Effect of Viscosity, Surface Tension and Nozzle Size on Atomization in Two-Phase Nozzles

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Abstract

This study compares the mean drop size (*SMD*) produced from sprays of different viscosities, surface tensions and sizes of small-scale two-phase nozzles. A drop size correlation was established as a function of nozzle size, viscosity, surface tension and flow conditions. The small-scale nozzles are geometrically similar to commercial scale nozzles used in fluid coker (FC) nozzles. The experiments were performed using mixtures of air with various liquids - water, canola oil and a glycerine-water mixture. The liquid viscosities varied from 1mPa-s to 67mPa-s, and the surface tensions varied from 25mN/m to 70mN/m. All fluid properties were at 21°C. The nozzles used were a one-quarter and one third scale nozzle, which were geometrically similar to a full-size (or commercial) FC nozzle. The liquid flow rates varied from 95g/s to 196 g/s, and the *GLR* was fixed at 1%, similar to the commercial FC nozzles. . The mean drop size (*SMD*) within the spray was measured using a 2-D Phase Doppler Particle Analyzer (PDPA). Measurements were performed at an axial distance of 100 mm from the nozzle exit and across the spray within the range -50 mm to 50 mm in the horizontal plane. The results show that at the representative spray radius, the *SMD* increased with viscosity by a maximum of 40%. A decrease in surface tension increased the *SMD* by a maximum of 9%, which is not significant. Negligible difference in *SMD* with increase in nozzle size was observed across the spray for the glycerine-water spray. However, for the water spray, the *SMD* produced at representative spray radius increased by up to 32%. Finally, the correlation obtained using an area-averaged *SMD* across the spray showed a strong relationship with liquid viscosity and nozzle exit diameter, but a weak relationship with surface tension. The correlation gave a maximum deviation of about 17% from measured drop sizes. Results from this study provide a comprehensive means of improving the design of two-phase nozzles, which can be used in the FC.

Introduction

Processes involving the application of two-phase (gas-liquid) sprays can be found in aircraft, marine and industrial gas turbine combustors, incinerators, industrial furnaces and boilers, and internal combustion (IC) engines. These applications require breakup (or atomization) of the bulk liquid (i.e. fuel) with assistance from the gas, to produce small drops with high surface area-to-volume ratio in the combustion zone. This increases fluid mixing and evaporation resulting in more complete fuel combustion with reduction in soot and unburnt fuel emission.

Understanding atomization in two-phase nozzles is also important in fluid coking processes, which are used in the petroleum industry. In a fluid coker (FC), heavy oil or bitumen is upgraded to lighter petroleum by-products e.g. naptha, kerosene distillates and gas oils. Increased product yield depends on effective liquid atomization. Lefebvre [1] has stated that liquid atomization is affected by the liquid viscosity, surface tension, nozzle size and flow conditions through the nozzles. Large-scale studies to determine the effects of the above parameters are not feasible due to inaccessibility of measurement instruments resulting from high temperatures in the FC. Furthermore, it is not cost-effective to carry out drop size measurements using a full-scale nozzle at commercial operating conditions. Small-scale laboratory tests provide inexpensive and easily accessible alternatives to study the atomization behaviour of FC nozzles in situ. The correlation obtained from such studies provides guidelines in the nozzle development stage and reduces time required to design the next generation of commercial nozzles.

Drop size and distribution within a two-phase spray depend on liquid physical properties such as surface tension (γ), viscosity (μ_L) and density (ρ_L) and nozzle characteristic dimensions such as exit orifice diameter (D) [1]. Liquid atomization also depends on nozzle operating conditions such as gas-to-liquid mass ratio (*GLR*), operating pressure (P), and the ambient gas density. For given flow conditions it implies the characteristics of the liquid and nozzle are vital to the atomization performance of two-phase nozzles. Classical twin-fluid atomization studies by Elkotb et al. [2], and El Shanawany and Lefebvre [3], to mention but a few, have combined the above atomization parameters in dimensionless from to develop mean drop size correlations. The mean drop size referred to is the Sauter Mean Diameter and is denoted as *SMD* henceforth. These correlations distinctly highlight the effect of the associated fluid properties, flow conditions and nozzle geometry on *SMD*. Elkotb et al. [2] used air and kerosene as the gas and liquid phases, respectively. Their results showed that *SMD* is directly proportional to exit orifice diameter ($D^{0.4}$), absolute viscosity of the liquid ($\mu_L^{0.4}$) and surface tension ($\gamma^{0.2}$). El Shanawany

