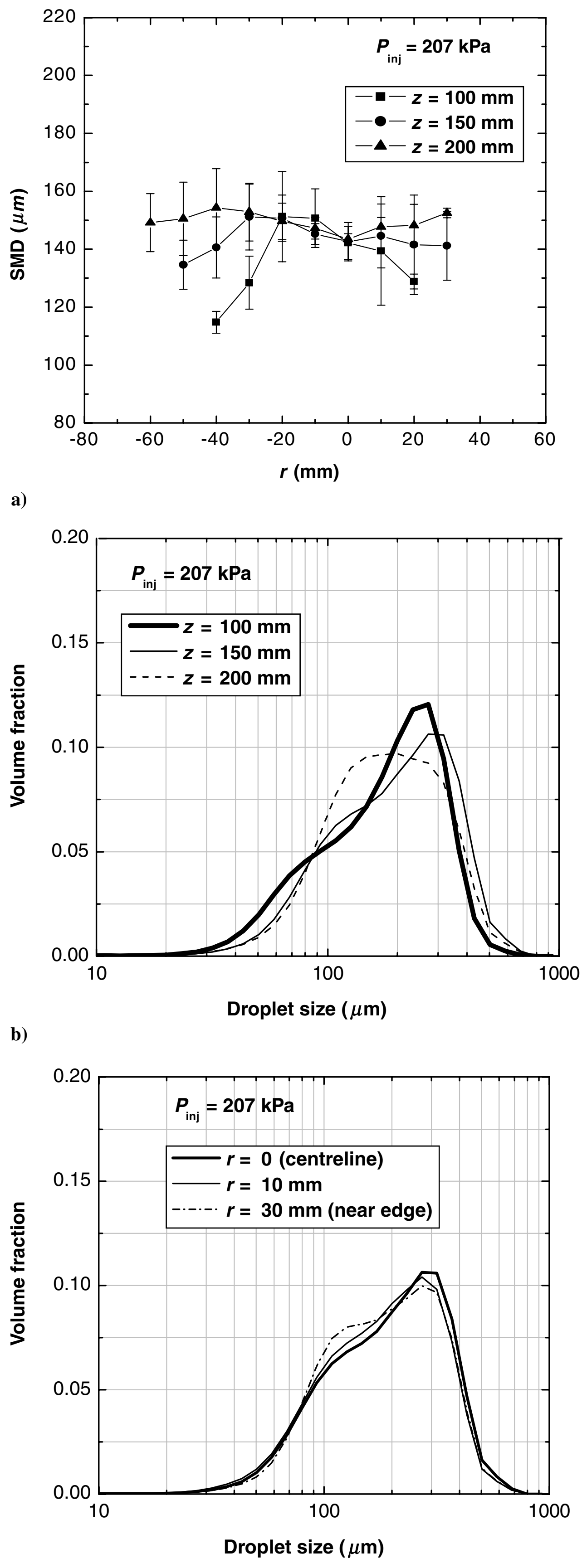


Fig. 7 Collapsed regime: a) radial distribution of SMD with axial distance, b) particle size distribution for three axial locations at $r = 0$, and c) particle size distribution for three radial locations at $z = 150$ mm.

