Springer

Journal of Mechanical Science and Technology

Journal of Mechanical Science and Technology 22 (2008) 1633~1639

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0420-y

Geometrical effects on spray characteristics of air-pressurized swirl flows

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(Manuscript Received December 14, 2007; Revised April 7, 2008; Accepted April 21, 2008)

Abstract

In an effort to obtain the significant features associated with the ALR and length/diameter ratio of the final discharge orifice in swirling flows, experimental observations using a 3-D PDPA system were carried out. Profiles of SMD distributions depending on l_o/d_o, correlation between SMD and turbulence intensities in terms of l_o/d_o and correlations between droplet size and turbulence components were quantitatively analyzed. As discussed in a previous literature, an axisymmetric swirl angle of 30^o was selected for this investigation because of its strong turbulence levels in the flowfield and finer droplet disintegrations. Three ALRs of 0.093, 0.106, and 0.122 as well as the length/diameter ratio of 0.15, 0.45, and 0.60 were chosen as parameters. Due to the complex interactions in swirling flows under these variables, this experimental observation will be of fundamental importance to the understanding of geometrical effects on spray trajectory. From the observations, it is indicated that increasing the ALR causes the spray development to be more dependent on number density and volume flux. The results indicated that the SMD decreases discernibly with smaller l_o/d_o, substantiating the fact that turbulence intensities are inversely proportional to the SMD. But, l_o/d_o is quite proportional to the SMD.

Keywords: l_o/d_o (length-to-diameter ratio of the final discharge orifice); ALR (Air-to-Liquid Mass Ratio); PDPA (Phase Doppler Particle Analyzer); SMD (Sauter Mean Diameter); Volume flux; Number density

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1. Introduction

Pressurized swirl atomizers are comprehensively applied for injecting liquids into a wide range of internal combustors, gas turbines, and aircraft. Applying the best suitable swirl atomizers into the combustors provides better mixing enhancement, improves combustion efficiency, and reduces the pollution problem. Therefore, understanding the disintegration mechanism from atomizers and finding the optimal conditions is of fundamental significance to atomizer designers. To have a sharp understanding of the various requirements associated with mean velocity distribution, turbulence intensity development, SMD levels, effects of geometry, number density variation, and volume flux concentration are the essential prerequisites. Disintegration mechanisms from pneumatic swirl atomizers have been investigated extensively for the past decades by researchers (Chen, et al., Lee, and Chehroudi, B et al, and Ramamurthi, et al.) [1, 2, 3]. In spite of the extensive experimental observation regarding this consideration, the fundamental observations on the effects of geometry are still being investigated. As pointed out by Li, X and Tankin, R. S. [4], the strong turbulent swirling components are of equal importance to improve the jet mixing process, facilitating the combustion efficiency.

It is a widely recognized fact that breaking up the liquid issuing from a pneumatic atomizer into multitudinous small droplets is to increase the liquid surface area for improving disintegration. In other words, atomization in two-phase flows is most effectively achieved by generating a high relative velocity between the liquid jet and the surrounding air, resulting from higher momentum by the mutual interactions between working fluids (Feyedelem, et al, and Schefer, et al.) [5, 6]. There are a number of studies closely

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related to the present investigation (Moses, et al.) [7]. Much of what is known about important parameters affecting the mixing process has been obtained from experiments with air-to-liquid mass flow ratio (ALR) and geometric configuration of the nozzle.. A progressive understanding of the disintegration process has been achieved in experimental approaches of the swirling turbulent velocity, and improved results were obtained (Ramamurthi, and Tharakan, , Mansour, et al., [8, 9]. With the development of laser diagnostics, many experimental investigations on turbulent mixing enhancement have been performed (Hardalupas, and Whitelaw et al.,) [10]. Their experimental observations were mainly focused on the3-D mean velocities, 3-D RMS velocity fluctuations, liquid flux, and SMD, concluding that the turbulence close to the nozzle exit may influence the droplet dispersion and, thus, the rate of spread of the spray, which is determined by the initial droplet trajectories after the breakup of the liquid jet and the droplet centrifugal effect due to air swirl. In an attempt to understand the disintegration mechanism, which is affected by swirl flows, researchers (Lee et al. and Elkotp et al.,) [11, 12, 13, 14] measured mean and fluctuating velocities. They found that the droplet diameter is progressively reduced as the ALR is increased. Kennedy [15] reviewed these studies and pointed out that the SMD changed linearly with the surface tension while the influence of the viscosity was minimized. To study the flow patterns at the spray boundary region, Lee et. al. [11, 12] made phase Doppler particle analyzer (PDPA) measurements of the fluctuating quantities, and the results showed that smaller droplets are inwardly entrained from the spray boundary.

