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INVESTIGATION ON SPRAY BEHAVIOR IN THE TRANSITION REGIME OF A PRESSURE SWIRL ATOMIZER

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ABSTRACT 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 which in turn may cause an increase in pollutant emissions and thermal spikes. Also the solid and developing cone regimes are susceptible to flow instabilities. Flow regime in sprays from these atomizers varies depending upon the injection pressure· The transition regime from a collapsed to a developed 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. Investigations were also carried out in terms of spatial drop size distribution and patternation. Average drop-sizes were found to decrease from 150 to 100 µm for a two-fold increase in injection pressure drop with the transition from collapsed to developing cone regime. Drop-sizes (SMD) increased with increasing axial distance at both pressures which may be due to coalescence of drops. However, the spray farther downstream of the exit orifice was found to be more uniform in the collapsed regime in contrast to the hollow cone. 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.

Keywords: Atomization, Collapsed spray, Hollow-cone, Transition regime, SMD, Patternation

1. 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 distribution, cone angle and patternation (spatial distribution) determine to a great extent the fuel-air mixing in the combustor and hence pollutant formation, life and durability of the combustor and temperature distribution at the inlet of turbine in case 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. Development of sprays produced by simplex swirl atomizers has five stages depending upon the injection pressure [1,2]. These are illustrated in Figure 1.

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 the spray cone angle is an important characteristic of swirl atomizers. Chen et al [3] 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). Increase in length/diameter (l_o/d_o) ratio of the final discharge orifice leads to a reduction in spray cone angle and no optimum value could be found. The decrease in spray cone angle was attributed to the increasing frictional losses resulting from increase in l_o/d_o. However, in all the cases the Swirl number was kept constant. Ramamurthi & Tharakan [4] 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.

Several authors have reported the variation in spatial distribution of Sauter mean diameter (SMD) with injection pressure [3-9]**.** It has been found that SMD increases with radial distance indicating the presence of smaller drops at the centre and the larger ones at the edge of the spray, the prominence of the trend increasing with increasing axial distance. This is attributed to the entrainment of smaller drops by the air core. Also it was found that the SMD along the centerline decreases whereas along the edge it increases with increasing axial distance [10]. However, some recent studies [8-9] showed that the SMD increases along the centerline. These differences in the literature have not been explained satisfactorily.

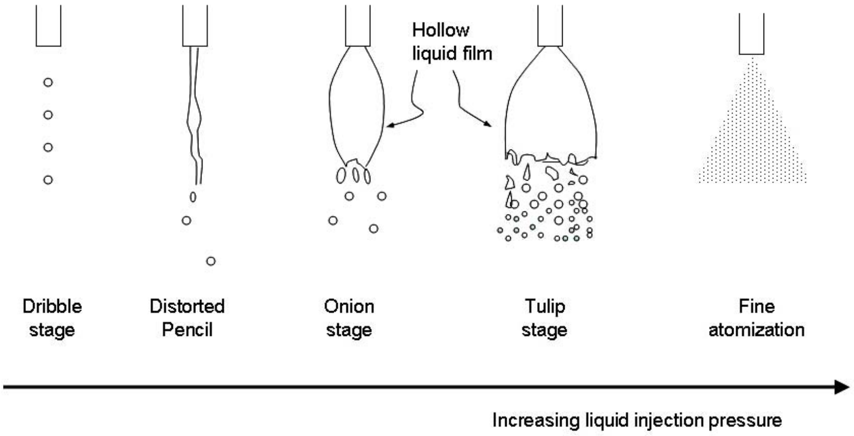

Fig. 1. Stages in spray development in a simplex atomizer with injection pressure

Another parameter of consequence in combustion applications with regard to combustion efficiency and pollutant formation is the mass distribution (spray patternation) achieved by the atomizers. Spray patternation studies are useful in the identification of spray non-uniformities and thus combustor non-idealities. Santolaya et al. [9] & Cohen & Rosfjord [11] studied the spray patternation resulting from pressure swirl atomizers and concluded that the regime of spray evolution dictates the mass distribution. Under low flow conditions the spray indicated a collapsed single, coarse jet with the mass flux being maximum at the centre. This trend changed at higher flow rates producing a pattern with the mass flux being minimum at the centre and showing a peak along the tangential direction with all conditions tested giving a symmetric spray.