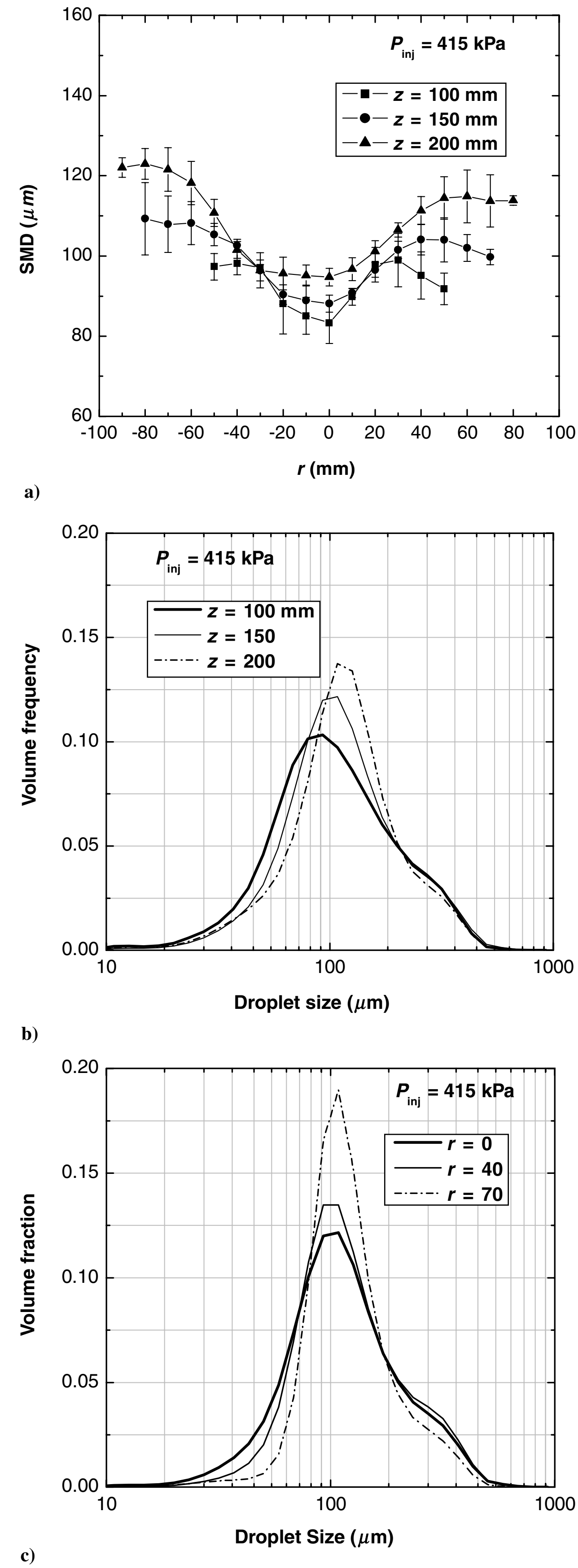


Fig. 8 Developing cone regime: a) radial distribution of SMD for three axial locations, b) particle size distribution for three axial locations at $r = 0$, and c) particle size distribution for three radial locations at $z = 150$ mm.