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and Lefebvre [3] used air as the gas phase, whereas the liquid phases were water, kerosene and specially prepared liquids of high viscosity. The spray data from these fluids were studied using three geometrically similar nozzles. Similar to the observations in [2], their results showed that *SMD* increases with a characteristic nozzle diameter, surface tension (γ) and absolute liquid viscosity (μ_L). In the studies mentioned above ([2], [8]), the general explanation of the results is that *SMD* increases with liquid viscosity because the latter inhibits the change in liquid geometry and delays atomization. The increase in *SMD* with surface tension is because surface tension acts to prevent the formation of a new liquid surface. Finally the increase in *SMD* with exit orifice diameter is mainly because the liquid jet issuing from the bigger nozzle produces thicker ligaments than in a smaller nozzle. The larger ligaments result in bigger drop sizes.

In more recent years Buckner and Sojka [5], Lund et al. [6] and Santangelo and Sojka [7] have studied the influence of fluid properties on atomization in effervescent atomizers. Sovani et al. [8] have presented a comprehensive literature on effervescent atomizers, which are two-phase (gas-liquid) atomizers in which the gas is injected as bubbles into the liquid through tiny pores very close to the nozzle inlet section. To study the effect of viscosity on *SMD*, Buckner and Sojka [5] used aqueous glycerine mixtures ($400 < \mu_L < 968$ mPa-s and γ = 67 mN/m,) as the liquid phase with $5\% < GLR < 35\%$. Liquid flow rates and injection pressures varied between 11 and 26 g/s, and 1,000 and 2,400 kPa, respectively. They [5] concluded that *SMD* was relatively independent of liquid viscosity. Lund et al. [6] studied the effects of viscosity on *SMD* using glycerine-water mixtures and Solvent Neutral Oil (SNO)-100 and Bennzoil Universal Calibration fluid in the range $20 < \mu_L < 80$ mPa-s and γ = 30 and 67 mN/m, within $1\% < GLR < 7\%$. Typical mixing chamber pressure and liquid flow rates varied between 239 and 515 kPa, and up to 1.5 g/s, respectively. The final observation from this work was that *SMD* increased slightly with viscosity based on drop size data obtained at the centreline of the spray. Santangelo and Sojka [7] used corn syrup, SNO-320 oil and corn/water mixtures to study the effects of viscosity on *SMD* for the fluid property range: $112 < \mu_L < 820$ mPa-s and γ = 29 and 74 mN/m. within $2\% < GLR < 10\%$. The liquid mass flow rate was maintained at 5 g/s, with liquid pressure between 102 and 1088 kPa They observed that *SMD* increased by about 115% at the lowest *GLR*, whereas at the highest *GLR*, the *SMD* increased by 75%. The conclusion from this study was that *SMD* increased significantly with liquid viscosity. From [5], [6], and [7], comparison of viscosity effects on *SMD* shows that it can be different or similar to those of twin-fluid atomizers ([2], [3]), where *SMD* increases with increase in liquid viscosity.

Lund et al. [6] and Santangelo and Sojka [7] also studied the effect of surface tension on *SMD* at the spray axis for effervescent atomizers discharging into ambient air. Lund et al. observed that *SMD* decreased significantly (between 14 and 23%) when surface tension increased from 30 to 67 mN/m. The decrease in *SMD* was found to increase with *GLR*. Santangelo and Sojka [6] observed a maximum of 12% decrease in *SMD* (occurred at *GLR* = 2%) when the surface tension was increased from 29 to 74 mN/m. The conclusion was *SMD* increased slightly with a decrease in surface tension. Santangelo and Sojka [6] mentioned that the effect of SMD on surface tension can attributed to differences in breakup mechanisms. The first mechanism is the formation of ligaments from which *SMD* is directly proportional to surface tension. The second mechanism is the further breakup of the ligaments formed into drops due to the action of aerodynamically induced shear and disturbances. The *SMD* produced from this mechanism is inversely proportional to the surface tension. Santangelo and Sojka [14] concluded that the first step of drop formation was more prevalent in their work since there was less dependence of *SMD* with surface tension. The observations in [6] and [7] regarding the effect of surface tension on *SMD* is opposite to those seen in twin-fluid atomizer studies ([2], [3]).

