Predicting the Two-Phase Gas/Liquid Spray Break-up Mechanism by the Dimensionless Numbers

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Abstract

In two-phase gas/liquid (*TPGL*) sprays, traditional dimensionless numbers are limited in their use of understanding atomization behaviour. In *TPGL* sprays, the important dimensionless numbers are: Stokes Number (*St*), Reynolds Number (*Re*), Froude Number (*Fr*), Galileo Number (*Ga*), aerodynamic Weber Number (We_g), Eotvos number (*Eo*), and Ohnesorge number *(Oh)*. These numbers are very useful when explaining the droplet break-up mechanism further downstream of the spray. As an example, in this study it was observed that the We_g and *Re* decreased remarkably with the radial distances (*r*) before the We_{crit} limit ('*crit*' stands for critical). However the We_g and *Re* decreased slowly with the variation of the gas-to-liquid ratio (β) values after the We_{crit} limit indicating that no further break-ups would occur after this limit. In this study, radial and axial *TPGL* spray profiles were measured using a Phase-Doppler-Particle-Analyzer (*PDPA*) system. The diameter of the nozzle was 3.10 mm. 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 of 0.30 to 15%. The outcome of this research will assist in the optimization of commercial process conditions and provide a comprehensive means of improving the design conditions of the *TPGL* flow/atomization process.

Introduction

Oilsands are a naturally occurring mix of water, clay or sand and bitumen. The bitumens need to pass through a cracking process in order to convert them into lighter hydrocarbons that can be refined under existing technologies. The cracking process occurs in a fluidized bed reactor unit which allows the interaction of a two phase gas-liquid flow of steam and bitumen droplets, which can be catalogued as a spray with coke particles. A desirable feature for high productivity is to produce a thin uniform layer of bitumen over the coke particles. This layer is possible when the droplets generated from the atomization process are dispersed and uniform. To generate the droplets, the two-phase flow is passed through a ring of patented nozzles which requires mixing the gas and liquid well upstream prior to feeding the mixture through the nozzles.

One of the drawbacks of this spray characteristic is the inherent pulsation within it and in the feeding conduit, which results in a poorly atomized flow that undermines the performance of the whole process. The formation of the coated particles is strongly dependent on the features of the multiphase stream that enters the reactor, so the foremost improvements are related to deeply understanding the characteristics of this type of flow. A stable spray with a minimum Sauter mean diameter (D_{32}) is sought-after in order to produce an optimum coating of the coke particles, thus improving the upgrading process of the hydrocarbons. It is recommended that the bitumen drop size has the same nominal diameter of the coke particle that it is in contact with [1]. Previous studies have shown that at high β, the instabilities in the two phase gas/liquid flow are more frequent [2,3]. The pulsation phenomenon is attributed to any of the following characteristics or a combination of them: the improper conditions of *TPGL*, such as the void fraction (α), the mixing pressure (P_m), and the gas-to-liquid ratio; the flow patterns formed upstream of the nozzle; the design used for the mixing chamber for the two fluids; the nozzle geometry selected; or a possible back pressure effect originating from the high temperature bed coker [4]. As the value of β is increased, at constant P_m, there is a transition point at which the spray changes from steady to unsteady patterns [5,6]. A homogeneous mixture of the two phase gas/liquid flow upstream of the nozzle is likely to maximize the decompression effects in the gas phase resulting in a stable spray . If the two-phase flow present in the feeding conduit is clearly heterogeneous, an unstable spray is produced [7]. Due to the flow intermittency, the non-uniform volumetric distribution, and the possibility of rapidly changing flow patterns; the measurement of two phase gas/liquid flows and sprays is a difficult task. The prediction of droplet sizes (d_d) and flow pattern distributions is a task with a high degree of uncertainty, which becomes accentuated if the feeding conduit is not long enough to allow the flow to become fully developed. Moreover, if the conduit is too long the phases could be separated due to the long residence time, producing an unstable spray which leads to a poor mixing process. The design of the nozzle used in this study is the combined design of typical twin-fluid nozzles and effervescent nozzles.

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Although in previous years atomization studies related to the feed nozzle have been conducted [5,8-10], most of them were based on the equilibrium flow condition, used vertical configurations that neglected the gravitational effects and used a larger length scale set-up. The current study differs from those in that the atomization system is horizontally oriented, a smaller length scale is used, and the flow is under the non-equilibrium condition.

