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AN EXPERIMENTAL STUDY OF THE ATOMIZATION OF A TWO-PHASE INDUSTRIAL NOZZLE

M.A. Rahman, A. Amirfazli, T. Heidrick and B A. Fleck

Department of Mechanical Engineering, University of Alberta, Canada
E-mail: marahman@ualberta.ca

ABSTRACT
Droplet size distribution measurement of a two-phase two-component spray is an intricate process. Radial spray profiles were measured using a Phase Doppler Anemometer (PDA) system on 15D_n, 30 D_n, 60 D_n, 120D_n (D_n represents nozzle diameter =3.10 mm) axial distances. The average void fraction in the feeding conduit was measured by a pneumatic controlled quick-closing-valve (QCV). The length and diameter of the feeding conduit was 36.8 cm and 6.35 mm, respectively. The experiments were performed using the mixtures of air with water at water flow rates of 1.50 to 7.50 $kg/\min$ and air-to-liquid mass ratios of 0.30 to 15 %. At 0.30 % and 3.20 % ALR by mass, and 29 % and 81 % entrance void fraction (α), the horizontal velocities at the center of the spray and at 60 D_n axial distance from the tip of the nozzle are 41.36 m/s and 58.48 m/s, respectively. For the similar conditions, the SMD(D_{32}) at the center of the spray is 193 μm and 171 μm, respectively. Thus result indicates that at the higher ALR and α, at the center of the spray, the penetration is higher and droplets are more dispersed with enhanced pulsation.

Keywords: Two-phase gas/liquid spray, Phase Doppler Anemometer, air-to-liquid mass ratio, void fraction.

1. INTRODUCTION
Enhanced heat and mass transfer can be achieved from a spray, which is composed of dispersed droplets with larger spread rates. Moreover, as the droplet/particle sizes are reduced, the energy of the droplets is more readily transferred to the surrounding fluid [1]. This would ensure proper mixing with the surrounding fluids. Furthermore, in processes where the feed needs to be injected into a cross-flowing stream, the droplets in the spray must have enough momentum to penetrate the cross-flowing fluid stream [2]. Continuous and fine spray characteristics are desirable in the feeding nozzle. This feed nozzle is used in the heavy oil process industry. Preheated bitumen and steam is mixed upstream of the nozzle and subsequently injected into fluid bed coker reactors via feed nozzles. One of the drawbacks of this spray characteristic is the pulsation within the spray and in the feeding conduit, which is highly undesirable to yield high productivity. These pulsations result in poor atomization and in most instances, a slug of liquid is ejected out of the nozzle. This pulsation is attributed to the two-phase fluids conditions (air-to-liquid ratio, ALR, void fraction, α or the mixing pressure), the design of the mixing chamber of two-phase two-component fluids, the geometry of nozzle or due to the back pressure from the high temperature bed coker [3].

2. EXPERIMENTAL SET-UP
In this study, a laboratory scale nozzle assembly was implemented. The dimension was one-quarter scale of a patented full-scale design (US Patent #: 6003789) employed in a fluidized bed coker for heavy oil upgrading. 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 experimental schematic diagram is presented in Fig. 1.

Mean drop size was measured using a 2D-Particle Dynamics Analyzer (PDA) from the Dantec Dynamics specifications [4]. The focal lengths of the PDA transmitter and receiver lenses were 400 and 310 mm, respectively. During data collection, the PDA was operated in refraction and forward-scatter mode, and the receiver was set to a scattering angle (ϕ) of 30° for the air-water tests. Dantec [5] specified that first order refraction is the most dominant scattering mode at ϕ = 30° for water droplets in air..