Lefebvre et al. [9], and Roesler and Lefebvre [10] have studied the effect of exit orifice diameter on *SMD* in effervescent atomizers discharging into ambient air. Lefebvre et al. [9] used water and nitrogen as the liquid and gas phases, respectively. Tests were performed for liquid injection pressures 34.5 kPa, 138 kPa and 345 kPa, liquid flow rates up to ~ 1.5 g/s, and gas-to-liquid ratios, $0.2\% \leq GLR \leq 22\%$. The nozzle exit orifice diameter was varied by inserting three different screw caps of diameters 0.8, 1.6 and 2.4 mm, and drop size measurements were taken at the spray centreline. They observed that for $GLR \leq 1\%$, the smallest nozzle exit diameter produced the smallest drop sizes, but drop sizes were about the same at higher *GLR*. Analysis of their data (for $GLR \leq 1\%$) showed that the maximum difference in *SMD* between the smallest and largest exit orifice diameters was about 90% at 138 kPa and *GLR* of 0.2%. Lefebvre et al. [9] concluded that except for the lowest *GLR*, where the smallest nozzle exit diameter yields the smallest drop sizes, the *SMD* was largely insensitive to the exit orifice diameter, when operating at the same *GLR*. In the study by Roesler and Lefebvre [10 air and water were used at $0.1\% \leq GLR \leq 5\%$. The liquid injection pressures were between 173 kPa and 690 kPa, and the nozzle exit orifice diameters were also replaceable, with diameters of 1.0, 1.5 and 2.0 mm. The conclusion from [10] was an increase in nozzle exit diameter had little effect on *SMD*. The insignificant dependence of SMD on nozzle exit orifice diameter observed in [9] and [10] was attributed to bubble explosion energy, which was sufficient to atomize the bulk liquid, just after the nozzle exit. This energy does not depend on the size of the nozzle exit, hence the variation of *SMD* does not vary with nozzle exit diameter. The final conclusions in [9] and [10] about the effect of nozzle exit orifice diameter is different in twin-

fluid atomizer studies, where the *SMD* increases with nozzle exit orifice diameter.

From the atomization studies mentioned above, it is evident that the different designs and classes of two-phase nozzles exhibit different atomization characteristics. As such, the atomization characteristics of FC nozzles using various liquid properties are likely to behave differently from the other classes of gas-liquid nozzles. To the best of the author's knowledge there has been no study on the effects of liquid properties and nozzle size on the atomization behaviour of FC nozzles. This is the main motivation of the current study.

Specific Objectives

This study is aimed towards comparing the differences in radial profiles of *SMD* in sprays produced from two-phase nozzles. All comparisons are made at an axial position near the nozzle exit i.e. ~ 100 mm. The flow conditions studied have a gas-to-liquid ratio by mass (*GLR*) of 1%, which is similar to those in the FC. The first and second objectives of this study are to quantify the variations in *SMD* for different liquid viscosities and surface tensions, respectively, in sprays produced from a typical one-quarter scale FC nozzle. The third objective is to quantify the variation of *SMD* for two nozzle exit orifice sizes. The final objective is to establish an empirical relationship for an area-averaged *SMD* in the spray as a function of nozzle size, liquid viscosity, surface tension and flow conditions. It is intended that the results from this small-scale nozzle study could be applied to the full-scale FC nozzles to better understand their operating performance and aid in the design of future of nozzles.

Methods and Apparatus

The smallest nozzle assembly used during the test had conduit length and internal diameter of 368 and 5.2 mm, respectively. The nozzle exit diameter (*D*) was 3.1 mm. This nozzle was geometrically one-quarter scale of a patented full-scale design (US Patent #: 6003789) employed in a fluidized bed coker for heavy oil upgrading. The second nozzle used in the test was manufactured to be geometrically-similar and was one-third scale of the full-scale nozzle used in commercial applications in the fluid coker. During the test, the nozzles were mounted on a traversing rig, which was capable of three-dimensional motion.

