The influence of atomizer internal geometry on the drop size distribution of pressure-swirl atomized non-Newtonian liquids

Shyamal R. Pidaparthy and Paul E. Sojka

Maurice J. Zucrow Laboratories
School of Mechanical Engineering
400 Allison Rd.
Purdue University
West Lafayette, IN 47907-2014
Tel: 765-494-4665; Fax: 765-496-7534
Email: sojka@ecn.purdue.edu; shyamal@purdue.edu

Drop size distributions of sprays of non-Newtonian liquids produced using a pressure-swirl atomizer are the focus of this experimental investigation. Detergent slurries of 67 %(w/w) were sprayed using five different atomizer internal geometries. The internal geometry was varied by changing the exit orifice length-to-diameter ratio (l_O/d_O) and the number of swirl chamber inlet ports. These configurations included various combinations of sloped roof and flat roof swirl chambers with exit orifice l_O/d_O ratios of 0.85 and 1.7. Two different flat roof swirl chambers were used, one with a single inlet and another with two inlet ports. Drop size distributions were obtained over a range of supply pressures for each geometric configuration. The D_{32}, $D_{0.1}$ and $D_{0.9}$ data were used to check the influence of geometric variables on the drop size distribution. The relative span factor (RSF) for each configuration was also considered--a narrow drop size distribution was obtained for the flat roof swirl chamber as compared to the sloped roof swirl chamber. Narrowing of the drop size distribution was also noticed when the l_O/d_O ratio was doubled. Finally, an increase in D_{32} was observed with increasing l_O/d_O, an increase in the number of inlet ports, and upon switching from sloped roof to flat roof.

1. Introduction

Pressure-swirl atomizers produce sprays via the breakup of a thin film that is produced at the nozzle exit. They are used in applications having a wide range of pressures, flow rates, liquid properties and atomizer geometries.

The sprays produced by pressure-swirl atomizers have been studied for years. Their formation is known to be influenced by atomizer geometry, fluid physical properties, and operating conditions. Both experimental and computational investigations have been performed to consider the influence of such aspects. For example, Yule and Chinn [1] outline an inviscid treatment for pressure swirl atomizer internal flows. They presented results for the discharge coefficient, spray angle and velocity distributions obtained using computational models and compared their predictions to experimental data, and discussed the influence of the air core on the exit sheet and its subsequent breakup. Schmidt and Sojka [2] found that for air-assisted pressure-swirl atomizers the Sauter mean diameter decreases with an increase in supply pressure, and liquid mass flow rate, and that injecting air into the air core stabilizes the liquid film formed at the atomizer exit plane. In addition, Dorfner *et al.* [3] found that an increase in liquid viscosity leads to an increase in mean diameter and that a more narrow drop size distribution is obtained at low viscosities, when spraying Newtonian fluids. They also predicted a decrease in the number of droplets in the smaller size ranges for non-Newtonian fluids. Couto *et al.* [4] studied the aerodynamic instability and disintegration of viscous liquid flat sheets. Through theoretical analysis they derived a formula for predicting drop mean diameter (D_{32}), which included the effects of liquid flow (i.e., supply pressure) and atomizer geometric parameters (exit orifice diameter). They presented D_{32} results obtained for various spray cone angles and different supply pressures, and also discussed the scaling of mean diameters with increasing viscosity. Their viscosities and supply pressures were much lower than those used in the present investigation. Chen *et al.* [5] studied the influence of geometric parameters on pressure-swirl atomizer performance using water as the working fluid. They measured mean drop sizes and effective spray cone angles at various injection pressures, and checked the influence of l_0/d_0 ratio on drop size distributions. Chen *et al.* [6-7] also studied the influence of the l_0/d_0 and supply pressure on circumferential liquid distribution and effective spray cone angle. Their results were compared with those obtained in the present investigation using a non-Newtonian fluid. Cooper *et al*. [8] present experimental results obtained using LDA measurements for large scale pressure-swirl atomizers of various geometries. The geometric parameters varied include the number of inlet ports and the length of the swirl chamber.

While several studies on pressure-swirl atomizer produced sprays have been carried out, most considered Newtonian liquids and aimed to produce relatively small mean drop size sprays (D_{32} typically less than 100 μm). The present work is an extension of those studies to non-Newtonian fluids such as detergent slurries where large drops (D_{32} typically around 200 μm) are desired.