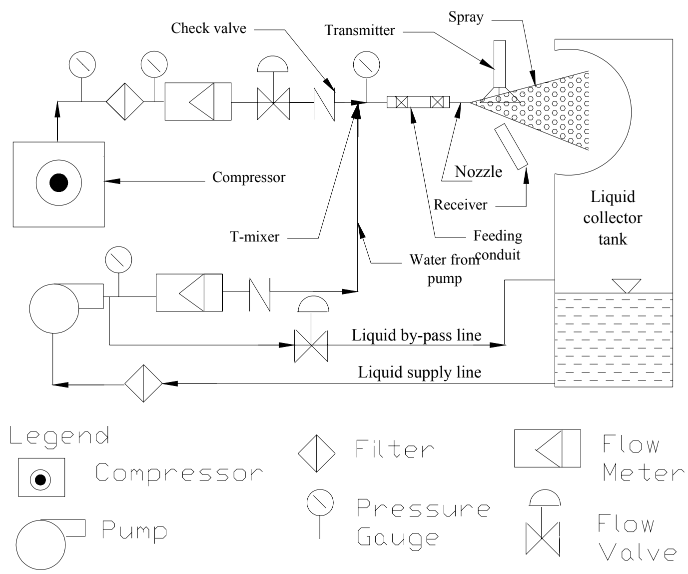

Fig 1: Schematic of the experimental set-up.

Radial spray profiles were measured using a Phase Doppler Anemometer (PDA) system on $15D_n$, $30D_n$, $60 D_n$, $120D_n$ (D_n represents nozzle diameter = 3.10 mm) axial distances downstream of the nozzle. The measurements were taken varying the radial positions (R) of +30 mm to –30 mm by the 3-D traversing rig. The values of D_{32}, D_{10}, and axial velocity were measured with changing the ALR by mass and void fractions.

3. RESULTS AND DISCUSSION

A strong positive correlation may be a result of smaller droplets having lower velocities or larger droplets traveling at higher velocities. Similarly, a strong negative correlation may result either due to larger droplets associated with lower velocities or smaller droplets associated with higher velocities [6]. In the previous study, the total number of samples (N) was 10,000. In the present study, we used the total number of 20,000 samples. The previous study pointed out that large droplets exist near the spray periphery and smaller droplets exist at the center of the spray. In addition, they indicated that the correlation factors close to zero at the center of the spray, whereas a strong positive correlation exists at the periphery of the spray. However, in the present study, we observed that large droplets exist near the spray periphery and at the center and smaller droplets exist in between the center and periphery of the spray. Due to the existence of the large liquid ligaments at the center of the spray, nearby the tip of the nozzle, the droplet sizes are also higher. Further downstream in the spray (axially) this effect diminishes and primary and secondary break-up completes.

In Figure 2, axial velocity with changing axial distances across the spray (radial) is depicted for the 1% ALR case. In each case the radial distance, R, is –30 mm to +30 mm. Here 'r' represents the radial axis. In Figure 2, it is demonstrated that axial velocity of the spray decreases with axial distances further downstream of the spray ($30D_n$, $60D_n$, and $120D_n$). However, near the tip of the spray ($15D_n$), axial velocity is lower than the further downstream of the spray. In two-phase, gas/liquid spray near the tip of the nozzle there is sudden expansion of the gas phase in the radial direction. However, the liquid phase does not follow this sudden expansion. In addition, near the tip of the nozzle the mixture pressure is not atmospheric like a single-phase flow. It requires certain time to reach the atmospheric pressure further downstream of the spray. Near the tip of the nozzle ($15D_n$), the gas phase momentum is not totally transferred to the liquid phase. Thus, a substantial amount of drag force reduces the axial velocity of the spray near the tip of the nozzle.

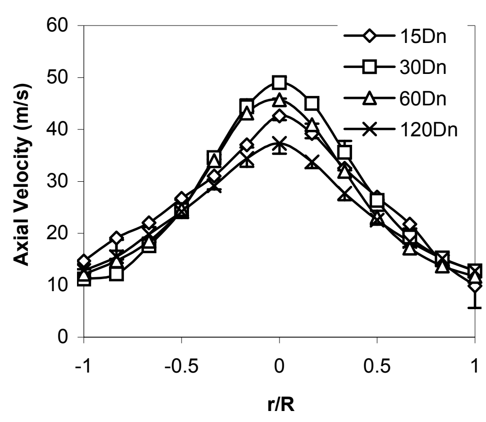

Fig 2: Axial velocity variation with the radius of the spray for the changing axial distances ($15D_n$, $30D_n$,,$60D_n$, $120D_n$,) and 1% ALR by mass.

