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Mass Flux Measurement of Two Phase Dense Spray Using a Coupled Impulse Probe and PDPA Technique

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Abstract

Mass flux and void fraction measurement in a multiphase dense spray is a challenging task. The Phase Doppler Particle Anemometer (PDPA) cannot provide accurate mass flux measurements in a highly turbulent multiphase spray due to the presence of non-spherical and multiple droplets in the probe volume. A combined measurement of momentum data from the impulse probe and velocity data from the PDPA provides a fairly reasonable estimate of mass flux data in the two phase spray envelope. Experimental results show that mass flux at 60D_n (Dn= nozzle diameter of 3.10 mm) downstream of a horizontal nozzle tip is 0.033 kg/s, 0.034 kg/s and 0.0005 kg/s obtained from the theoretical value, impulse probe method and PDPA technique, respectively. This study will help answer some of the fundamental questions about the mass flux distribution in the two phase dense spray, which will aid in the improvement of the multiphase atomization design process in industrial applications.

Keywords: Two Phase, Atomization, Droplet, Mass Flux, Impulse Probe, PDPA.

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Introduction

Gas assisted atomization is a popular technique in industrial applications. Two-phase gas/liquid atomization characterization is challenging task [1-4]. It is very common to have pulsations in the gas assisted atomization. Our experimental observations indicate that the available experimental techniques, such as Phase Doppler Particle Anemometer (PDPA), are not able to characterize the multiphase spray accurately. The PDPA technique can only reliably measure the droplet velocity. However, the PDPA cannot measure the mass flux very accurately due to high rejection rate of non-spherical data. Thus, using the velocity data from the PDPA and force data from the impulse probe can assist to calculate the momentum flux very reliably. A study in fuel spray indicated that spray momentum flux information is very critical to characterize a spray as spray momentum determines the spray penetration, spray cone, air entrainment and mixing potential in the reactor (jet bed interaction). In the experiment, they used an impingement force measurement technique and validated the results obtained by the macroscopic spray visualization method [5]. Several other studies are found in literature that used the spray momentum flux to understand the spray characteristics [6,7]. A simulation of water jet which was validated by the experimental data indicated that the peak of a impulsive impact force in the pulsating spray was found to be 3.5–4 times greater than that of the continuous water jet [8]. There are few other studies that used the impact probe to measure the spray momentum in multiphase spray. In one study, a piezoelectric dynamometer was used to measure high-speed water jet characteristics [9]. In this study, two phase spray momentum was measured using a coupled PDPA and impulse probe technique. This novel method assists to understand the fundamental behavior of multiphase spray in industrial applications.

Theory

Consider a steady flow impinging on a perpendicular flat plate as shown in Figure 1.

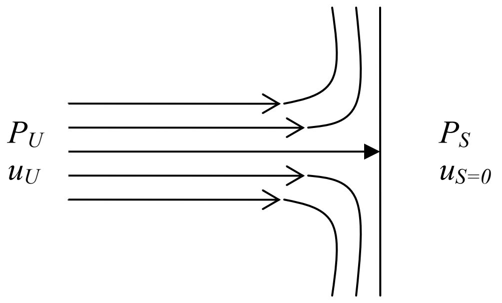


Figure 1. Stagnation point flow

The streamline in Figure 1 divides into two segments. The stream lines goes above the dividing line flows over the plate and the stream lines goes under the dividing line flows under the plate. Since the flow of the dividing stream line cannot pass through the plate, the fluid must comes to rest at a point. Thus, fluid along this line slows down without deflection the plate and it stagnates. The Bernoulli's equation along the stagnation streamline gives:

$$P_u + \frac{1}{2}\rho u_u^2 = P_S + \frac{1}{2}\rho u_S^2 \qquad (1)$$

here, the subscript '*u*' indicates the upstream condition and subscript '*S*' indicates the stagnation condition. Since at the stagnation condition the stagnation velocity is zero, the Equation (1) can be written as follows:

$$P_u + \frac{1}{2}\rho u_u^2 = P_S \qquad (2)$$

In other words we can write: static pressure + dynamic pressure = stagnation pressure or total pressure. The stagnation pressure is the highest pressure in the flow where the fluid motion comes to a rest. The effects of the gas phase pressure are negligible as the density of air is way less than the density of water. Sometimes the piezoelectric sensors only measure the dynamic pressure of the fluid motion, which reflects the momentum flux of droplets impacting on the tip of sensor. In any axial location perpendicular to the spray, the liquid mass flux is conservative. Thus, the liquid mass flux exiting the nozzle orifice should be equal to the integral mass flux at any cross section in the spray. One can write:

$$M_S = \sum_{i=1}^{N} M_x$$

where, 'x' indicates the axial location and 'i' indicates local mass flux. As the mean dynamic force can be measured inside the spray and any section perpendicular to the spray axis, the mean droplet velocity can be calculated for each point on this section. As this force is referred to effect of droplets, the total water mass flow rate can be obtained if the mean velocity is integrated in this section. To measure the droplet velocity the Phase Doppler Particle Analyzer was used.

Experimental Set-up

In this study, a one-quarter of a patented full-scale nozzle, US Patent of 6003789 [10], was used as shown in Figure 2. The full scale nozzle is used in a fluidized bed coker for heavy oil upgrading. In the laboratory experiment, a feeding conduit of 36.8 cm length and 6.35 mm ID was used prior to the nozzle. The nozzle diameter (D_n) was 3.10 mm. This nozzle assembly was mounted on a 3-D automated traversing rig. The experiments were performed using mixtures of water (0.04 l/s to 0.11 l/s) with air or mixed gas (0.16 l/s to 0.48 l/s), which gave air to liquid mass ratios (β) of 1 to 4%. The experimental schematic diagram is presented in Figure 2. Mean drop size was measured using a 2-D Phase Doppler Particle Anemometer (PDPA) from the Dantec Dynamics specifications [11]. The working principal of the Phase Doppler Particle Analyzer can be found in literature [12-16]. The force generated from droplets in any axial cross section of the spray was measured by a piezoelectric force sensor, Kistler 9203, and a charge amplifier, Kistler 5010B. This force sensor is high sensitive and capable of resolving the smallest changes in contact force. Charge amplifier was used to convert the transmitted charge from high impedance piezoelectric force into a high level output voltage and provide excitation power along. This high level voltage output can be readout online using an oscilloscope. In the current experiment, a digitizing oscilloscope Tektronix TDS 410A with record length of 15000 points per minute was used to readout the output voltage.

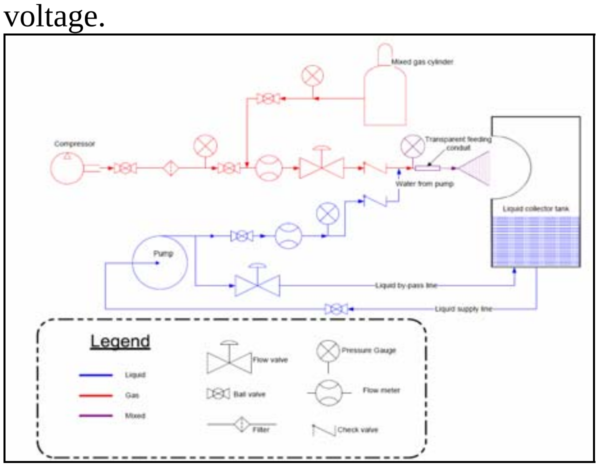


Figure 2. Experimental set-up.

Quartz force sensor as shown in Figure 3(a) measured dynamic and quasistatic forces. The device can measure the force in the range of a few N up to 400 kN. The Quartz force sensor is mounted tightly in a welded steel housing. Quartz yields an electric charge proportional to the mechanical load.

Figure 3(b) shows the schematic of the charge amplifier used to convert the transmitted charge into a high level output voltage.