The few previous efforts that did treat non-Newtonian fluid sprays were concerned primarily with atomizer discharge coefficient and spray cone angle for fluids obeying power law rheology [9]. None of the published works were concerned with spray formation using slurries having high solids loading.

To help fill the gaps in our knowledge of pressure-swirl atomizer design we report the results of a study on how internal geometry influences the performance of pressure-swirl atomizer produced sprays, in particular on how it controls the drop size distribution for non-Newtonian fluids. That topic is addressed here by varying atomizer swirl chamber roof slope, the number of inlet ports, and the exit orifice length-to-diameter ratio. Detergent slurry was used as the working fluid because its behavior is predominantly non-Newtonian.

2. Experimental Apparatus

The baseline atomizer was a commercially available unit having a cylindrical swirl chamber body (1.105 cm diameter and 1.105 cm depth), a conical 45° contraction, and an 0.285 cm diameter exit orifice. Three types of bodies were used: a sloped top single inlet unit, a flat top single inlet unit, and a flat top double inlet unit with the total inlet area remaining constant in all cases. Two exit orifices were used: one had a l_0/d_0 ratio of 0.85 and the other had a value twice this. The variation in l_0/d_0 ratio was achieved by doubling the exit orifice length. A schematic of the atomizer is included in Fig. 1.

The working fluid was a proprietary mixture of 67 weight-% detergent powder and preheated (80 - 90°C) tap water. The slurry was prepared in a large drum fitted with two three-blade propellers fixed on a single pneumatically driven shaft. The slurry was then forced into the reservoir using a centrifugal pump and a disintegrator (mill). The purpose of passing the slurry through the disintegrator was to ensure that it had a homogenous composition before it was sprayed. It was supplied to the atomizer at a temperature near 70°C under high pressure (up to approximately 7 MPa). The inlet pressure upstream of the atomizer was read using a transducer.

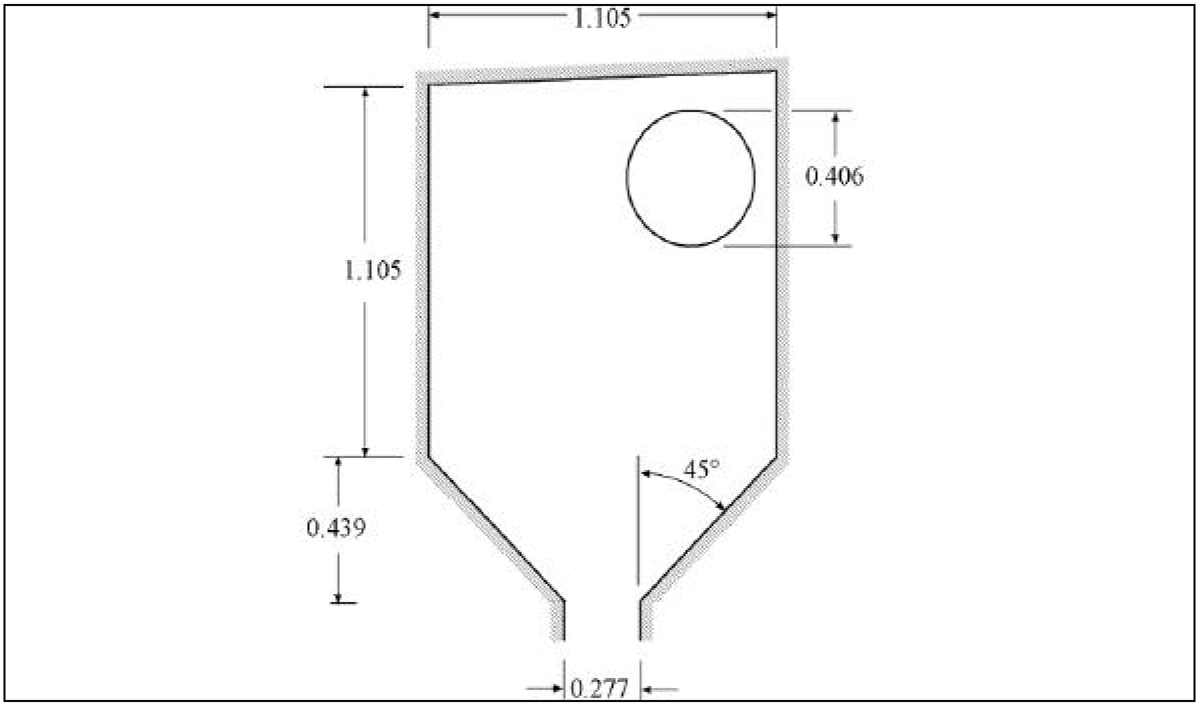

Fig. 1. Atomizer geometry. All dimensions are in cm.