In Figure 3, the ALR by mass of the two-phase, air/water was changed from 0.30% to 15%. In this case the mixture pressure was remained constant at 482kPa. The axial velocity decreases with the increases of the ALR by mass ratio. It is recognized that higher ALRs by mass (15%, 7.06%, 3.33%) induce higher axial velocity at the center of the spray. However, very shortly from the center of the spray, the axial velocity decreases steeply as the droplet diameter starts to decrease. This steep decrease of the axial velocity is more dominant with the high ALRs as with the high ALR the droplets are smaller with enhances pulsation.

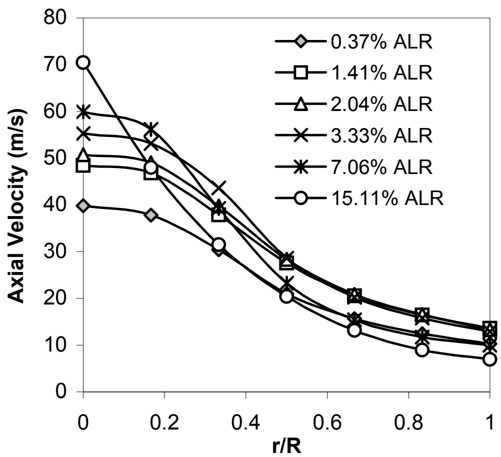

Fig 3: Axial velocity variation with the radius of the spray for the changing axial ALR by mass. In this case mixture pressure was remained constant at 482 kPa

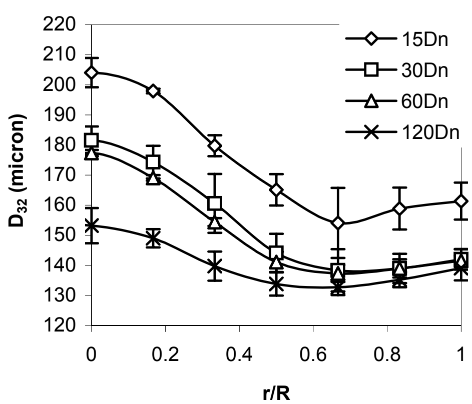

Fig 4: Sauter mean diameter (D_{32}) variation with the radius of the spray for the changing axial distances ($15D_n$, $30D_n$, $60D_n$, $120D_n$,) and 1% ALR by mass.

In Figure 4, the Sauter Mean Diameter with changing axial distances across the spray (radial) is depicted for the 1% ALR case. The radial distance, R, varies from –30 mm to +30 mm. Generally the Sauter Mean Diameter or SMD (D_{32}) provides a good indication of the drop size dispersion characteristics. The SMD can be expressed as follows:

$$D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \tag{1}$$

A remarkable peak is observed at the center and the periphery of the spray. As the SMD is based on the volume-to-surface ratio, a few larger droplets will increase the SMD value significantly in the spray. It is observed that at the center of the spray, the SMD values are 204 μm, 182 μm, 177 μm, and 153 μm at $15D_n$, $30D_n$, $60D_n$, $120D_n$, respectively. Whereas in between the center and periphery (r/R=0.7-0.8) the SMD values decreases to values of 154 μm, 138 μm, 137 μm, and 133 μm at $15D_n$, $30D_n$, $60D_n$, $120D_n$, respectively. At the periphery (r/R=1, which correspond to 30 mm from the center of the spray) again the values of the SMD increases to values of 161 μm, 142 μm, 141 μm, and 139 μm at $15D_n$, $30D_n$, $60D_n$, $120D_n$, respectively.

