Correlations between the Two-Phase Gas/Liquid Spray Atomization and the Stokes/Aerodynamic Weber Numbers

Mohammad A. Rahman ¹, Ted Heidrick ², Brian A. Fleck ³

¹ The Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada
¹ marahman@ualberta.ca

Abstract. The effects of air-to-liquid ratio ($\beta$) and void fraction ($\alpha$) on Sauter mean diameter (SMD or $D_{32}$), arithmetic mean diameter ($D_{10}$), surface mean diameter ($D_{20}$), and radial velocity profiles were experimentally investigated for a two-phase gas/liquid (TPGL) nozzle with a hybrid design of classical twin-fluid and effervescent nozzles. Radial spray profiles were measured using a Phase-Doppler-Particle-Anemometer (PDPA) system on $15D_n$, $30D_n$, $60D_n$, $120D_n$; ($D_n$ represents nozzle diameter = 3.10 mm) axial distances. In addition, the effects of spray break-up patterns were analyzed with changing axial distances. The average void fraction in the feeding conduit (FC) was measured by a pneumatic controlled quick-closing-valve (QCV). The experiments were performed using mixtures of air with water at water flow rates of 1.50 to 7.50 kg/min and air-to-liquid mass ratios ($\beta$) of 0.30 to 10 %. The length and diameter of the FC was 36.8 cm and 6.35 mm, respectively. Result indicates that as the St number reaches the value of one, no more break-up continues, thus the droplets start to coalesce each other forming bigger droplets ($D_{10}$ values) with increasing radial distances. Knowledge from this study will provide better understanding that ensures an increase in plant efficiency and product yield in oil sands bitumen upgrading.

1. INTRODUCTION

In fluid coking, the gas (steam) and liquid (bitumen) mix well upstream of the feed nozzles where the mixture is atomized to form a spray. One of the drawbacks found with the fluid coking nozzles is the development of instabilities in the spray caused by the TPGL flow patterns formed inside or upstream the nozzle at the higher $\beta$ (Ariyapadi et al., 2005; Maldonado, 2006). A stable spray is demonstrated by a good dispersion of the liquid phase. It is desirable to produce a stable spray with minimum SMD ($D_{32}$) and well-dispersed liquid droplets. A desired bitumen drop size in contact with a given coke particle is one with the same nominal diameter as the coke particle. This ensures that the coke is adequately and sufficiently coated with a thin layer of bitumen (Ejim, 2008). On the other hand, an unstable spray is characterized by intermittency/pulsation in its flow regime with the random formation of fine and coarse droplets in the spray. These pulsations are attributed to the TPGL fluids conditions, such as $\beta$, $\alpha$, the mixing pressure, $P_m$, the design of the mixing chamber, and the geometry of nozzle (Tafreshi et al., 2002). Previous studies (Roesler et al., 1989; Whitlow et al., 1993) showed that as the $\beta$ is increased, for a constant operating pressure, at a certain transition point (e.g. $\beta >1.0$ % in the large-scale nozzle) the spray becomes unstable. A homogeneous mixture of the gas-liquid
entering the nozzle would maximize the effect of the decompression of the gas phase, resulting in a stable spray. On the other hand, a heterogeneous flow entering into the nozzle cause an unstable spray formation (Barker et al., 1991).

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 sizes are reduced, the energy of the droplets is more readily transferred to the surrounding fluid (MacGregor, 1991). 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 (Ariyapadi et al., 2000). 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.

It is convenient to work with mean drop sizes instead of complete drop size distributions in the TPGL atomization characterization. The mean drop size distribution is generalized as follows (Lefebvre, 1989; Mugele et al., 1951):

\[
(D_{ab})^{a-b} = \frac{\int_{D_a}^{D_b} D^a (D N / dD) dD}{\int_{D_a}^{D_b} D^b (D N / dD) dD}
\]  

(1)

The values of \( a \) and \( b \) can be found in Lefebvre (1989) and the mean diameter expression is presented in Table 1.