The experimental investigation described in this paper concentrates on geometrical effects for spray characteristics issuing from air-pressurized swirl flows.

2. Experimental apparatus

The nozzle configuration used to establish counterswirling mixing of an axisymmetric jet is schematically shown in Fig. 1. The body of a prototype nozzle for generating a counter-flowing spray was specifically manufactured for this experiment.

These nozzles have the same discharge orifice diameter d_o of 2 mm, swirl chamber diameter D_s of 9 mm, but the length-to-diameter ratio of the discharge orifice is different for the experiment, with the actual values being 0.15, 0.45, and 0.60. The working fluids were flowed through the tangential ports, which results in an angular velocity between two fluids, interacting together in the mixing chamber and injected into the quiescent ambient air at room temperature.

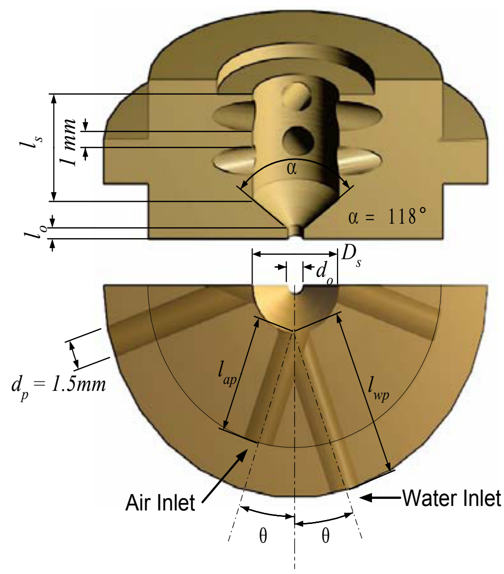

Fig. 1. Specification of nozzle used for the experiment.

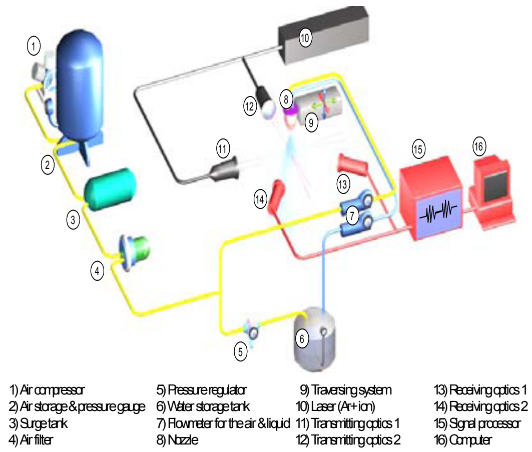

Fig. 2. Experimental setup and diagnostics.