This study examines and presents some preliminary results obtained on the effect of liquid injection pressure on spray cone angle, SMD and its spatial distribution and patternation of a helical groove simplex atomizer with a swirl number of 3.6 under low injection pressure conditions.

2. EXPERIMENTAL PROCEDURE

The Pressure swirl atomizer 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 was chosen for the atomizer studied. A helical insert with a swirl number of 3.6 was used in the present. The diameter of the helical insert (D_s) and Length (L_s) were both 5 mm.

All experiments were done with water as the test fluid. A schematic of the experimental set-up used is shown in Fig. 2. The set-up includes Air and water supply lines, Mass flow meter, pressure regulators, Bourdon pressure gage, Filters & Fine control valves. Water pressurized to 860 kPa (~125 psig) passed through a series of valves, flow meters before being discharged through the swirl atomizer. Axial and radial distributions of average drop sizes were obtained with the Malvern's Spraytec analyzer. The instrument uses a 5 mW laser beam at a wavelength of 670 nm, beam diameter of 5 mm, 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). It must be remembered that the instrument is based on line-of-sight measurement and does not make a point measurement. Figure 3 illustrates the measurement volume as sampled by the Malvern's analyzer. For ensuring accurate measurements, data with higher transmission levels of laser power (> 50%) only have been used. In most of the cases the sprays were dilute and hence higher transmission levels were achieved. Spray cone angle was measured with the aid of a 100 mW laser and a CCD camera (SONY DCR PC350E). A mechanical patternator was used to obtain the mass distribution of spray at an axial distance of 150 mm. The data presented is an average from atleast three set of experiments in all the cases.

3. RESULTS AND DISCUSSIONS

3.1 Discharge co-efficient

It has been demonstrated by several authors [12-14] that at low Reynolds number (≤ 2000) C_d decreases with increasing Reynolds number and at higher Reynolds number (> 2000), it is independent of the Reynolds number. Figure 4 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 ranging from 4000 – 10,000, consistent with the earlier observations. However, the actual value of discharge coefficient is lower than the theoretical value. This could be attributed to poor surface finish of the helical swirler and viscosity effects.