In Figure 5, the ALR by mass of the two-phase, air/water was changed from 0.30% to 15% and the corresponding change in the SMD values are depicted. In this case the mixture pressure was remained constant at 482kPa. The SMD values decreases with the increases in the ALR by mass ratio. It is recognized that higher SMD values exist at the center of the spray. This behavior is more dominant for the lower ALRs by mass. However, shortly from the center in the radial direction, the SMD values decreases steeply. This decrease of the SMD values is steeper for the lower ALR cases. This also indicates that there exits a strong positive correlation between the droplet diameter and axial velocity at the center of the spray and in between the spray and periphery, and a strong negative correlation at the periphery of the spray.

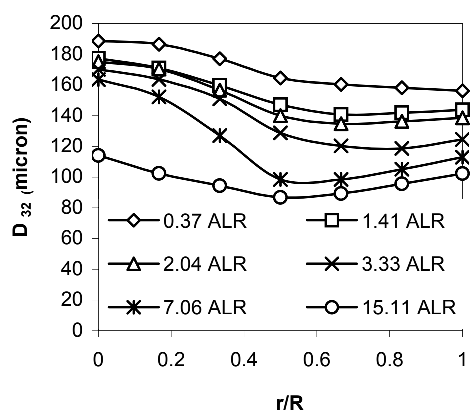

Fig 5: Sauter mean diameter (D_{32}) variation with the radius of the spray for the changing ALR by mass. In this case mixture pressure was remained constant at 482 kPa.

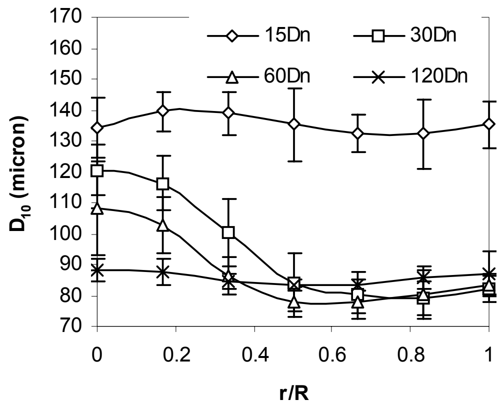

Fig 6: Mean diameter (D_{10}) variation with the radius of the spray for the changing distances ($15D_n$, $30D_n$, $60D_n$, $120D_n$,) and 1% ALR by mass.

In Figure 6, the mean diameter with changing axial distances across the spray (radial) is depicted for the 1% ALR case. In each case the radial distance, R, is –30 mm to +30 mm. Mean diameter can be expressed as:

$$D_{10} = \frac{\sum N_i D_i}{\sum N_i} \qquad (2)$$

If the mean diameter is small, the droplets are fully responsive to the fluid fluctuations. Whereas if the mean diameter is large, the droplets have excess inertia and do not follow the fluctuations in the carrier phase. This droplet response with the fluctuation can be better resented by the Stokes numbers. In Figure 6, it is observed that at the center of the spray near the tip of the nozzle ($15D_n$) the droplet sizes are small. This can be the result of the less spherical validation and data rate the tip and center of the nozzle. However, further downstream of the nozzle ($30D_n$ and $60D_n$) the D_{10} values are higher at the center of the spray and shortly further from the spray the values of the D_{10} decreases steeply. Further downstream of the spray ($120D_n$), the secondary break up of the spray completes and less variation in the D_{10} profile is observed. Secondary break-up in a spray occurs when larger droplet or liquid ligaments break down into smaller droplets. The breakup of a single droplet in a gas is caused by either relative velocity, turbulence, or shock structure interaction, acting separately [7]. If the aerodynamic forces overcome the forces due to surface tension, the droplet will deform [8]. If the relative velocity between the two phases is small, droplet will be stable. If the relative velocity between the phases is larger, the droplet starts to break-up. At this stage Aerodynamic forces overcome the surface tension of the liquid phase. The aerodynamic Weber number plays an important role in droplet break-up. If the aerodynamic Weber number exceeds the critical Weber number, secondary break-up occurs. As surface tension has a stabilizing effect, an increase in viscosity damps unstable perturbations [7].