Table 1. Mean diameters (adapted from Lefebvre, 1989).

| Symbol | Name of mean diameter | Expression |
|--------|-----------------------|------------|
| \( D_{10} \) | Length | \( \frac{\sum N_i D_i}{\sum N_i} \) |
| \( D_{20} \) | Surface area | \( \left( \frac{\sum N_i D_i^2}{\sum N_i} \right)^{1/2} \) |
| \( D_{30} \) | Volume | \( \left( \frac{\sum N_i D_i^3}{\sum N_i} \right)^{1/3} \) |
| \( D_{32} \) | Sauter mean \((SMD)\) | \( \frac{\sum N_i D_i^3}{\sum N_i D_i^3} \) |
Generally $D_{32}/SMD$ provides a good indication of the drop size dispersion characteristics and used for mass transfer application. The $D_{10}$ diameter is used for comparison purpose, the $D_{90}$ diameter is used for surface area controlling application, the $D_{50}$ diameter is used for volume controlling application, the $D_{43}$ diameter is used for combustion equilibrium application. In the droplet motion, the Stokes number ($St$) is a very important parameter. The $St$ is defined as the ratio of the particle momentum response time over a flow system time, defined as: $St = \tau_p / \tau_s = \rho_p d_p^2 u_p / 18 \mu_L$. Two types of situations can be observed for particles (bubbles/droplets) suspended in fluid, namely: a) if the $St<<1$, the particles will have ample time to respond to changes in fluid velocity, b) if $St>>1$, then the particle will have essentially no time to respond to the fluid velocity changes and the particle velocity will be little affected by fluid velocity change (Crowe, 2006).

A spray breaks up further downstream from the tip of a nozzle. A typical $TPGL$ atomization process involves a) primary atomization ($PA$), b) secondary atomization process ($SA$). The dominant forces involve in the atomization process are: (i) hydrodynamic or inertial force attributed to undulations/perturbations, (ii) aerodynamic force attributed to drag/shearing effect, (iii) viscous force attributed to oppose a change in liquid geometry, and (iv) surface tension forces attributed to a minimum surface energy (Nasr et al., 2002). The first two forces are disruptive in nature and second two forces are cohesive in nature. Due to the interaction of internal forces such as: a) turbulence, b) inertial effects, c) momentum transfer between transverse layers of a jet are mainly responsible for the $PA$ (McCarthy et al., 1974). At this stage the disruptive forces exceed the consolidating forces resulting the oscillations on the liquid surface and subsequently disintegrate the bulk liquid into drops (Liu, 1999; Shavit et al., 1996). The $SA$ in a spray occurs when larger droplets or liquid ligaments break down into smaller droplets. The breakup of a single droplet in a gas is caused by either greater relative velocity, or turbulence (Crowe, 2006). The $SA$ occurs due to two force ratios acting on the drop (Pilch et al., 1987). Firstly, if the aerodynamic forces overcome the forces due to the surface tension, the droplet will further deform (Low et al., 1982). The ratio of this two forces can be represented by the Weber number, which can be defined as: i) aerodynamic/gas Weber number: $We_g = \rho_g u_g^2 d_d / \sigma$ or ii) liquid Weber number: $We_l = \rho_l u_l^2 d_d / \sigma$. Secondly, the Ohnesorge number/Laplace number, denoted by: $Oh = \sqrt{We_l / Re_l} = u_l / \sqrt{\rho_l d_d \sigma} = 1/\sqrt{Lp}$, which is the ratio of liquid viscous force to surface tension force on the drop, also plays an important role in the $SA$. Here $Re_l$ is the liquid Reynolds number defined: $Re_l = \rho_l u_l d_d / \mu_l$. Mathematically, if the $We_g$ exceeds the $We_{crit}$, the $SA$ occurs. For low-viscosity liquids, $We_{crit} = 6$ to 13 for $Oh < 0.1$, $We_{crit} \approx Oh^2$ for $Oh > 0.1$ (Faeth, 1990). In the $TPGL$ spray characteristics measurement, the PDPA system and digital image analysis techniques has been using as an advanced experimental techniques. The PDPA measurement techniques to measure the $TPGL$ spray can be found in literature (Ariyapadi et al., 2000; Ariyapadi et al., 2001; Ariyapadi et al., 2003; Copan et al., 2001; Ziesenis et al., 2002). Recently developed digital image analysis techniques potentially are also capable of sizing particles of arbitrary shape and size and with a wide dynamic range (Ariyapadi et al., 2005; Kashdan et al., 2003; Zama et al., 2004).