The apparatus used to measure spray characteristics is shown schematically in Fig. 2. Continuous and steady flowing water and the pulsation-free air are supplied to the mixing chamber from the pressurized storage tank. Working fluids were properly filtered and regulated. A number of valves, pressure gauges, and flow meters are set up to control the flow rates. Experiments were conducted for the liquid flow rate being kept constant at 7.95 g/s and the air pressures were gradually increased from 20 kPa to 200 kPa, and ALR could be varied from 0.054 to 0.132. A phase Doppler particle anemometer was installed to measure the droplet's behavior of the spray. It provides information on individual particle size between 1 μm and 250 μm passing through the measurement volume in this investigation. The focal lengths of the transmitting and receiving optics were 400 mm and 500 mm, respectively. The photo-multiplier detector voltage of 1400 V was optimized to provide the greatest sensitivity, and 45° of scattering was made in the forward direction. Also, a Bragg cell was used to shift the frequency of one beam by 40 MHz to provide directional sensitivity. Data acceptance rate in this experiment was too low for distances less than 20 mm from the nozzle exit. Reasons for the low S/N ratio were usually attributed to the presence of non-spherical particles in the PDPA probe volume. Because the PDPA works on the principle of light scattering by spherical particles, signals from non-spherical particles will be rejected by the instrument. Data acceptance rate varied from 60% to 98% depending on the experimental conditions and the location of the probe volume in relation to the spray geometry. Radial profiles of a geometric sequence space at each measurement locations were obtained at six axial positions downstream from the nozzle exit, respectively. The coordinate Z corresponds to the downstream direction at the nozzle exit and y signifies radial outward direction. The measurement volume can be positioned easily at various stations without moving the diagnostic systems in three orthogonal directions by using a computer-controlled traversing system that permits positioning to within 0.02 mm. The droplet quantities were calculated by collecting 10,000 sample data at each point. The sampling time depends on the local number density of drops, and the 10 sec. was set as the upper limit to record data. Precautions for the accurate measurement were taken to avoid possible sources of error during the experiments such as mistracking the particles, nozzle vibrations, and the reading of the flow meters, etc. Also, the mists of small droplets were discharged to an exhaust system to prevent splashing. To establish the repeatability of the data received, each profile was measured at least twice at different times.

3. Results and discussion

Fig. 3 illustrates the comparisons of droplet diameter of SMD to establish the effects of l_o/d_o as a function of radial distance. These data were obtained at fixed axial station of Z/d_o=60.

It shows that the droplet mean size is reduced remarkably by the decrease of final discharge orifice length at this location, indicating higher dependence of SMD variation in terms of l_o/d_o. Thus, the reduction in SMD with decrease in discharge orifice length may be attributed directly to the shorter breakup regions of the spray that accompany higher turbulence intensity. Accordingly, this result implies that the final discharge orifice length on turbulent disintegration is apparently one of the influential factors in designing the optimal nozzle. Especially, for the lower cases of l_o/d_o (i.e., 0.15 and 0.45) the levels of SMD variation attain the gradual increase from the centerline to the spray peripheries. But, a higher l_o/d_o it shows a different trend, getting an abrupt change in SMD and largest droplet diameters. This difference is attributed to the centrifugal forces depending on its axial penetration and radial dispersion, displacing the bulk of larger droplets radially outward from the spray centerline. Also, the existence of relatively smaller droplets near the centerline and larger ones near the spray periphery according to the l_o/d_o is ascribed to the unique characteristics in swirling spray.

Fig. 4 represents the correlation between SMD and turbulence level as a function of length to diameter of final discharge orifice. The magnitudes are represented for the mean value obtained from the sum of spray droplets in the central regions, which are defined as spray half width. The half width is the distance from the axis to the position where the mean axial velocity of the spray is developed. The influence

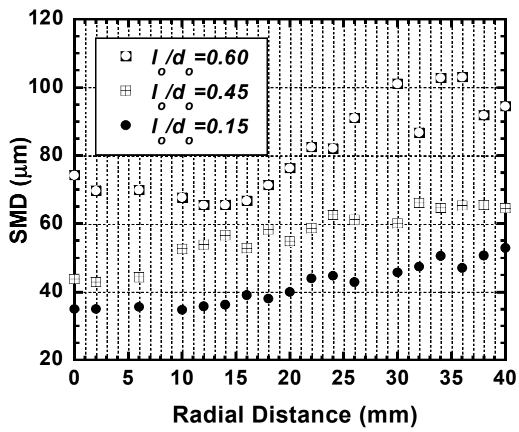

Fig. 3. Comparison of SMD variation in terms of length-to-diameter ratio in final discharge orifice.