Drop size distribution data were obtained using a Malvern 2600, fitted with a 300 mm focal length collecting lens. All data were obtained at 12 cm below the atomizer exit orifice and analyzed using the model independent mode of operation. Obscurations were less than 0.6 so corrections for multiple scattering were not needed.

3. Results and Discussion

The objective of this investigation was to determine how the drop size distribution width varied with changes in atomizer internal geometry. The effects of swirl chamber roof configuration, number of inlet ports, and exit orifice length-to-diameter ratio, l_0/d_0, were all considered. Five different geometric configurations were used: (i) sloped roof swirl chamber having a single inlet and $l_0/d_0 = 0.85$ (SSO); (ii) flat roof swirl chamber having a single inlet and $l_0/d_0 = 0.85$ (FSO); (iii) flat roof swirl chamber having a single inlet and $l_0/d_0 = 1.7$ (FSN); (iv) flat roof swirl chamber having two inlets and $l_0/d_0 = 0.85$ (FDO); (v) flat roof swirl chamber having two inlets and $l_0/d_0 = 1.7$(FDN).

Drop size data were obtained for all configurations using the Malvern particle size analyzer for sprays produced under supply pressures ranging from about 2 to approximately 6 MPa. The data were then plotted as $D_{0.1}$, $D_{0.9}$ and D_{32} (in µm) versus supply pressure (in MPA) for each geometric configuration. The relative span factor (RSF), defined as $(D_{0.9}-D_{0.1})/D_{0.5}$, was also plotted for each configuration and the same supply pressure range.

Figure 2 presents D_{32} versus injection pressure for the five configurations at supply pressures ranging from approximately 2 to 6 MPa. Note the marked increase in D_{32} when switching the swirl chamber from the sloped roof (SSO) to the flat roof (FDO, FSO, FDN, and FSN) designs. Also note that for the flat roof swirl chamber cases and a given orifice length-to-diameter ratio the D_{32} values decreased for double inlet port designs as compared to their single inlet counterparts (compare FDO with FSO and FDN with FSN). Finally, note that increasing l_0/d_0 while holding all the other geometric variables constant leads to an increase in D_{32} (compare