Measurement techniques of the $TPGL$ flows/sprays are a challenge. Due to highly non-uniform volumetric flow distributions and intermittency in the flow, it is extremely difficult to predict accurate droplet sizes ($d_d$) and flow pattern distributions in this type of flow. This uncertainty of the $d_d$ prediction is exaggerated if the $FC$ length of the nozzle is short, as in the present study (36.8 cm long); since the $TPGL$ flow cannot be fully developed within this short pipe length. The nozzles currently used in this study do not belong specifically to any of the nozzle classes for the $TPGL$ flows existing such as twin-fluid nozzles and effervescent nozzles. Moreover, in
recent years Nasr et al. (2002), Hsiang et al. (1992), Lefebvre (1989), Lefebvre et al., (1988), and Roesler et al. (1989) conducted atomization studies in the feed nozzles. However, these studies were based on the equilibrium flow condition, in vertical nozzle configurations and in a larger length scale set-up. In contrast to the above studies, the current study deals with the non-equilibrium flow condition (in which the FC is very short), in a horizontal nozzle configuration, and in a smaller length scale set-up.

The objectives of this study are: i) to predict correlations between the spray disintegration process and the upstream FC flow characteristics, ii) to understand the fundamentals of the TPGL flow patterns, and spray characteristics. The proposed study will contribute to the fundamental knowledge of the TPGL flows and make concrete headway in the design of an industrial nozzle used in a large-scale high impact operation.

2. EXPERIMENTAL SET-UP

In this study, a laboratory scale nozzle assembly was implemented. The dimension was at 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 in length and 6.35 mm ID was used upstream of the nozzle. The nozzle diameter ($D_n$) was 3.10 mm. Gas (air) was supplied from a compressor and liquid was supplied from a reciprocating pump. These two fluids mixed together at a T-mixer prior to the FC. This nozzle assembly was mounted on a 3-D automated traversing rig. The experimental schematic diagram is presented in Fig. 1.

![Fig. 1 Schematic of the experimental set-up (adapted from Rahman et al., 2008)](image)

Mean drop size was measured using a 2D-PDPA from the Dantec Dynamics specifications (Ejim et al., 2005). The focal lengths of the PDPA transmitter and receiver lenses were 400 mm and 310 mm, respectively. During data collection, the PDPA was operated in refraction and forward-scatter mode, and the receiver was set to a scattering angle ($\phi$) of 30° for the air-water tests. Dantec (Dantec Dynamics, 2003) specified that first order refraction was the most dominant scattering mode at $\phi = 30°$ for water droplets in air (about $10^2$ orders of magnitude higher compared to the backward scattering mode).

This technique can measure simultaneously velocity and particle size of known refractive index. This method is termed as “2D-PDPA” as this technique can measure
velocity of two orthogonal axes. The optical setting of the 2D-PDPA is presented in Table 2.

Table 2. Optical settings of the PDA unit used in the study

| Parameter                        | Unit | Values  |
|----------------------------------|------|---------|
| Scattering angle                 | (-)  | 30°     |
| Beam spacing                     | mm   | 38.0    |
| Beam expansion ratio             | (-)  | 1.0     |
| Receiver focal length            | mm   | 310     |
| Beam diameter                    | mm   | 1.35    |
| Transmitter focal length         | (mm) | 400     |
| Receiver slit width or aperture  | mm   | 0.1     |
| He-Ne laser wavelength           | nm   | 632.8   |
| Nd-YAG laser wavelength          | nm   | 532     |

The green Nd-YAG and red He-Ne laser power are 200 mW and 20 mW, respectively. Their wavelengths are 532 and 632.8 nm, respectively. Each laser split in two laser beams using the unit’s Bragg cell. The resulting four beams (two pairs for each laser) are apart of 90° each other and converge at the focal length of the transmitter lens to form a control volume. Droplet size was measured by detecting the incident droplets on the receiver detectors. The size of a droplet is directly proportional to the phase shift of scattered light in the control volume. The velocity of droplets can be found also by detecting the incident droplets on the receiver detectors. However, in this case the droplets passing through the control volume transmit Doppler frequencies or signals that are directly proportional to their velocity. These Doppler frequencies are detected by the receiver.