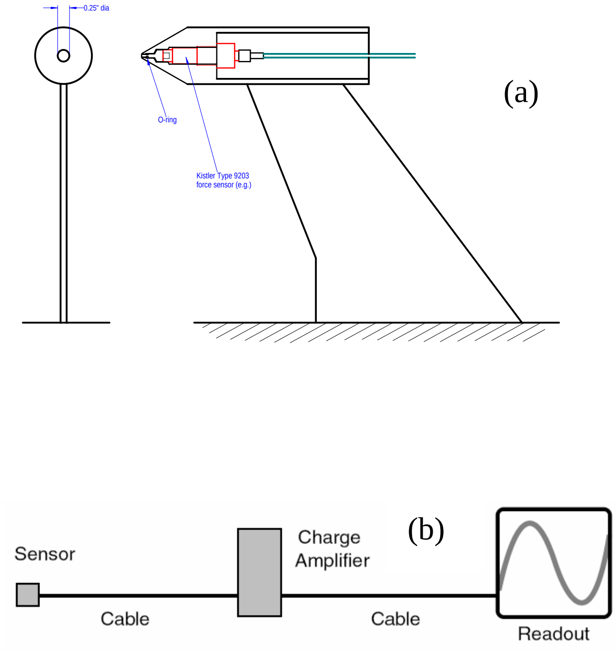


Figure 3. Quartz force sensor (a) and the charge amplifier output.

Results and Discussions

In Figure 4 a good and bad atomized spray is depicted. Due to greater pulsations in Figure 4 (a) the droplets are non uniform. However, due to less pulsations in Figure 4 (b), the droplets are nicely dispersed. In Figure 5, droplets force data obtained by the impulse sensor is depicted. The brevity of the force data is the uniformity in both radial directions. Data obtained from the Phase Doppler Particle Anemometer is not symmetrical in both the radial directions due to the less visibility for the receiver if one traverses from one direction to another direction. In Figure 6, the effects of the air to liquid mass ratio on the droplet force is presented. Figure 6(a), Figure 6(b), Figure 6(c) and Figure 6(d) correspond to the 15D$_n$, 15D$_n$, 15D$_n$, and 15D$_n$, nozzle downstream form the tip of the nozzle. Here, D$_n$ corresponds to the nozzle diameter of 3.10 mm. In all the cases of nozzle downstream, the force profiles are similar. Most importantly it is notable that if the air to liquid mass ratio increases the force produced from droplets also increases. At higher air to liquid mass ratio, the momentum is transferred to the liquid phase and provide greater force in the droplets.

(a) coarse atomization

(a) fine atomization
(b)

Figure 4. Spray images.

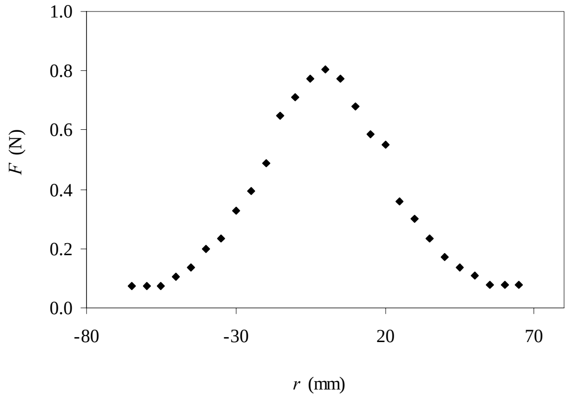
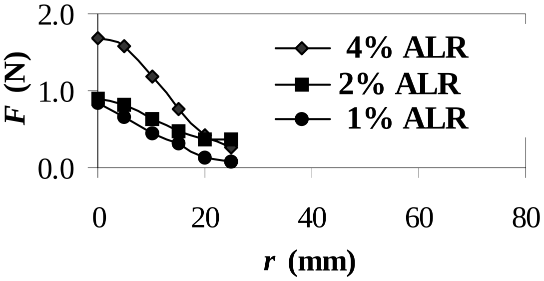
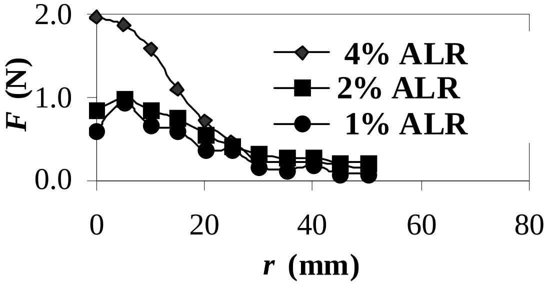