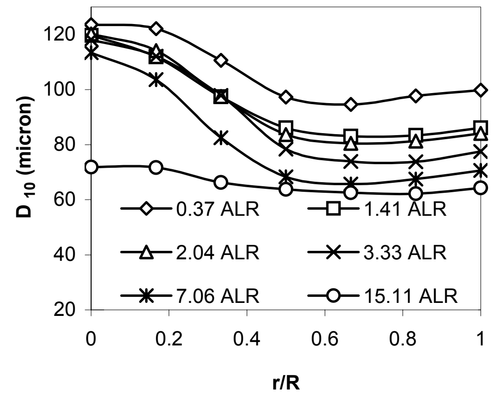

Fig 7: Mean diameter (D_{10}) variation with the radius of the spray for the changing ALR by mass. In this case mixture pressure was remained constant at 482 kPa.

In Figure 7, the ALR by mass of the two-phase, air/water was changed from 0.30% to 15% and the corresponding change in the D_{10} values are depicted. In this case the mixture pressure was remained constant at 482kPa. The D_{10} values decreases with the increases in the ALR by mass ratio. It is recognized that higher D_{10} values exists at the center of the spray. This behavior is dominant with the lower ALRs by mass cases. However, shortly further from the center of the spray in radial direction, the D_{10} values decreases steeply. This decrease of the D_{10} values is more prominent for the lower ALR cases. The effects of the mixture pressure in the D_{10} profile is depicted in Figure 8. In this figure it is observed that the D_{10} values at the center of the spray are 118 μm and 124 μm at the at lower mixture pressure (482 kPa, 3.3% ALR by mass) and higher mixture pressure (620kPa, 3.2% ALR by mass), respectively. However, at the periphery of the spray, this variation of the D_{10} values are is not significant with the change in mixture pressure.

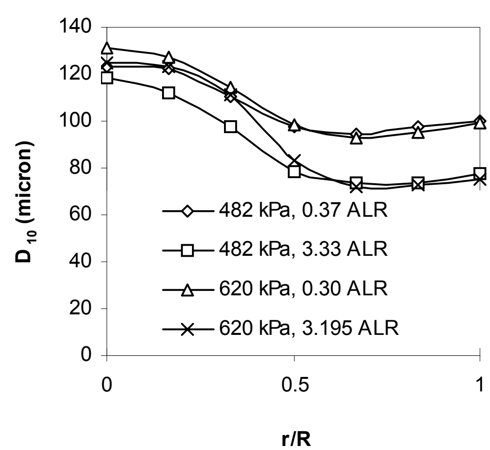

Fig 8: Mean diameter (D_{10}) variation with the radius of the spray for the changing mixture pressure of 482 kPa and 620 kPa.

4. CONCLUSIONS

Particle Dynamic Analyzer (PDA) has been using for the spray characteristics measurement issuing from a wide variety of nozzles. However, the application of the PDA is still a challenge in highly concentrated multiphase spray.

In this study, it is observed that the axial velocity of the spay is predominant at the center of the spray. Further downstream of the spray this axial velocity reduces. At this point secondary break-up of the spray completes. This completion of the break-up induces more dispersed and tiny droplets further downstream of the spray. The mean droplet and Sauter mean diameter are an important parameter to characterize a spray. This also indicates that there exits a strong positive correlation between the droplet diameter and axial velocity at the center of the spray and in between the spray and periphery, and a strong negative correlation at the periphery of the spray.

Two-phase two-component atomization from an industrial nozzle depends on many factors, such as: gas molecular weight; ambient density; temporal and special coordinates; liquid types: Newtonian/non-Newtonian; liquid physical properties: viscosity, surface tension, and density; operating parameters: gas/liquid ratio, injection pressure, pressure drop; atomizer internal geometry. Several parameters are important to characterize the spray after proper atomization, such as: liquid flow rate, drop size distribution, drop velocity distribution, spray cone angle, penetration, spray momentum rate, and entrained gas flow rate.

5. ACKNOWLEDGMENT

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