Radial spray profiles were measured using the PDPA on the 30Dn, 60Dn, and 120Dn; axial distances downstream of the nozzle orifice. Measurements were taken varying the radial positions (r) by the 3-D traversing rig. The values of D32, D10, and u_x were measured with the changing β, r, and x positions. In Fig.1, the ‘R’ indicates the radius of the spray.

3. RESULTS AND DISCUSSIONS

The SMD (D32) provides a good indication of the drop size dispersion characteristics in the TPGL spray. From Fig. 2 it is evident that D32 values are greater at the center of the TPGL spray due to higher non-spherical droplet density persists around this zone. However, further away from the center of the spray, the D32 values significantly decrease as around this zone droplets are more disperse. At the periphery of the spray, the D32 values are flattened out and in some cases a bit increase as around this region droplets may coalesce to each other.
Fig. 2 Effects of the GLR (gas-to-liquid-ratio, \( \beta \), by mass) on the SMD/D_{32} profiles with changing \( r \) at a fixed axial distance of 60 \( D_n \) and 620 kPa mixing pressure.

Fig. 3 Profiles of \( D_{10}, D_{20}, D_{30}, D_{32}, D_{43} \) with changing \( r \) at a fixed axial distance of 60 \( D_n \) and 620 kPa mixing pressure.
In Fig. 3, $D_{10}$, $D_{20}$, $D_{30}$, $D_{32}$, and $D_{43}$ profiles with changing $r$ at a fixed axial distance of 60 $D_n$ and 620 kPa mixing pressure ($P_m$) is depicted. All the profiles indicate that the droplet sizes are greater at the center of the spray. However, further away from the center of the spray, the droplet size decreases significantly and finally fattens out at the periphery of the spray.

The $PDA$ provides the two-component droplet velocity ($u_x$, $u_y$) and droplet diameter ($d_d$). However, it cannot provide the continuous phase gas (air) velocity data in the TPGL sprays. Experimentally it is difficult to obtain the continuous phase gas velocity data in the TPGL atomization process. However, Crowe (2006) provided a correlation for how to obtain the continuous phase gas velocity by solving a particle motion equation and knowing the droplet velocity from the $PDA$. This correlation was subsequently defined:

$$
\frac{U_d}{U_g} \approx \frac{1}{1+St}
$$

Here, $St$ was the Stokes number. If the $St$ number tends to be zero, there would be no slip between the two phases of fluid. In this study, the $U_g$ value was obtained from the $St$ number and by knowing the $U_d$ and $D_{10}$ values from the $PDA$ data.

![Graph](image)

**Fig. 4** Effects of the GLR (gas-to-liquid-ratio, $\beta$, by mass) on the $St$ and $D_{10}$ profiles with changing $r$ at a fixed axial distance of $60D_n$ and 620 kPa mixing pressure.

In the atomization process, the $St$ number is a very important parameter. The $St$ number is defined as the ratio of the droplet momentum response time over a flow system response time, defined as:

$$
St = \tau_p/\tau_c = \rho_d D_{10}^2 U_l/18 \mu_l r
$$

In Fig. 4, the droplet $St$ number and $D_{10}$ profiles with changing $r$ and $\beta$ at a fixed axial distance of 60 $D_n$ are depicted. The $P_m$ was maintained at a constant pressure of 620 kPa and the flow rates of gas/liquid were varied to obtain different $\beta$ of 0.60%, 1.20%, and 1.85% at the constant pressure of 620 kPa. Here, $R$ is the radius of the spray which is 65 mm. First, it is observed that if the '$r$' increases, the $St$ number decreases remarkably due to the smaller droplet response time at the periphery of the spray. If the $St$ number tends to be less than 1, the droplets will have ample time to respond to changes in continuous phase flow velocity. However, if $St$>>1, then the droplets will have essentially no time to respond to the continuous phase fluid velocity changes and the droplet velocity will be affected very little by the fluid velocity change (Crowe, 2006). In our study similar observations for droplets suspended in the atmospheric air were noticed. The $St$ number reached a value of one at $r/R$ of 0.25. Thus, at the center of the spray the droplet response time is much higher than that of the continuous air phase. At the center of the spray, a remarkable amount of slip exists between the liquid and gaseous phases. However, at the spray outer region, the droplet response time followed the...
continuous phase response time. In addition to the above fact, it is also observed that the $St$ number profiles do not differ significantly in the radial direction for the $\beta$ values of 0.60%, 1.20%, and 1.85% at the constant pressure of 620 kPa until the point where the $St$ number is equal to 1. However, after the point where the $St$ number is equal to 1, the higher $\beta$ exhibits the lower $St$ numbers in the radial direction due to the reduction of the jet half width.

![Diagram](image_url)

**Fig. 5** Effects of the $GLR$ on the $We_g$, $Re_d$ and $U_g$ profiles with changing $r$ at a fixed axial distance of 60 $D_n$ and 620 kPa mixing pressure.

Droplet response with the $St$ number can be further demonstrated by the $D_{10}$ profile data set. In Fig. 4, it is initially observed that if the $\beta$ values are increased, the $D_{10}$ values are decreased. Secondly, until the $St = 1$ at the radial distance of $r/R = 0.25$, the $D_{10}$ values are decreased as the droplets continue to break-up up to this point. However, as soon as the $St$ reached 1, droplet break-up began to cease, thus the droplets started to coalesce forming bigger droplets (higher $D_{10}$ values) with increasing radial distances.

The $TPGL$ atomization behavior can be fully understood by the aerodynamic $Weber$ number ($We_g$) and droplet $Reynolds$ number ($Re_d$). The $We_g$ is the measure of the relative importance of the fluids’ inertia compared to its surface tension, which can be defined as $We_g = \frac{\rho(\bar{U}_l-\bar{U}_g) r}{\sigma}$. Whereas the $Re_d$ is the measure of the relative importance of the droplet’s inertia compared to its viscosity, which is defined as $Re_d = \frac{\rho \bar{U}_l r}{\mu}$. A spray breaks up further downstream from the tip of a nozzle. A typical $TPGL$ atomization process involves primary atomization (PA) and secondary atomization (SA). The dominant forces involved in the atomization process are (Nasr et al., 2002): a) hydrodynamic or inertial force attributed to undulations/perturbations, b) aerodynamic force attributed to drag/shearing effect, c) viscous force attributed to an oppositional change in liquid geometry, and d) surface tension forces attributed to a minimum surface energy. The first two forces are disruptive in nature and the second two forces are cohesive in nature. Another mechanism for the $TPGL$ atomization mechanism is the ‘bubble energy’ explosion (Lefebvre et al., 1988; Roesler et al., 1989). It was postulated that jet break-up occurs when the bubbles within the bulk liquid possess enough energy to overcome the surface tension forces that hold the liquid jet together. When the bubbles have enough energy, the
In Fig. 5, the droplet break-up mechanism was investigated by the \( We_g \), \( Re_d \) and \( U_g \) profiles with changing \( r \) and \( \beta \) at a fixed axial distance of \( 60 D_n \). Here, \( R \) was the radius of the spray which was 65 mm. The \( P_m \) was maintained at a constant pressure of 620 kPa and the flow rates of gas and liquid were varied to obtain the \( \beta \) of 1.20\%, 1.85\%, and 3.20\% at that constant pressure. An interesting observation is that the \( U_g \) has higher values between the center and periphery of the spray in the radial direction (\( r \)). Due to this peak of the \( U_g \) value, the droplets break-up further downstream radially and axially, which is termed as the \( SA \). In literature, several correlations were hypothesized to predict the \( SA \) in terms of the \( We_g \). The interaction of internal forces such as turbulence, inertial effects, and momentum transfer between transverse layers of a jet, are mainly responsible for the \( PA \) (McCarthy et al., 1974). At this stage the disruptive forces exceeded the consolidating forces which resulted in oscillations on the liquid surface and subsequently disintegrated the bulk liquid into drops (Liu, 1999; Shavit et al., 1996). The \( SA \) in a spray occurs when larger droplets or liquid ligaments break down into smaller droplets. The breakup of a single droplet in a gas is caused by either greater relative velocity, or turbulence (Crowe, 2006). In Fig. 5, the greater relative velocity exists at this peak point of \( U_g \) profile. The \( SA \) occurs due to two force ratios acting on the drop (Pilch et al., 1987). If at first the aerodynamic forces overcome the forces due to the surface tension, the droplet will further deform (Low et al., 1982). The two dimensionless numbers can represent the ratio of these two forces. The \( We_g \) plays a vital role in the first stage of the \( SA \) process. Secondly, the \( Ohnesorge \) number, denoted by \( Oh (\mu / \sqrt{\rho} d_n \sigma) \), which is the ratio of liquid viscous force to surface tension force on the drop, also plays an important role in the \( SA \) process. It was postulated that if the \( We_g \) exceeds the \( We_{crit} \) (‘crit’ denotes for critical), the \( SA \) occurs. For low-viscosity liquids, \( We_{crit} = 6 \) to 13 for \( Oh<0.1 \), \( We_{crit} \approx Oh^2 \) for \( Oh>0.1 \) (Faeth, 1990). To find out the \( We_{crit} \) in Fig. 5 a perpendicular line was drawn from the peak value of the \( U_g \) profile that intersects the \( We_g \) number profile at a point. The value of the \( We_g \) number at this point can be termed as the \( We_{crit} \) which is approximately 500. In Fig. 5, it is also observed that the \( We_g \) and \( Re_d \) decreased remarkably with the radial distances up to the \( We_{crit} \) limit. However, after a few radial distances from the \( We_{crit} \) limit, the \( We_g \) and \( Re_d \) decreased slightly with the variation of the \( \beta \) values.