To study the effects of surface tension, viscosity or nozzle geometry on *SMD* the flow conditions were determined using the dynamic similarity procedure for two-phase (gas-liquid) flow stated by Chesters [11]. This procedure was applied experimentally by Geraets [12] to estimate the pressure drop along two-phase (gas-liquid) horizontal flows with an uncertainty of ±5%. A similar method was also applied by Hurlbert et al. [13] in predicting pressure drops along horizontal tubes. Note that the above technique is applicable to isothermal gas-liquid flows with without mass transfer. In this study *SMD* is the dependent variable (instead of pressure drop), and flow conditions are based at the nozzle exit orifice. For a nozzle discharging into ambient surroundings of given temperature and pressure, the following can suffice:

$$SMD = f(D, L, \boldsymbol{\rho_G}, \boldsymbol{\rho_L}, \boldsymbol{Q_G}, \boldsymbol{Q_L}, \boldsymbol{\mu_G}, \boldsymbol{\mu_L}, \gamma, g) \quad (1)$$

In the above equation, *L*, *g* and *Q* denote nozzle length, acceleration due to gravity and volume flow rate, respectively. Subscripts "*L*" and "*G*" denote liquid and gas properties, respectively. Applying the Buckingham PI principle, and re-writing the gas density using the ideal gas equation, one can obtain the following dimensionless groups:

$$\frac{SMD}{D} = f\left(\frac{L}{D}, \frac{\mu_G}{\mu_L}, \frac{m_G}{m_L}, \frac{P_G}{R_G T_{abs} \rho_L}, \frac{\rho_L Q_L}{\mu_L D}, \frac{Q_L^2}{gD^5}, \frac{\rho_L Q_L^2}{\gamma D^3}\right) \quad (2)$$

In Eqn. (2), P_G is the absolute pressure of the gas phase at the nozzle just before the exit, which is also the pressure of the liquid phase at the nozzle exit. The symbols R_G and T_{abs} denote the characteristic gas constant and absolute temperature of the gas, respectively. Note that the third term in the brackets is the *GLR*, whereas the last three terms are the *Reynolds number* (*Re*), *Froude number* (*Fr*), and *Weber num*ber (*We*) based on the liquid superficial conditions. Ideally, to study the effect of surface tension on *SMD*, all terms within the brackets in Eqn. (2) must be matched, but the *We* term must be significantly different. Similarly, to study liquid viscosity effects on *SMD*, all terms within the brackets in Eqn. (2) must be matched, but the *Re* term must be significantly different. In most cases matching the required terms may not be practically feasible [12]. Hence, similar to standard dimensionless analysis, restriction on some of the quantities may be relaxed depending on knowledge of the dominant forces (in this case forces affecting atomization) in the system as stated by Douglas et al. [14]. In this study, the nozzles used were geometrically similar hence the first condition within the brackets in Eqn. (2) is satisfied. Secondly, since for all fluids used $\mu_G << \mu_L$, the second condition is also satisfied. The *GLR* (third term in the brackets) is an important atomization parameter in gas-liquid flows (as stated earlier), hence it was kept constant (*GLR* = 1%) in our analysis. Note that *GLR* is fixed at 1% because it is the flow condition in the commercial FC. The mixture pressure, P_G is an important parameter in the gas-liquid atomization of a given liquid density. Therefore the gas-liquid density ratio (*DR*), i.e. the fourth term in the brackets in Eqn. (2) was also conserved in this study.

The test liquids were water, canola oil and aqueous glycerine mixture. Liquid density, ρ_L, was obtained by measuring the volume and mass of liquid samples, using a graduated cylinder and electronic mass balance, respectively. The liquid viscosity was measured using Cannon-Fenske Routine viscometers, whereas surface tension, γ, was measured using the pendant-drop technique in conjunction with the computer code

ADSA-P (Axisymmetric Drop Shape Analysis-Profile). From the image of the drop and known drop density, the software computes the liquid surface tension. The properties of the test liquid are presented in Table 1.

Table 1 – Properties of the test liquids at 21°C. Data with superscripts '∗' were adopted from White [14].