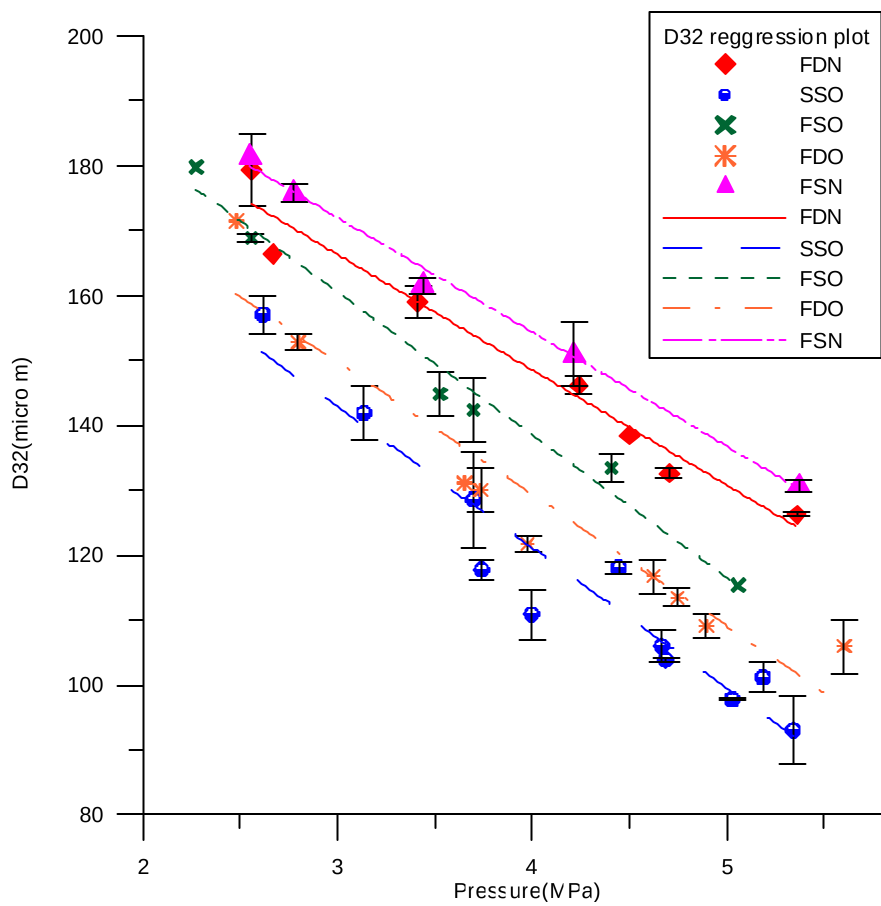

Fig. 2. Sauter mean diameter (D_{32}) versus atomizer supply pressure.

Fig. 3 shows $D_{0.1}$ values corresponding to the D_{32} values of Fig. 2; the same geometric and operating variables were changed. Note that exactly the same qualitative behavior is observed for $D_{0.1}$ data as was observed for D_{32} data.

Finally, Fig. 4 shows $D_{0.9}$ values corresponding to the $D_{0.1}$ and D_{32} values of Figs. 3 and 2. The qualitative behavior of $D_{0.9}$ is the same as that of D_{32} and $D_{0.1}$ for most configurations, with some discrepancies. The $D_{0.9}$ values for flat roof double inlet atomizer having an l_0/d_0 ratio of 0.85 are found to be less than those obtained the for sloped roof single inlet geometry case with an l_0/d_0 ratio of 0.85. Also the gradient of $D_{0.9}$ values for the FSN case is found to be less than that for the other geometries. One reason for this behavior may be the increased uncertainty in the results (statistical scatter in the FSN data for that set).