In Fig. 5, it was also observed that the \( Re_d \) varied from 700 to 7000 due to the variation of the \( r/R \) values. If the \( Re_d < 1 \), the \( TPGL \) flow can be termed as \( Stokes \) flow. In the \( Stokes \) flow regime, viscous droplets remain spherical. The wake formed behind the droplets became stronger as the \( Re_d \) increases and the inertia of the flow around the droplets overcame the viscous effects on the surface of the droplets (Crowe, 2006). It is also observed that the \( Re_d \) value decreased with the radial distances. However, the \( U_g \) still has enough momentum, which can induce a slip between the two phases. Thus, although the \( Re_d \) value increases with the \( r \), the higher relative velocity between the phases is still responsible for the \( SA \) process.

In Fig. 6, the droplet \( St \) and \( D_{10} \) profiles with changing axial distances (\( x \) of \( 30D_n, 60D_n, 120D_n \)) and radial distances (\( r \)) are depicted. Here, \( R \) is the radius of the spray which was 40 mm with the \( \beta \) of 2\% at a \( P_m \) of 520 kPa. It was initially observed that if the ‘\( r \)’ and ‘\( x \)’ increase, the \( St \) number decreases remarkably due to smaller droplet response time compared to that of the continuous phase gaseous medium. Secondly, the \( St \) number reaches the value of 1 at \( r/R \) of 0.40 for axial distances of \( 30D_n, 60D_n, 120D_n \), respectively. Droplet break-up characteristics with the \( St \) number can also be verified with the \( D_{10} \) data. It was observed that at \( 120D_n \) downstream of the nozzle orifice, the droplets are more disperse compare to other two cases. Thus, near the center (\( r=0 \)) of the spray at \( 120D_n \) downstream from the nozzle orifice, the \( D_{10} \) values are lower than at \( 30D_n \) and \( 60D_n \) downstream \( D_{10} \) values at the similar radial position (\( r=0 \)). In the later cases, the droplets were not fully atomized, which can be further explained with the \( We_g \) and \( Re_d \) profiles. However, as soon as the \( St \) value reaches 1, further away from the center, the \( D_{10} \) values...
are higher at $120D_n$ downstream from the nozzle orifice than at $30D_n$ and $60D_n$ downstream values at the similar radial position. This is due to the fact of coalescence of droplets around this zone.