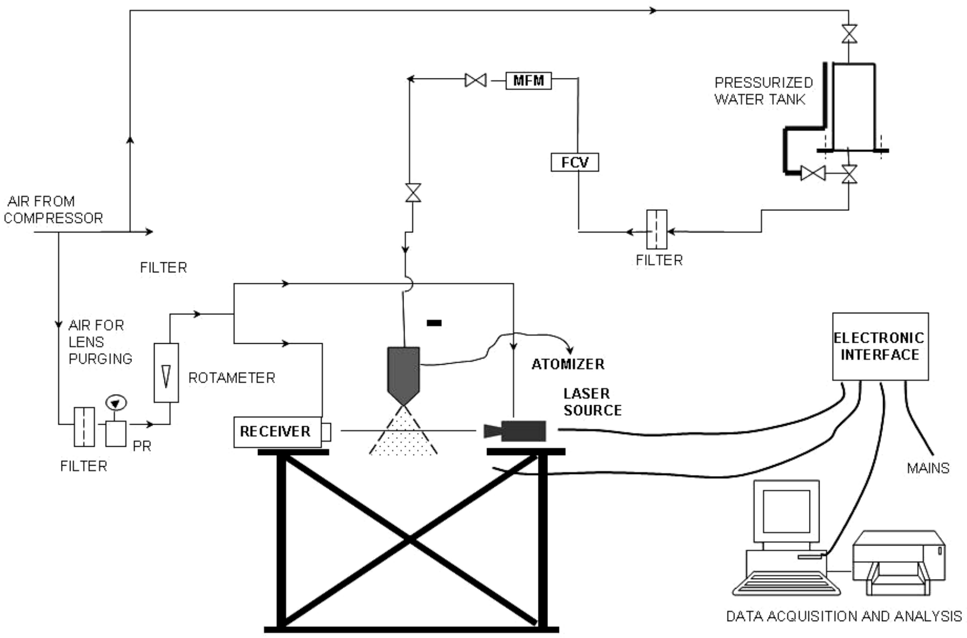

Fig. 2. Schematic of Experimental Setup

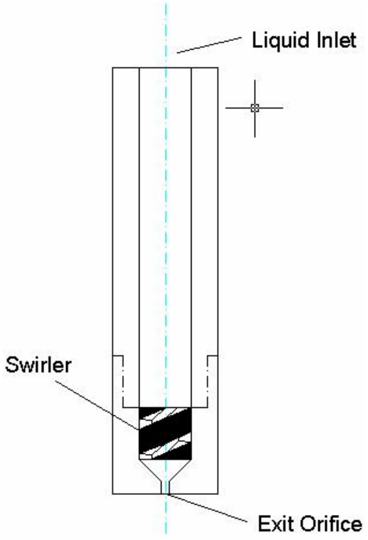

Fig. 3(a) Schematic of the swirl atomizer

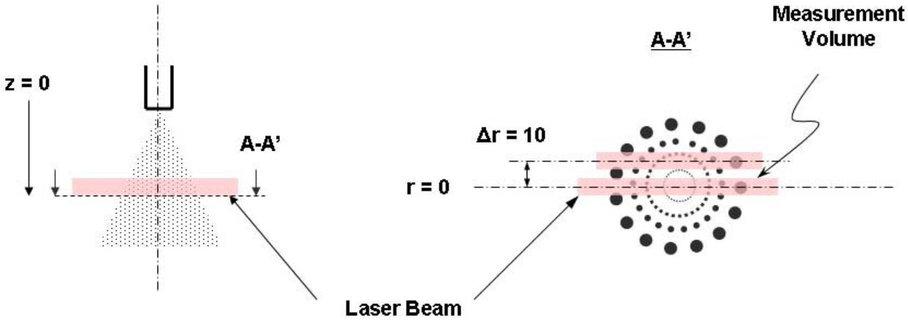

Fig. 3(b). Measurement volume for drop-size measurement

3.2 Effect of Injection pressure on cone angle

Figure 5 is a plot of the initial divergence angle 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 Laser sheet. The angle was measured using MATLAB's image processing toolbox. Each point is an average of atleast three time-averaged images. At low injection pressures it was found that the cone angle did not change appreciably. This regime is dominated by surface tension forces. As the applied pressure (centrifugal forces) is not sufficient enough to overcome the surface tension, the conical sheet collapses after emerging out 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. For the swirl number and exit orifice diameter investigated in this case the values were slightly higher in comparison to the results of Ramamurthi & Tharakan [4].