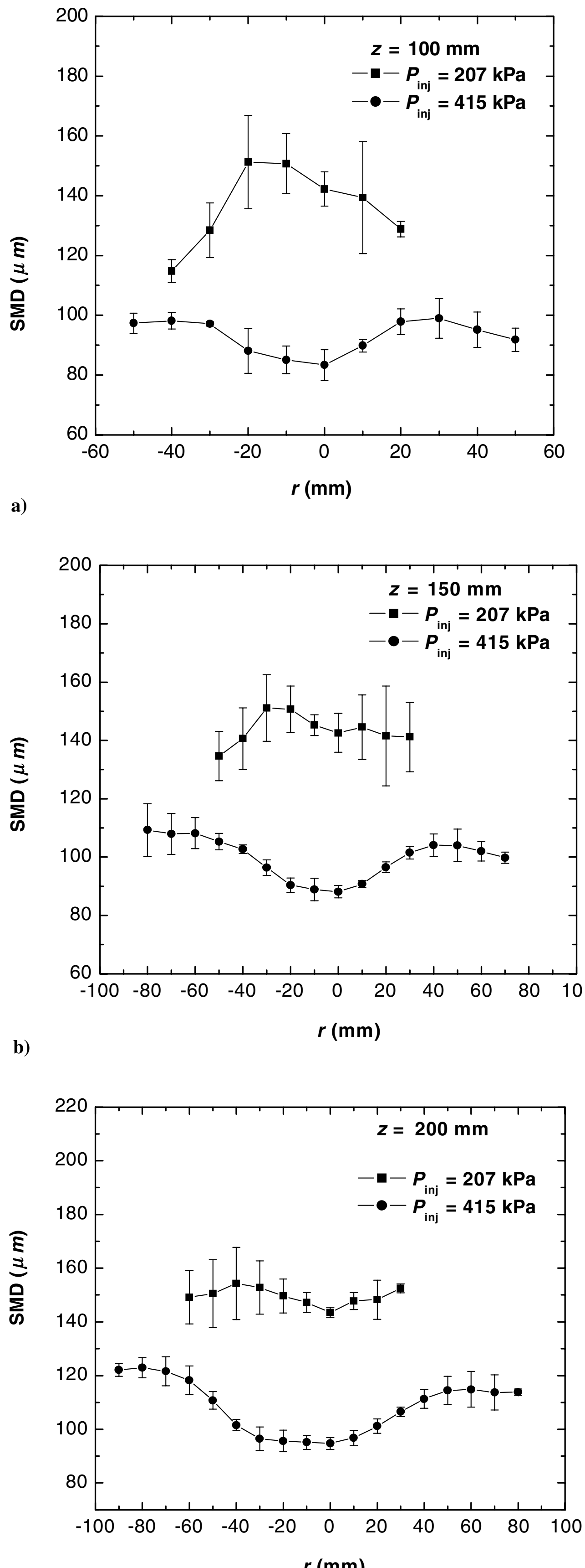


Fig. 9 Comparison between the radial distributions of SMD at a) $z = 100$ mm, b) $z = 150$ mm, and c) $z = 200$ mm.

coalescence and evaporation [14]. The results are also consistent with the observations of Santolaya et al. [6,8]. The spatial evolution of spray indicates a narrower drop-size spectrum with increasing radial distance (q changes from 2.10 at the center to 3.10 along the edge at a distance of $z = 150$ mm). A similar feature is observed in the axial direction though with reduced prominence.

The radial evolution of SMD is compared in Figs. 9a–9c for the two injection pressures. These two cases represent different regimes (or stages) of atomization (as described earlier). In the first case, the SMD distribution becomes more uniform with increasing distance from the nozzle exit, whereas in the second case, a reverse trend is observed. Another factor to be noticed is the good repeatability of SMD measurements at higher injection pressures. This could be due to the fact that the spray at lower injection pressure is more susceptible to perturbations, manifesting into higher levels of fluctuations. At higher pressures, on the other hand, a more steady spray was obtained resulting in good repeatability of drop-size data.

IV. Conclusions

In the present work, the performance of a pressure-swirl atomizer in the transition regime, from collapsed spray at low injection pressures to a developing hollow-cone spray, is investigated in terms of spray cone angle, patternation, drop size, drop-size distribution, and spectrum.

1) The initial divergence angle was found to be independent of the injection pressure at low ΔP_{inj} but increased monotonically with further increase in ΔP_{inj}.

2) Mass distribution of the spray further substantiated the transition in the flow regime.

3) The drop size along the spray axis was found to decrease with increasing ΔP_{inj}, the effect being more prominent at lower injection pressures.

4) The drop-size distribution followed different trends depending upon the flow regime (collapsed or hollow cone). The drop size increased with increasing axial distance, due largely to coalescence in the collapsed regime and to the combined effect of coalescence, evaporation, and aerodynamic forces at higher pressures.

5) The drop-size spectrum was found to get narrower with increasing axial and radial distance in the developing cone stage than the collapsed regime.

6) The spray was more unsteady at low pressures, with higher pressures producing a more stable and steady spray.

The work clearly illustrates the poor atomization quality in terms of drop sizes as well as drop size/mass distribution (collapsed flow regime) at low injection pressures. During throttling and under low thrust requirements, this could lead to a substantial increase in pollutant formation and poor efficiency. One way of alleviating the problem could be the use of aeration (using a small amount of air) within the atomizer. This is currently being explored by the authors.

References

[1] Lefebvre, A. H., *Atomization and Sprays*, Taylor and Francis, London, 1989.