In Fig. 7, the droplet break-up mechanism was examined by the $We_g$, $Re_d$ and $U_g$ profiles with changing axial distances ($30D_n$, $60D_n$, $120D_n$) and radial distances ($r$). Here, $R$ is the radius of the spray which was 40 mm. The $\beta$ for this condition was maintained at 2% with a $P_m$ of 520 kPa.

![Graph showing droplet St and D10 profiles with changing radial distances (r) at 2% GLR.]

An interesting observation in Fig. 7 is that the $U_g$ had higher values between the center and periphery of the spray in the radial direction. Until the highest $U_g$ value, the droplets had a tendency to breakup further. Thus, in Fig. 7, again the $We_{crit}$ value was obtained by drawing a perpendicular line from the $U_g$ profile that intersects the $We_g$ profile at a certain point. The value obtained at this point is termed the $We_{crit}$. In Fig. 7, it was also observed that the $We_g$ and $Re_d$ decreased remarkably with axial distances and radial distances. If the $We_g$ exceeds the $We_{crit}$, droplets will have the tendency to break-up further due to higher momentum transfer between the phases. Thus, it was observed that further downstream of the spray ($120D_n$), the $We_{crit}$ value was less compared to the upstream condition ($30D_n$). However, the reverse case was observed for the $U_g$ values. At $120D_n$ downstream from the orifice of the nozzle, the $U_g$ had greater values compared to $30D_n$ downstream of the spray, indicating the bubble explosion imparted higher momentum than the gas phase further downstream.

In Fig. 7, it is also observed that the $Re_d$ varied from 800 to 6500 in the radial direction. Downstream of the spray ($120D_n$), the momentum of the droplet decreased remarkably compared to the upstream condition ($30D_n$). However, for similar positions the gas phase still had enough momentum as it had just been exploded at the nozzle orifice. This also provides the
basis for why the $U_g$ exhibits higher values at 120$D_n$ compared to 30$D_n$ and 60$D_n$ downstream from the nozzle orifice. However, it seems that the $Re_d$ values are lower further downstream as the droplets lose momentum. Thus, the $Re_d$ values are not fully capable of explaining the droplet atomization behavior further downstream of the spray.

![Graph](image)

**Fig. 7** Effects of the axial distances on the $We_g$, $Re_d$ and $U_g$ profiles with changing radial distances ($r$) at 2% GLR.

### 4. CONCLUSIONS

The fundamental knowledge of the TPGL flow/atomization process in nozzles is important for many industrial and chemical reactions. The outcome of this research will help in optimization of commercial process conditions and provide a comprehensive means of improving the design conditions of the TPGL flow/atomization process. Specifically, this project will assist to optimize the operating range of the existing steam/bitumen fluid cooking nozzles used in the heavy oil upgrading process. Knowledge obtained will contribute to the development of a new series of nozzles heavy oil industry is currently bringing to market. Atomization from the nozzle likely depends on flow patterns, void fractions, and bubble size distribution in the upstream FC. Thus, it is essential to have a good understanding and a reasonable estimate of the bubble size, flow regime, void fraction, pressure drop, and subsequent droplet size distribution in turbulent TPGL flow. A wide variety of operating conditions need to be introduced in the experiment to obtain a better correlation of the flow conditions and spray characteristics.