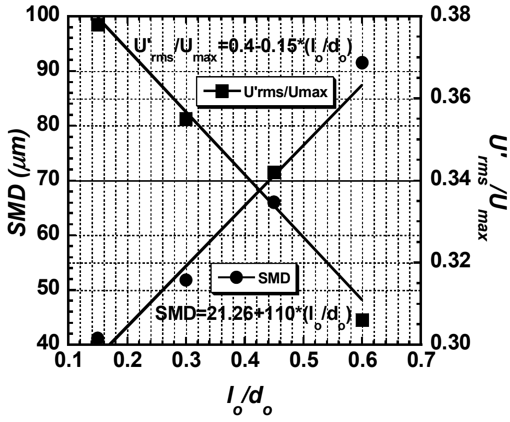

Fig. 4. Influence of length to diameter ratio of final discharge orifice on SMD and turbulence intensity.

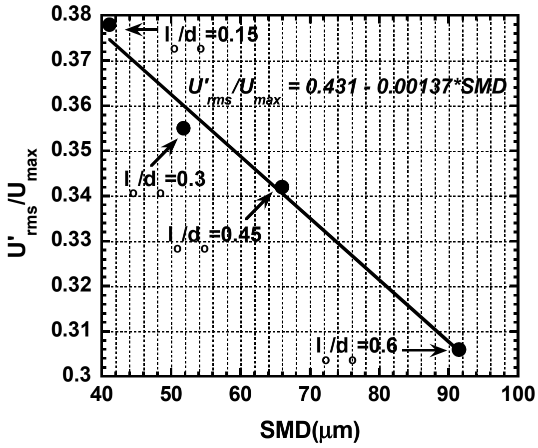

Fig. 5. Correlation of SMD and turbulence intensity in terms of l_o/d_o.

of discharge orifice length to diameter ratio on SMD and turbulence intensity is illustrated in Fig. 4, in which SMD and turbulence intensity is plotted against l_o/d_o for the values of 0.15 through 0.6, respectively. This figure evidently shows that the decrease of l_o/d_o leads to improved atomization with active turbulent breakups. This result is consistent with the previous analysis by Chen et al. [1]. They reported that disintegration quality enhanced continuously as the length to diameter was decreased in steps from 0.55 through 0.35. And it indicated that the increase of l_o/d_o caused the turbulence intensity to be spread farther apart, thereby indicating that mean drop size gets more dependent with the increase of l_o/d_o even in the central region where the influence on this configuration ratio is thought to be negligible.

For the analysis of correlation between the turbulence intensity and SMD, the data obtained is plotted as shown in Fig. 5. This figure shows clearly that the decrease of discharge orifice length to diameter ratio tends to enhance the positive effects on droplet breakup and disintegration. At the lowest value of l_o/d_o tested, it demonstrates the highest turbulence value with the smallest SMD. On the other hand, at the largest range of 0.6, the SMD value degenerates to the extent of 92 μm, achieving more than a factor of two when compared to the lowest value. Fig. 5 demonstrates a stronger linear dependence of turbulence intensity on SMD. An empirical linear expression can be obtained as u'_{rms}/U_{max}=0.431-0.00137* SMD.