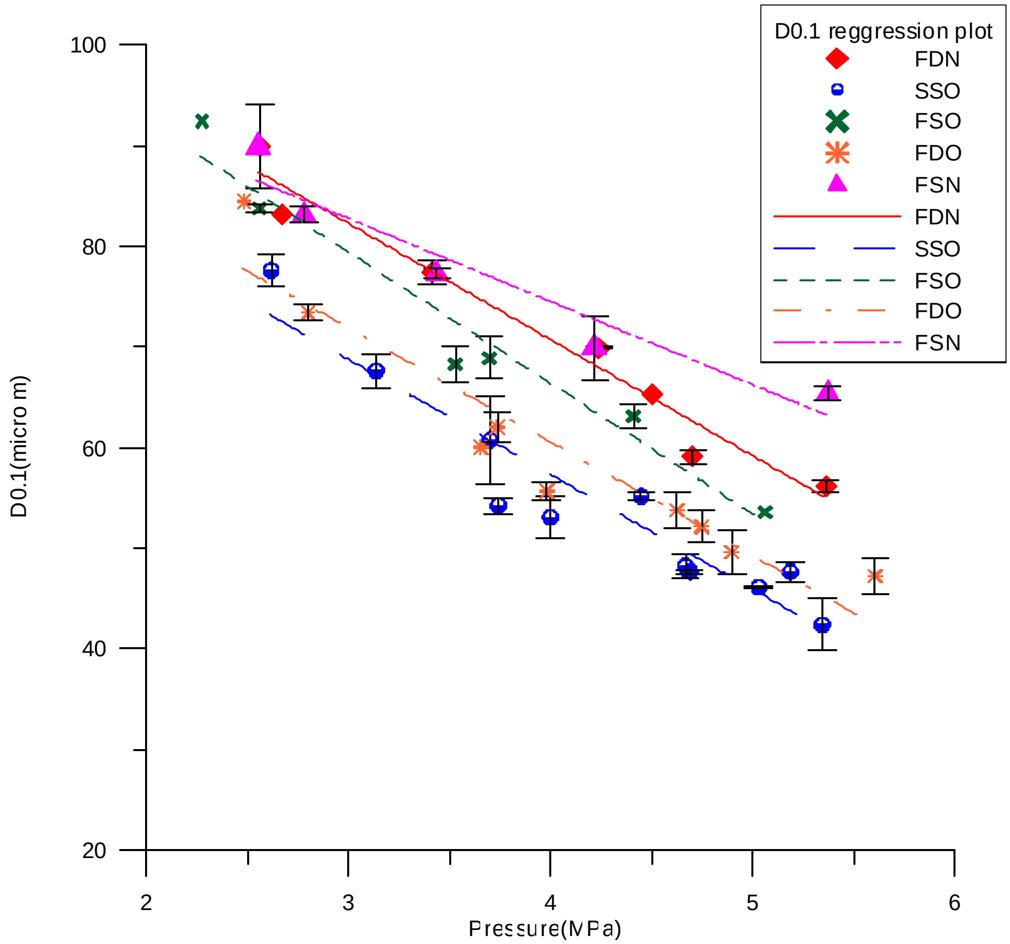

Fig. 3. $D_{0.1}$ versus atomizer supply pressure

Fig. 5 presents RSF for each geometric configuration, again plotted versus pressure. A key observation it is that the drop size distribution narrows (a decrease in RSF value) as the swirl chamber is switched from sloped roof to flat roof (compare SSO with FSO). A more narrow drops size distribution is also obtained when increasing l_0/d_0 from 0.85 to 1.7 (compare FSO with FSN and FDO with FDN). Also note that an increase in D_{32} is coupled to a decrease in RSF. Finally, for the flat roof swirl chamber with an l_0/d_0 of 0.85 the RSF values tended to increase when changing from the single inlet port to the double inlet port configuration (compare FSO with FDO and FSN with FDN).