The $St$ number is useful to evaluate the $U_g$ values using a particle motion equation. Eventually, the $U_g$ value is required to obtain the $We_g$ and $Re_d$ values, which are very useful dimensionless numbers used to predict the TPGL spray atomization and specially the droplet $SA$ commencement. In this study, two types of conditions were studied. The value of $\beta$ was first varied from 0.60%, 1.20%, and 1.85% at the constant pressure of 620 kPa at a fixed axial downstream of 60$D_n$. It was observed that the $St$ number reached the value of 1 at the $r/R$ of 0.25 distance. Thus, at the center of the spray the droplets response time was much higher than
that of a continuous phase gaseous medium. However, at the spray outer region, the droplet response time followed the continuous phase response time. As soon as the \( St \) reached 1, breakup stopped, thus the droplets started to coalesce forming bigger droplets (higher \( D_{10} \) values) with increasing radial distances. It was also observed that the \( We_g \) and \( Re_d \) decreased remarkably with the radial distances \( r \) before the \( We_{crit} \) limit. However, the \( We_g \) and \( Re_d \) decreased slowly with the variation of the \( \beta \) values after the \( We_{crit} \) limit.

In the second set of studies, the droplet atomization behavior was examined with changing axial distances \( x \) of \( 30D_n, 60D_n, 120D_n \) and radial distances \( r \). In this case the \( \beta \) was 2% at a \( P_m \) of 520 kPa. It was observed that if the \( 'r' \) and \( 'x' \) was increased, the \( St \) number decreased remarkably due to smaller droplet response times compared to the continuous phase response time. The \( St \) number reached the value of 1 at the \( r/R \) of 0.40 for axial distances of \( 30D_n, 60D_n, 120D_n \) respectively. Thus, near the center \( (r = 0) \) of the spray at \( 120D_n \) downstream, the \( D_{10} \) values were lower than that of \( 30D_n \) and \( 60D_n \) at the similar radial positions \( (r = 0) \) due to greater droplets break-up in further downstream.

5. ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support used to carry out this study provided by Syncrude Canada Ltd., CRD grant, Alberta Ingenuity, and NSERC.

6. LIST OF SYMBOLS, NOMENCLATURE, OR ABBREVIATIONS

**Abbreviations**

- GLR: gas to liquid ratio by mass
- FC: feeding conduit
- PDPA: Phase-Doppler-Particle-Analyzer
- PA: primary atomization
- SA: secondary atomization
- TPGL: two-phase gas/liquid flow

**Symbols**

- \( D_n \): nozzle diameter (m)
- \( D_{10} \): arithmetic mean diameter (m)
- \( D_{12} \): sauter mean diameter (m)
- \( D \): diameter (m)
- \( d_d \): droplet diameter (m)
- \( d_b \): bubble diameter (m)
- \( m_g \): mass flow rates of the gas phase (kg/sec)
- \( m_l \): mass flow rates of the liquid phase (kg/sec)
- \( N \): number of samples (-)
- \( P_m \): mixing pressure (Pa)
- \( Q_g \): volume flow rate of the gas phase (m³/sec)
- \( Q_l \): volume flow rate of the liquid phase (m³/sec)
- \( r \): radial position (m)
- \( R \): radius of the spray (m)
- \( U_g \): velocity of the gas phase phases (m/sec)
- \( U_l \): velocity of the liquid phases (m/sec)
- \( U_d \): velocity of the droplet (m/sec)
- \( x \): axial distance (m)
Greek Letters

$\phi$  scattering angle (°)
$\beta$  gas to liquid ratio by mass (%)
$\rho$  density (kg/m³)
$\rho_l$  density of liquid phase (20°C pure water, 998 kg/m³)
$\mu$  viscosity (kg / m.s)
$\mu_c$  viscosity of the carrier fluid (20°C pure water, 1.00×10⁻³ kg/m.s)
$\mu_g$  viscosity of the gas phase (20°C air, 1.82×10⁻⁵ kg/m.s)
$\sigma$  surface tension (20°C pure water, 72.8 N/m)
$\tau_p$  particle momentum response time (s)
$\tau_c$  flow system time (s)

Subscripts

$c, l, w$  continuous/liquid/water phase
$p,d, g, a$  particle/dispersed/gas/air phase
$d$  droplet

Dimensionless numbers

$Oh$  Ohnesorge number
$St$  Stokes number
$Re$  Reynolds number
$We$  Weber number
$We_{crit}$  Critical Weber number

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