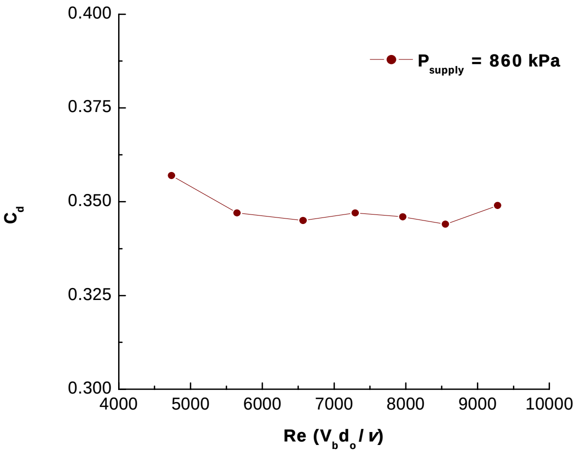

Fig. 4. Variation of discharge coefficient with Reynolds number

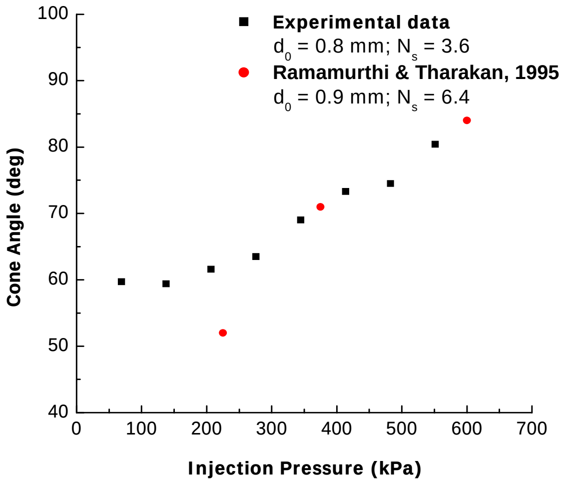

Fig. 5. Effect of Injection pressure on Spray cone angle

3.3 Drop-size distribution

Effect of Injection pressure on SMD. 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 the figure the drop size decreases rapidly with increasing pressure initially but the influence of injection pressure gradually decreases at higher ΔP_{inj} values as is evident from the later part of the graph. This is due to the fact that at low injection pressures the conical sheet collapses and produces large drops. With increasing pressure the liquid sheet diverges and the sheet break-up is controlled more by the surface waves due to increased aerodynamic drag resulting in finer atomization.

Spatial distribution of drop size The spatial evolution of the drop sizes were determined for two injection pressures of 207 kPa (~30 psi) and 415 kPa (~60 psi) and three axial distances (z = 100, 150 & 200 mm). As can be seen from figure 7, the drop-size distribution is slightly unsymmetric. This was observed in all cases studied in this work and can be attributed to the poor surface finish of the helical swirler. SMD increased with increasing axial distance and also the spatial distribution was more uniform further downstream of the exit orifice. This behavior is different from reported in literature [6-7, 9]**,** the main reason being that at the injection pressure used the liquid conical bulb formed just starts opening up and the spray thus would be characterized by a large degree of coalescence. This results in larger drops at the center. With increasing axial distance the droplets tend to spread producing a uniform spray. However this trend changes with increasing injection pressure as is evident from figure 8. 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 causes 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 radial distribution of SMD becomes flatter and SMD increases with increasing z mainly due to drop coalescence.

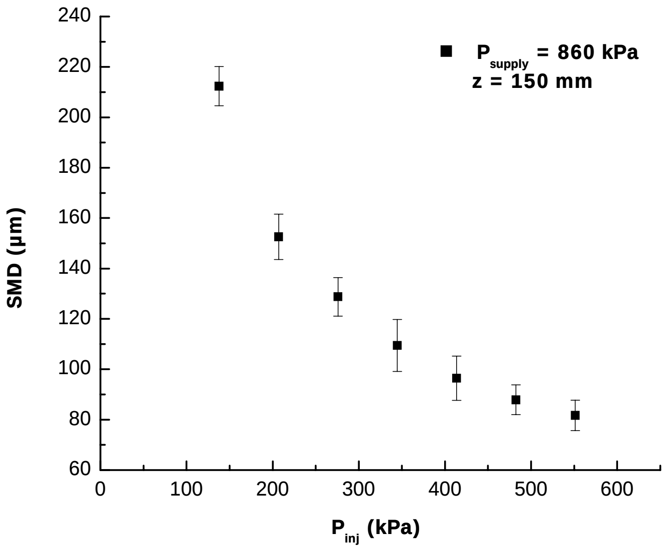

Fig. 6. Effect of Injection pressure on SMD

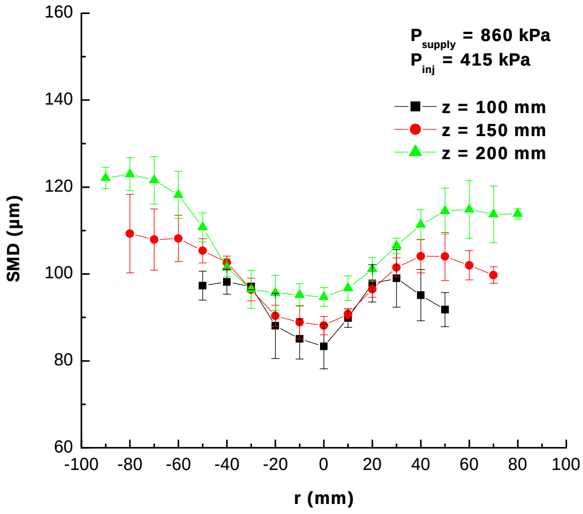

Fig. 8. Radial distribution of SMD for three axial locations (z = 100, 150, 200mm) downstream of atomizer (ΔP_{inj} = 415 kPa)