Liquid	Density, ρ_L (kg/m^3)	Surface tension, γ (mN/m)	Absolute viscosity, μ_L (mPa-s)
Water	998*	70 ± 2	1*
Glycerine solution	1200 ± 30	61 ± 4	67 ± 3
Canola Oil	905 ± 1	25 ± 3	66 ± 1

Figure 1 presents the schematic of the test set-up used in this study. Compressed dry air and filtered liquid were mixed at a tee junction and fed through the nozzle assembly. Air and liquid flow rates were measured with a thermal mass flow meter and variable area piston-type flowmeter, respectively. Static pressures close to the mixing point of the fluids and at the nozzle exit were measured using a pressure gauge and Validyne transducers, respectively. The room and liquid temperatures were measured using thermocouples. The temperatures near the mixing point of the fluids, at the nozzle exit and within the spray were also measured using thermocouples. The liquid flow rates varied from 95g/s to 195 g/s, and the *GLR* was fixed at 1%, similar

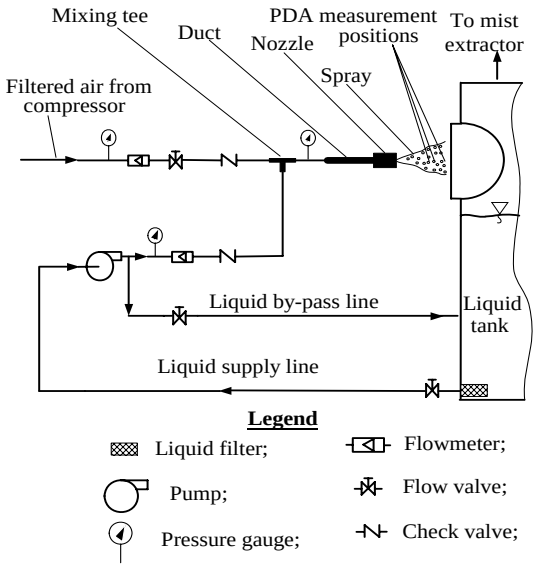

Figure 1 - Schematic of the experimental set-up.

to the commercial FC nozzles. The corresponding pressures at the fluid mixing section varied from 221 to 327 kPa, whereas the nozzle exit pressure varied from 508 to 990 kPa. Downstream of the gas and liquid mixing point the resulting spray was discharged into a liquid collector tank/reservoir, with the liquid re-circulated back to the nozzle. The mist produced during the spraying process was removed from the top of the liquid collector tank/reservoir using a mist extraction/ventilation system. The system consists of a blower and 2.2 kW (3 horsepower) motor assembly with the capacity to extract about 56.6 m^3/min (2000 CFM) of free air at a static pressure of 0.14 m (5.5") water column.

The *SMD* within the spray was measured using a 2-D Phase Doppler Particle Analyzer (PDPA). The focal lengths of the PDPA transmitter and receiver lenses were 400 and 310 mm, respectively. The PDPA unit consists of an Nd-YAG and He-Ne laser with wavelengths of 532 and 632.8 nm, respectively. During data collection, the PDPA was operated in forward-scatter and refraction mode, and the receiver was set to a scattering (or off-axis) angle (ϕ) of 30° for the air-water tests. Forward scattering is chosen in this study since from laser theory scattered light from particles in this mode is about 10^2 orders of magnitude higher compared to the backward scattering mode [16]. Furthermore, first order refraction is the most dominant scattering mode at $\phi = 30°$ for water drops in air [16]. However, a specific scattering angle was not stated for canola oil drops or drops from the glycerine-water mixture. For consistency and also based on the high confidence level in drop size measurement at this scattering angle [16], the scattering angle was also set to 30° for these tests. Each flow condition consisted of about 2 to 3 Runs. The typical sample size and sampling time during data collection were set to 12000 or 360 seconds, respectively. This sample size and time were sufficient to ensure data was collected for steady state conditions, and independent of velocity samples [16]. Profiles of *SMD* (and corresponding mean axial velocities) were obtained within radial (or horizontal) positions, y in the range $-50\text{mm} \le y \le 50\text{mm}$ about the spray axis, and axial positions, x = 100 mm downstream of the nozzle exit. Data at this axial distance was the main focus of study since this is the region of interest downstream of the full-scale (or commercial) nozzle in the fluid coker.