[2] Bayel, L., and Orzechowski, Z., *Liquid Atomization*, Taylor and Francis, London, 1993.

[3] Bazarov, V., Yang, V., and Puri, P., "Dynamics of Liquid Rocket Injectors," *Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis, and Design*, Vol. 200, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2004, pp. 19–103.

[4] Chen, S. K., Lefebvre, A. H., and Rollbuhler, J., "Factors Influencing the Effective Spray Cone Angle of Pressure Swirl Atomizers," *Journal of Engineering for Gas Turbines and Power*, Vol. 114, Jan. 1992, pp. 97–103.

[5] Ramamurthi, K., and Tharakan, T. J., "Experimental Studies of Liquid Sheets Formed in Coaxial Swirl Injectors," *Journal of Propulsion and Power*, Vol. 11, No. 6, 1995, pp. 1103–1109.

[6] Santolaya, J. L., Aisa, L. A., Garcia, J. A., Garcia Palacin, J. I., and Calvo, E., "Drop Sizes and Mass Fluxes Development in a Pressure Swirl Hollow Cone Spray," *Proceedings of the 9th ICLASS 2003* [CD-ROM], 2003.

[7] Cohen, J. M., and Rosfjord, T. J., "Spray Patternation at High Pressure,"

Journal of Propulsion and Power, Vol. 7, No. 4, 1991, pp. 481–487.

[8] Santolaya, J. L., Aisa, L. A., Calvo, E., Garcia, J. A., and Cerecedo, L. M., "Experimental Study of Near-Field Flow Structure in Hollow Cone Pressure Swirl Atomizers," *Journal of Propulsion and Power*, Vol. 23, No. 2, 2007, pp. 382–389. doi:10.2514/1.20713

[9] Chin, J. S., Nickolaus, D., and Lefebvre, A. H., "Influence of Downstream Distance on the Spray Characteristics of Pressure-Swirl Atomizers," *Journal of Engineering for Gas Turbines and Power*, Vol. 108, Jan. 1986, pp. 219–224.

[10] Zhao, Y. H., Li, W. M., and Chin, J. S., "Experimental and Analytical Investigation on the Variation of Spray Characteristics Along Radial Distance Downstream of a Pressure Swirl Atomizer," *Journal of Engineering for Gas Turbines and Power*, Vol. 108, July 1986, pp. 473–478.

[11] Herpfer, D. C., and Jeng, S.-M., "Planar Measurements of Droplet Velocities and Sizes Within a Simplex Atomizer," *AIAA Journal*, Vol. 35, No. 1, 1997, pp. 127–132.

[12] Santolaya, J. L., Aisa, L. A., Garcia, J. A., Garcia Palacin, I., and Calvo, E., "Dynamic Characterization of a Pressure Swirl Hollow Cone Spray," *ILASS-Europe 2002* [CD-ROM], Sept. 2002.

[13] Dodge, L. G., and Biaglow, J. A., "Effect of Elevated Temperature and Pressure on Sprays From Simplex Swirl Atomizers," *Journal of Engineering for Gas Turbines and Power*, Vol. 108, Jan. 1986, pp. 209–215.

[14] Rizk, N. K., and Lefebvre, A. H., "Influence of Downstream Distance on Simplex Atomizer Spray Characteristics," American Society of Mechanical Engineers 84-WA/HT-25, 1984.

[15] Ping Chung, I., and Presser, C., "Fluid Property Effects on Sheet Disintegration of a Simplex Pressure-Swirl Atomizer," *Journal of Propulsion and Power*, Vol. 17, No. 1, 2001, pp. 212–216.

[16] Inamura, T., Tamura, H., and Sakamoto, H., "Characteristics of Liquid Film and Spray Injected from Swirl Coaxial Injector," *Journal of Propulsion and Power*, Vol. 19, No. 4, 2003, pp. 632–639.

[17] Kennedy, J. B., "High Weber Number SMD Correlations for Pressure Atomizers," *Journal of Engineering for Gas Turbines and Power*, Vol. 108, Jan. 1986, pp. 191–195.

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