By comparing the volume flux at both axial upstream and downstream locations, the effects of ALR on spray distribution are emphasized as shown in Figs. 6-7. For a swirl spray, defining the location of spray boundary at the radial position where most of the droplets mass resides is necessary to see the spray transport. It is possibly obtained by observing the droplet volume flux, which is defined as the volume of the droplets passing through a unit cross-sectional area per unit of time. The peak in volume flux is coincident with the distribution in SMD as observed in the literature earlier (Lai, Huang, and Jiang, T. L.) [16]. The examination of these normalized profiles indicates a discernible difference in the presence of higher ALR at both axial upstream and downstream locations. The results show that the magnitudes of volume flux near the central region are the highest as shown in Fig. 6. There is a transfer of droplets quantitatively at the central region because of the rapid spreading of the droplets in the process of disintegration at higher ALR. With an increase of ALR, lower rates of volume fluxes exist by a factor of 2-4 at upstream. On the other hand, the profiles in Figs. 6 and 7 indicate that radial positions exist at each axial location where the volume flux has a maximum and thus signify the spray boundary. But, the trend at the spray boundary of Z/d_o=60 shows unique features of swirl spray. As shown in Fig. 7, the radial profiles exhibit the highest magnitudes at approximately $y/b=2$, substantiating the radial dispersion in a swirl spray. It also shows that the droplet volume fluxes increase monotonically from the axis to the boundary region up to $y/b=2$. However, after reaching the highest levels, it decreases rapidly along the radial distance while being surrounded by the droplets having a less

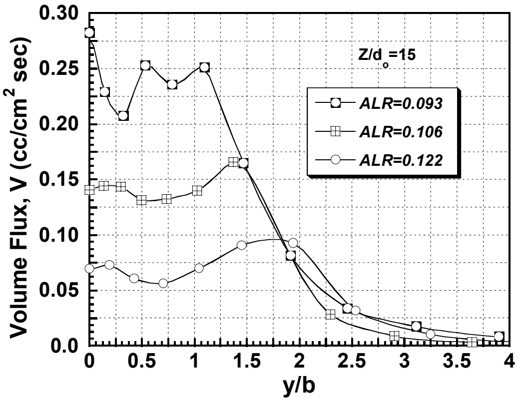

Fig. 6. Variation of volume flux with radial position in terms of ALR measured at axial upstream region of $Z/d_o=15$.

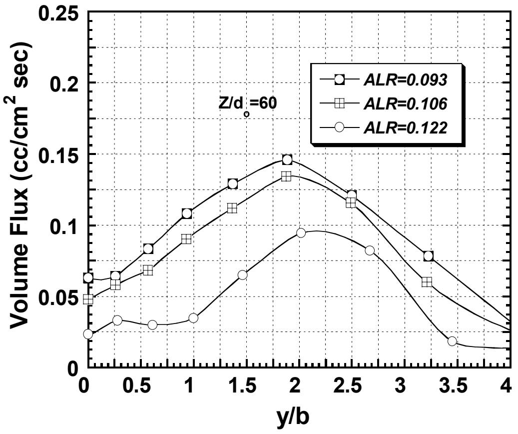

Fig. 7. Variation of volume flux with radial position in terms of ALR measured at axial downstream region of $Z/d_o=60$.

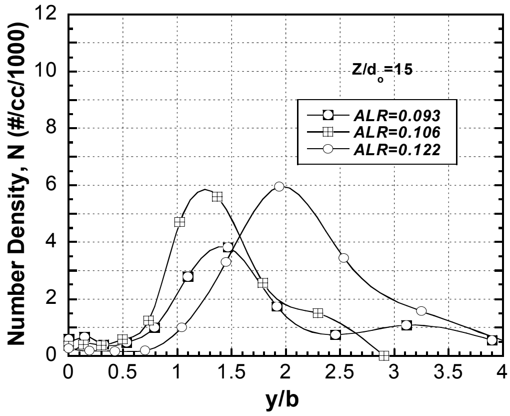

Fig. 8. Variation of number density in terms of ALR measured at axial upstream region of $Z/d_o=15$.

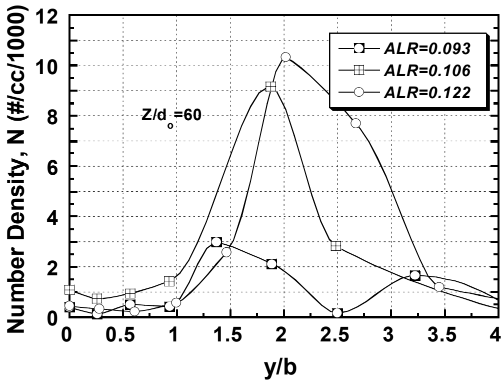

Fig. 9 Variation of number density in terms of ALR measured at axial downstream region of $Z/d_o=60$.

abundant and dilute concentration in the boundary. The reason for this is that the higher ALR tends to decrease the volume flux across the cross-sectional area, which is a desirable influence on the spray distribution.