Results and Discussion

The *SMD* profiles are presented in subsequent Figures below. Comparisons of the profiles in each plot are made at the radius corresponding to the highest liquid volume per unit radius for each spray. These radii are termed representative radii in this study.

Effect of viscosity

The *SMD* profiles across the spray in the air-water (μ_L = 1 mPa-s) and glycerine-water systems (μ_L = 67 mPa-s) at an axial distance of 100 mm downstream of the nozzle exit are presented in Figure 2. The corresponding liquid mass flow rates for same *GLR* (=1%) and density ratio (~0.0032) were 95 g/s and 137 g/s for the water and glycerine solution systems, respectively. The representative radii are 20 mm for the 67 mPa-s liquid and 15 mm for the 1 mPa-s liquid.

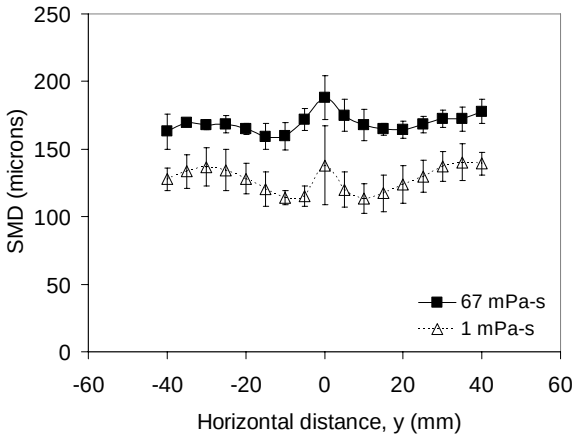

Figure 2: Profiles of *SMD* in two sprays with different liquid viscosities.

Comparing the *SMD* data at the representative radii for both systems the glycerine solution produces an *SMD* about 40% greater than that of the water system. A 5% test of significance suggests that this difference in *SMD* is significant. The presence of the large drops in the 67 mPa-s compared to the 1 mPa-s can be attributed to the inhibition of the change in liquid geometry and delay in atomization due to the higher liquid viscosity as suggested in atomization literature [1]. This viscosity effect on *SMD* is similar to observations in twin-fluid atomization studies ([2], [3]) and in the effervescent atomizer study of Santangelo and Sojka [6].

Effect of surface tension

Figure 3 shows the *SMD* profiles for two sprays with different surface tension tensions. The liquid mass flow rates at 1% *GLR* and a density ratio of ~0.0032, were 95 g/s and 137 g/s for the canola oil and glycerine solution systems, respectively. The representative radius for the canola and aqueous glycerine mixture systems occur at y = 15 mm and 20 mm, respectively. The corresponding *SMD* is about 165μm and 180μm for the glycerine solution and canola system, respectively. Therefore the lower surface tension liquid (canola) produces 9% higher *SMD* than the glycerine solution spray. A 5% statistical test of significance shows that this difference in *SMD* at this axial location is not significant. This slightly inverse relationship between *SMD* and surface tension was observed by Santangelo and Sojka [6], which corresponds to a liquid breakup mechanism where the effect of surface tension is not very distinctive in liquid atomization. The observed variation of *SMD* with surface tension is different in twin-fluid atomizers, where *SMD* increases with surface tension.

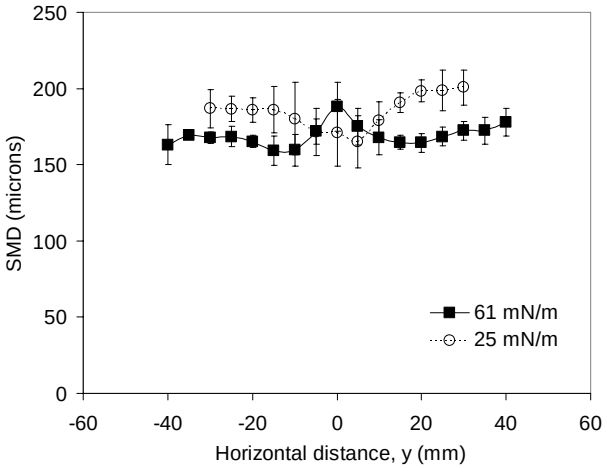

Figure 3: Profiles of *SMD* in two sprays with different surface tensions.