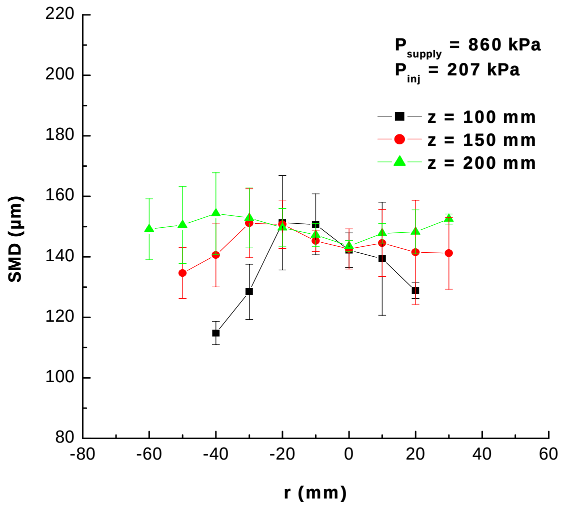

Fig. 7. Radial distribution of SMD for three axial locations (z = 100, 150, 200mm) downstream of atomizer (ΔP_{inj} = 207 kPa)

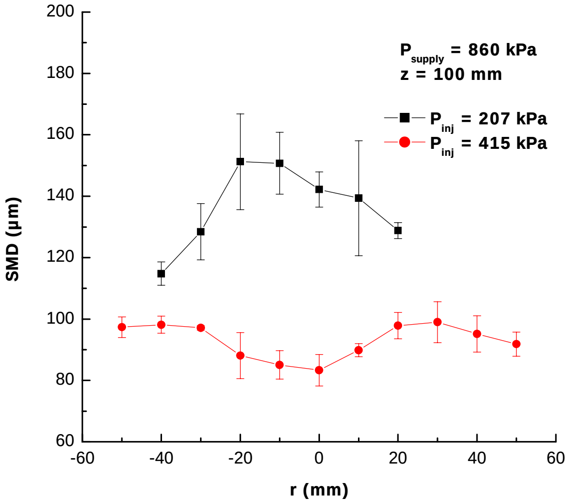

Fig. 9 (a) comparison b/w the radial distributions of SMD at z = 100 mm for ΔP_{inj} = 207 & 415 kPa

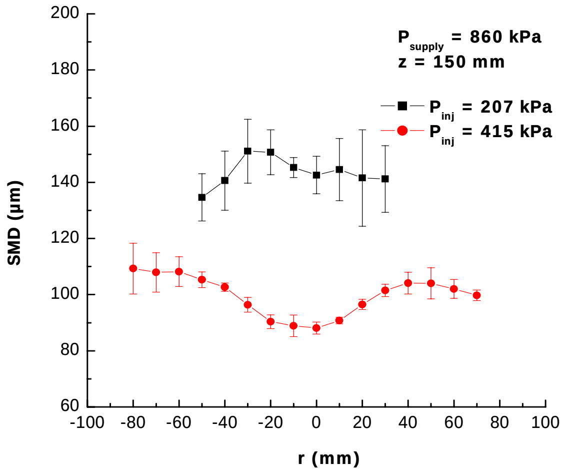

Fig. 9 (b) comparison b/w the radial distributions of SMD at z = 150 mm for $\Delta P_{inj} = 207$ & 415 kPa