To compare and substantiate the spray distribution in terms of ALR effects, the results for number density N measured at both the upstream and downstream axial locations are shown in Figs. 8 and 9. The definition of the number density is the number of droplets per unit volume. As shown in Figs. 8-9, the data indicate an increase in radial spread of the spray with both axial locations, keeping the highest concentration of the droplets at approximately $y/b=1.4$-2. However, at the center region, the concentrations of the number density are comparatively lower when compared to those at the boundary. Accordingly, the existence of the outer peaks due to the dense concentration of relatively larger droplets demonstrates that the positions of the spray boundary are essentially coincident with the volume flux distributions as indicated in Figs. 6-7. Meanwhile, as the ALR increases, the distributions of the spray extend much larger radial positions as compared to the lower ALR, proving the higher radial dispersions due to the augmented turbulent interaction of droplets with ambient air according to increasing ALR.

At upstream location, the maximum value of N for higher ALR (i.e., 0.106 and 0.122) is approximately 6000. In contrast, the maximum value of N for the same ALR at downstream as shown in Fig. 9 is about 9000-11000. The previous results obtained by Lee et al. [17] showed that the number densities in the external swirling spray decrease abruptly due to the larger radial dispersion and faster decay of axial momentum.

However, these profiles in this investigation are indicative of the dense concentrations of quantitatively smaller droplet diameter that dispersed to the boundary, showing definite similarity in trajectory pattern regardless of ALR. This is attributed to the comparatively larger radial dispersion issuing from an internal mixing nozzle, which consequently promotes outward growth-rate.

Thus, the outward peaks in number density with the increase of ALR provide evidence of the significant increase for the higher concentration in the spray periphery.

4. Conclusions

Geometrical effects of the length/diameter ratios of the final discharge orifice as well as the air-supplied ratios were the main consideration for analyzing the spray distribution. Profiles of SMD variation in terms of l_o/d_o, correlations between SMD and U'_{rms}/U_{max}, variations of volume flux and number density in terms of ALR were quantitatively obtained. The reduction in SMD with decreased l_o/d_o is attributed to the shorter breakup regions of the spray that accompany higher turbulence intensity. Accordingly, the final discharge orifice length on turbulent disintegration is apparently one of the influential factors in designing the nozzle. Also, SMD vs. turbulence intensity shows that the decrease of l_o/d_o leads to improved atomization with active turbulent breakups, leading the turbulence intensity to be spread farther apart. Meanwhile, the droplet volume fluxes increase monotonically from the axis to the boundary region. After reaching the highest levels, it decreases rapidly by the droplets having a less abundant and dilute concentration in the boundary. The reason for this is that the higher ALR tends to decrease the volume flux. The number density distributions indicate an increase in radial spread at both axial locations, keeping the highest concentration at approximately $y/b=1.4\text{-}2$. However, the concentrations are comparatively smallest at the center region. Accordingly, the dense concentration of relatively larger droplets demonstrates that the positions of the spray boundary are essentially coincident with the volume flux distributions.

Nomenclature

b : Spray half-width of the velocity
d_o : Final discharge orifice diameter
d_p : Diameter of passages for the fluids
D_s : Swirl chamber diameter
l_o : Length of final discharge orifice
l_s : Length of swirl chamber
l_{ap} : Length of air passages
l_{wp} : Length of liquid passages
N : Number density
θ_s : Swirl angle of the inlet passages for the fluids
ALR : Air to liquid mass ratio
SMD : Sauter mean diameter
U_m : Maximum axial velocity at the centerline
u'_{rms} : Root mean square of the axial fluctuating component
y : Radial distances
Z : Axial distances from the nozzle tip

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