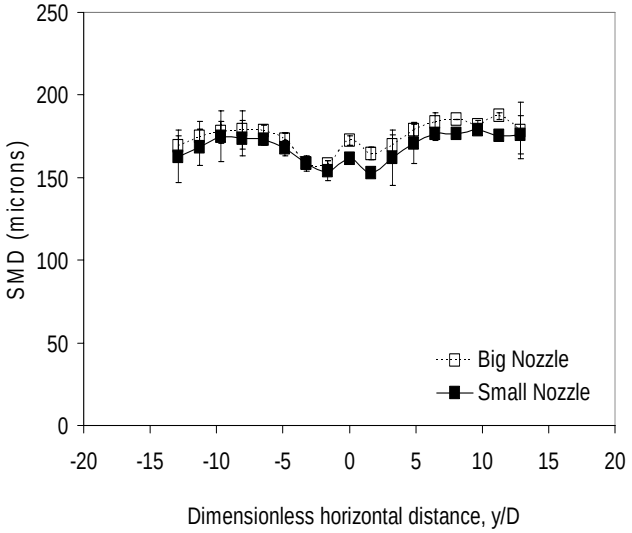

Figure 4: Profiles of *SMD* for the two nozzle sizes studied using the air-aqueous glycerine mixture system.

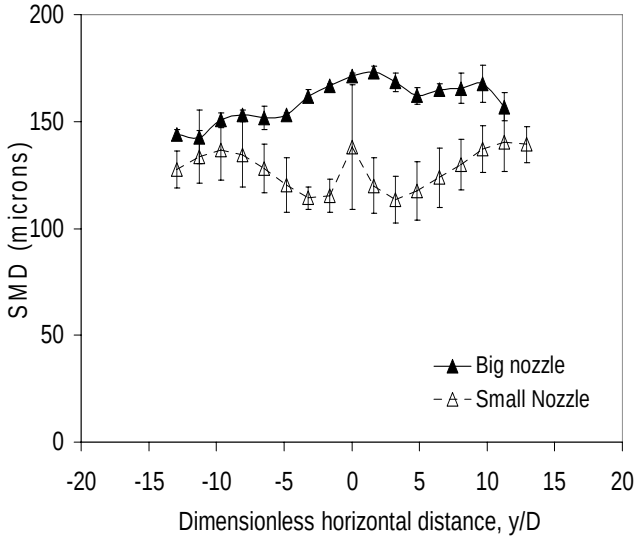

Figure 5: Profiles of *SMD* for the two nozzle sizes studied using the air-water system.

Effect of Nozzle size geometry

Figure 4 presents the *SMD* profiles within the sprays produced by the two nozzle sizes using air and the aqueous glycerine solution. The liquid mass flow rates at 1% *GLR* and density ratio of 0.0022 were 95 g/s and 196 g/s for the small (D = 3.1 mm) and big (D = 4.1 mm) nozzles, respectively. The representative radii are 15 and 20 mm for the small and big nozzles, respectively. The Figure shows that there is no significant difference between the *SMD*s from both nozzles. A similar test was also performed using air and water. In that study, the liquid mass flow rates at 1% *GLR* and a density ratio of 0.0034 were 95 g/s and 190 g/s for the small (D = 3.1 mm) and big (D = 4.1 mm) nozzles, respectively. The resulting *SMD* profiles are shown in Figure 5. In this case, the representative radii for the small and big nozzles were 25 and 33 mm, respectively. The corresponding *SMD*s were 120μm and 158μm, for the small and big nozzle, respectively. This gives an increase of 32%, and is statistically significant based on a 5% test of significance level. The general result from this section showed that an increase in nozzle size geometry may increase the *SMD* produced in the respective sprays. The observed increase in *SMD* with nozzle size in these tests is similar to studies in twin-fluid atomizers [2, 3]. However, the insignificant change in *SMD* observed in the tests using the aqueous glycerine mixtures is also a similar trend in effervescent atomization studies [8, 9].