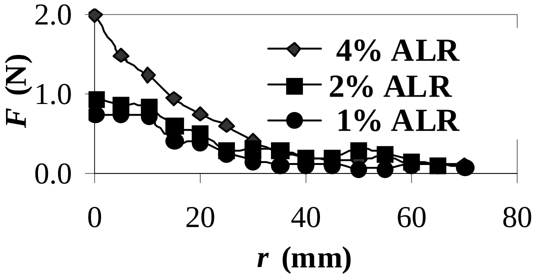
Figure 5. Symmetry obtained in the impulse sensor measurement. Data obtained for 2% air to liquid mass ratio, 30 Dn nozzle downstream and 482 kPa mixing pressure



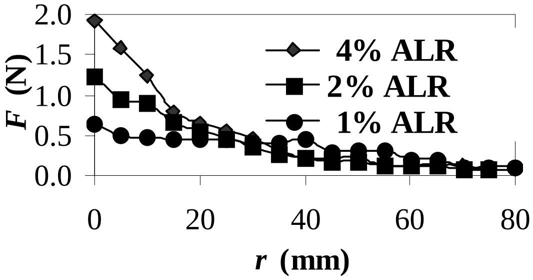
(a) $15D_N$



(b) $30D_N$



(c) $60D_N$



(d) $120D_N$

Figure 6. Force (*F*) produced from a spray with changing air to liquid mass ratio and radial distances (*r*).

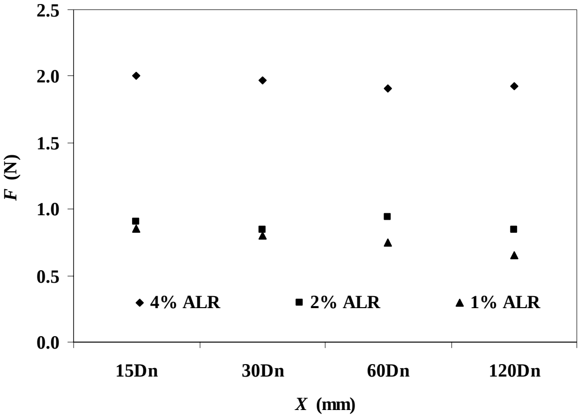


Figure 7. Force (*F*) produced from a spray with changing axial position (*x*) and air to liquid mass ratio.

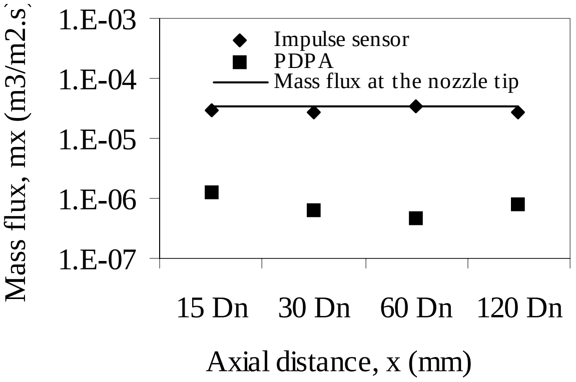


Figure 8. Mass flux variation with axial distance from the tip of the nozzle. Here, Dn indicates diameter of the of the nozzle tip of 3.10 mm.

Similar observations can be made in Figure 7 where the effects of the air to liquid mass ratio and the progress of the droplet force in different nozzle downstream are presented. As shown in previous figure, the droplets force increase linearly if the air to liquid mass ratio increases. Moreover, the droplet force decreases gradually if the droplet travels to the downstream of the spray. If the droplet travels to the downstream of the spray, the droplets loss its momentum providing less force in further downstream. Figure 8 is the most interesting figure obtained from the impulse probe. Figure 8 validates the mass conservation for the liquid volume. In Figure 8, the theoretical values were obtained from the liquid input condition, which was known in our experiment. Two experimental data sets were plotted varying the axial distances. (from 15Dn to 120Dn). From Figure 8,it is evident that the impulse probe mass flux data conserves the input liquid content. However, due poor data rate and spherical validation, the Phase Doppler Particle Analyzer underestimates the input liquid content, thus, fails to conserve the liquid volume in the system.

Conclusions

The mass flux measurement in two phase gas liquid spray is a challenging task as the traditional laser diagnostics cannot measure all the droplets shape (such as non-spherical droplets) very reliably. However, the Phase Doppler Particle Anemometer can measure the droplet velocity data very reliably. Thus, combining the Phase Doppler Particle Anemometer technique with the impulse probe technique can measure the mass flux of a multiphase pulsating spray very accurately.

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