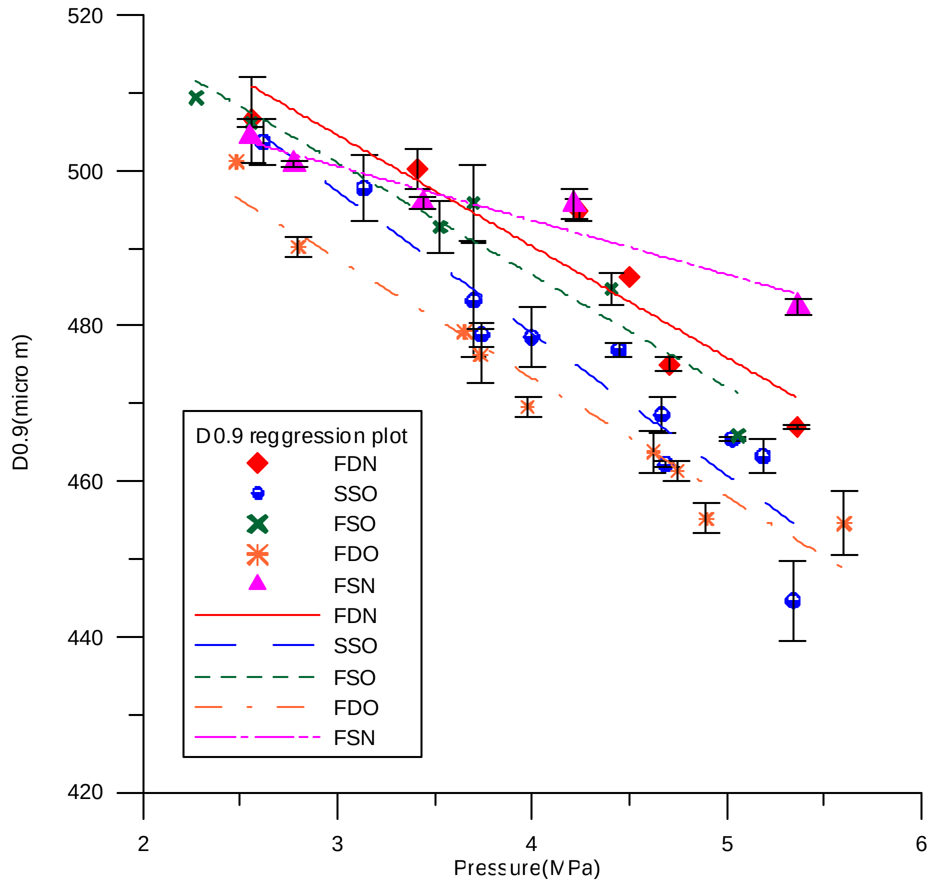

Fig. 4. $D_{0.9}$ versus atomizer supply pressure

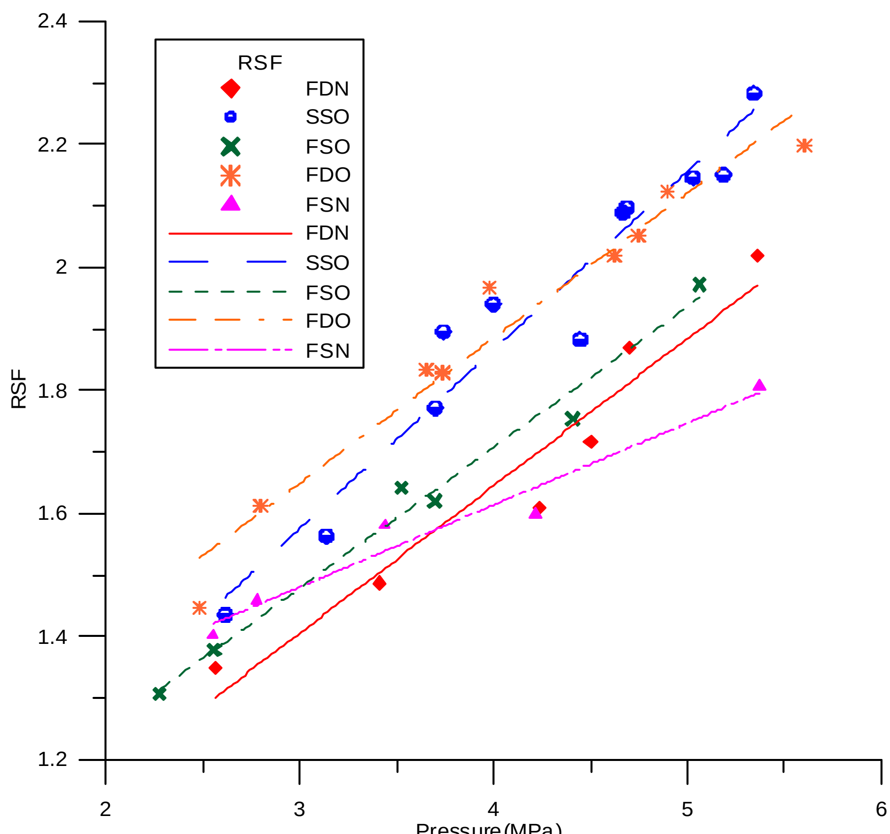

Fig. 5. Relative span factor (RSF) versus atomizer supply pressure.

A possible explanation for these behaviors is that the variation in the drop size distribution are the direct result of film thickness variations at the orifice exit, with these film thickness variations being due to different geometric configurations. In effect, we hypothesize that the exit film is asymmetric and that this asymmetry varies with the geometry of the swirl chamber, number of inlet ports and l_0/d_0 ratio. This hypothesis will be tested in the near future.

4. Summary and Conclusions

From results obtained in this study we conclude that:

- drop size distribution narrows with an increase in l_0/d_0 ratio for any given swirl chamber geometry
- flat roof swirl chambers give more narrower drop size distributions than sloped roof chambers. It is thought that an asymmetry in the liquid film at the atomizer exit orifice is introduced in the case of sloped roof chambers, which results in a broader drop size distribution
- single inlet ports give more narrower distributions than double inlet ports
- Sauter mean diameter increases upon switching from sloped roof to flat roof designs
- Sauter mean diameter also increases when increasing the l_0/d_0 ratio
- Sauter mean diameter decreases upon increasing the number of inlet ports

Finally, our results indicate that the flat roof single inlet swirl chamber with l_0/d_0 of 0.85, and the flat roof double inlet swirl chamber with l_0/d_0 1.7 configurations give the narrowest drop size distributions, with the former providing smaller mean drops sizes than the latter.

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