Correlation for SMD

The final objective of this study was to establish a correlation for the *SMD* in terms of nozzle operating conditions and fluid properties. The *SMD* used was averaged over an area of the spray swept by the *SMD* profiles within the positions $y = \pm$ 40 mm about the centre of the spray for both nozzles. This region was chosen because it contained most of the representative spray radii and liquid volume flux across the spray. The area averaged *SMD* is referred here as global *SMD* (or SMD_{gb}). The correlation for SMD_{gb} was obtained using some of the variable dimensionless parameters in Eqn. (2) and regression analysis. The final form using all experimental data is given as:

$$\frac{SMD_{gb}}{D} = 1641^{*}(GLR)^{-0.55}(DR)^{1.20}(\mathrm{Re}_L)^{-0.15}(Fr_L)^{-0.48}(We_L)^{-0.06} \quad (3)$$

The correlation in Eqn. (3) shows that the SMD_{gb} depends weakly on the We_L, and is negatively proportional to the Re_L and Fr_L. However, it increases with the density ratio (DR) at the nozzle exit. From twin-fluid *SMD* correlations by Elkotb et al. [2], and El-Shanawany et al. [3], the variations of the independent parameters in Eqn. (3) are: $GLR^{-0.29 \text{ to } -1.0}$, $DR^{0.1 \text{ to } 0.26}$, $Re_L^{-0.39 \text{ to } -0.5}$, and $We_L^{-0.18}$. Except for the exponent of DR in Eqn. (3), which is greater than unity, the exponents in Eqn. (3) are quite comparable to the *SMD* correlation in twin-fluid systems. The accuracy of Eqn. (3) was tested using SMD_{gb} measurements from four other test conditions. The results are presented in Figure 6. The open squares denoted 'correlation-fit data' are the data used to obtain the correlation in Eqn. (3). The Figure shows that the maximum deviation between estimated and actual SMD_{gb} data is about 17%.

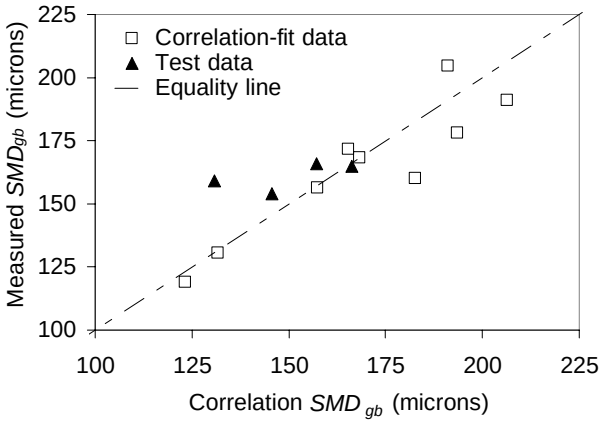

Figure 6: Comparison of correlation and measured SMD_{gb} for different nozzle sizes and flow conditions.

Conclusions

The objectives of this study were to quantify the variation of *SMD* with viscosity, surface tension and nozzle size in sprays produced from small-scale two-phase nozzles used in fluid cokers (FC). The final objective was to establish a correlation for *SMD* in terms of liquid properties, nozzle exit size and flow conditions. Different liquids with viscosities (1 and 67 mPa-s), surface tensions (25 mN/m and 61 mN/m) and nozzle sizes (linear scale of 1.3) were used in this study and the *GLR* was maintained at 1%. The advantage of this small-scale study is to provide a cost-effective means of studying atomization in FC nozzles. This in turn will aid in the design and development of next generation of FC nozzles.

The results show that at the representative spray radii, the maximum increase in *SMD* due to the liquid viscosity was 40%. This difference was determined to be significant, which suggests that liquid viscosity inhibits the complete atomization of the bulk liquid or already formed drops. A decrease in surface tension increases the *SMD* by 9%. This difference was found to be insignificant for this measurement region. Depending on the type of liquid used, an increase in nozzle size may increase the *SMD* produced at representative spray radius by up to 32% for similar flow conditions. Finally, the area-averaged (or global) *SMD* correlation derived from experimental data gave a 17% maximum deviation from the measured diameters.

The atomization results observed in this study are similar to, and also different from observations in twin-fluid and effervescent atomizer literature. This suggests that nozzle design is an important parameter in the atomization characteristics of two-phase nozzles. Therefore, atomization studies of new or different two-phase nozzle designs are required to understand their performance in the respective fields of applications.

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