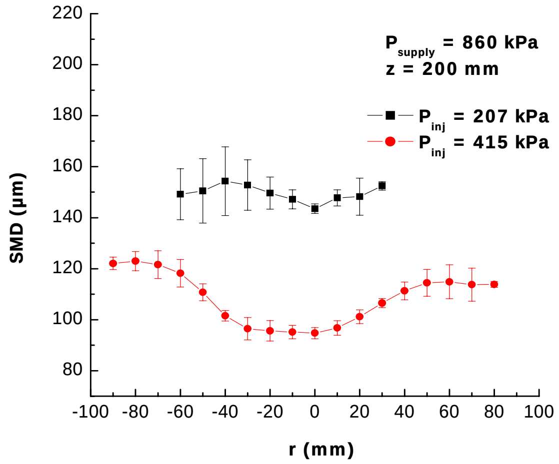

Fig. 9 (c) comparison b/w the radial distributions of SMD at z = 200 mm for $\Delta P_{inj} = 207$ & 415 kPa

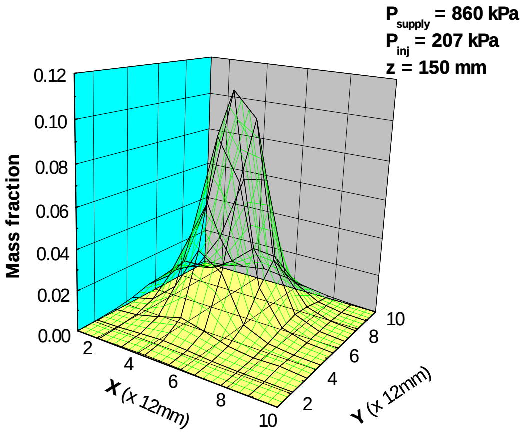

Fig. 10(a) Mass distribution at low injection pressures (collapsed spray)

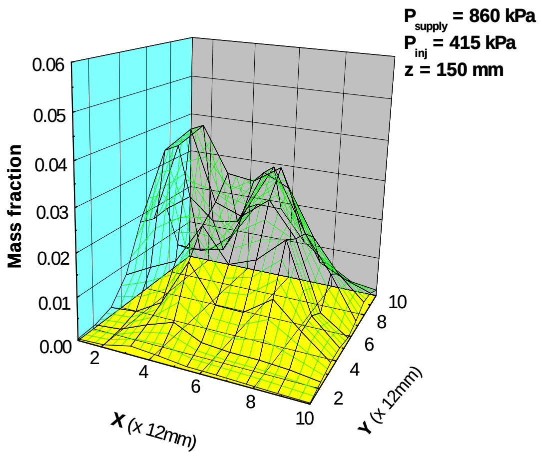

Fig. 10(b) Mass distribution at higher injection pressure (developing hollow cone)

The radial evolution of SMD is compared in Figs. 9(a)-(c) for the two injection pressures. These two cases represent different regimes (or stages) of atomization (as illustrated in fig. 1). In the first case the SMD distribution becomes more uniform with increasing z where as 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 as evident from the relative lengths of the error bars in the above figures.

To further substantiate the findings the liquid mass distribution was determined for these pressures at z = 150 mm and is shown in figure 10. A mechanical patternator was used (9×9 square cells, each having a dimension ~ 12 mm). The mass fraction in each cell was obtained by dividing the individual masses by the total liquid collected. As is evident from figure 10(a) at low injection pressures after a certain distance the collapse 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 centre than periphery as is evident from fig. 10(b). 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 by Cohen & Rosfjord [15].

4. 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, Drop-size, drop-size distribution and patternation. The drop size along the spray axis was found to decrease with increasing ΔP_{inj} , the effect being more prominent at lower injection pressures.

1. **The** spray cone angle was found to be independent of the injection pressure at low ΔP_{inj} but increased monotonically with further increase in ΔP_{inj}
2. The drop-size distribution followed different trends depending upon the flow regime (collapsed or hollow-cone).
3. Mass distribution of the spray clearly indicates the transition in the flow regime.

The work clearly illustrates the poor atomization quality in terms of drop-sizes as well as drop-size/mass distribution (collapsed flow regime). During throttling and under low thrust requirements, this could lead to a substantial increase in pollutant formation and thermal spikes. 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.

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