Dimensionless Numbers

There were few attempts to understand the behaviour of two phase gas/liquid spray atomization characteristics and relate them with the available standard dimensionless numbers. To understand the particle behaviour, one of the important dimensionless numbers is the Stokes number (*St*). The *St* is defined as the ratio of the particle momentum response time over a flow system time. Mathematically [11].:

$$St = \frac{\tau_L}{\tau_G} = \frac{\rho_L d_L^2 / 18\mu_L}{D_{10} / u_L} \tag{1}$$

Three types of situations can be observed for particles in fluid, namely: Case a) if $St < 1$, the particle response time is much less than the flow characteristic time. Case b) $St \sim 1$, where the two phases are in thermodynamic or velocity equilibrium. Case c) if $St > 1$, then the particle will have essentially no time to respond to the fluid velocity changes [12]. The relative Reynolds number is another important dimensionless number, which quantifies the relative importance of the inertial forces to viscous forces for given two phase flow conditions [11]:

$$\mathrm{Re}_{rel} = \frac{\rho_L d_L \left| u_L - u_G \right|}{\mu_L} \tag{2}$$

If $Re_{rel} < 1$, the two-phase flow will behave as the Stokes flow. In the Stokes flow regime viscous bubbles or drops remain spherical. In the two phase horizontal flow, *Fr* is the most important dimensionless number as this number can predict the initiation of perturbation in the smooth stratified flow. The *Fr* Number is the ratio of inertial forces to gravitational forces. The Froude number is given by [13]:

$$N_{Fr} = \frac{u_m^2}{gD} \tag{3}$$

Here u_m is the summation of gas phase and liquid phase superficial velocities. When $Fr \sim 1$, the flow velocity is equal to the surface waves' velocity. Another important number to demonstrate the surface tension effect is the Weber number. The *We* number is a measure of the relative importance of the fluid's inertia compared to its surface tension. The Weber number can be defined as [11]:

$$We = \frac{Inertia}{Surface} = \frac{\rho_c u_c^2 L}{\sigma} = Re^2 \left(\frac{Mo}{Eo} \right)^{-\frac{1}{2}} \tag{4}$$

The *Eo* number is proportional to the buoyancy force divided by the surface tension force. The *Eo* number can be defined as [11]:

$$Eo = \frac{Buoyancy}{Surface} = \frac{g d_p^2 \left| \rho_p - \rho_c \right|}{\sigma} \tag{5}$$

here, g is the gravity (m/s^2), ρ_L is the particle density, ρ_G is the continuous phase density (kg/m^3), d_L is the particle diameter (m), and σ is the surface tension (N/m).

In addition to the above dimensionless numbers, the Galileo number is also an important number in the two-phase gas/liquid flow. This number is important in the gravity-driven viscous flow. The *Ga* number is proportional to the ratio of the gravity force to viscous force and can be defined as [11]:

$$Ga = \frac{Gravity}{Drag} = \frac{g d_p^3 \left|\rho_p - \rho_c\right|}{\nu_c^2 \rho_c} \tag{6}$$

here, υ_c is the continuous phase kinematic viscosity (m^2/s). Another frequently used dimensionless number in multiphase atomization is the Ohnesorge number/Laplace number (*Oh*/*Lp*). The *Oh* number can be defined as [11]:

$$Oh = \frac{\sqrt{We_l}}{\mathrm{Re}_l} = \frac{\mu_l}{\sqrt{\rho_l \sigma D_l}} = \frac{1}{\sqrt{Lp}} \tag{7}$$

In the results section, the effects of the different operating pressures such as gas to liquid mass ratio and mixing pressure on the various useful proposed dimensionless numbers and subsequent expiation of two phase atomization will be explained.

Experimental setup

To study the characteristics of a two phase gas/liquid atomization, a small scale nozzle facility was used. The nozzle was scaled at a dimension equal to one-quarter of a patented full-scale design (US Patent #: 6003789) utilized in the coker unit for the heavy oil upgrading process. A nozzle assembly, with lengths of 36.80 cm and a nozzle ID of 6.35 mm (Figure 1), was used upstream of the nozzle section. This section was used as the mixing chamber. The nozzle diameter (D_n) was equal to 3.10 mm. The gas used in the experiments (air) was supplied from a standard compressor unit, while a reciprocating pump was used to create a recirculating current from the liquid collector tank to the mixer section located before the conduit.

To measure the mean drop size, a 2D-Phase Doppler Particle Analyzer was the chosen technique. The focal lengths of the lenses used were 400 and 310 mm respectively. The *PDPA* was operated in refraction-scatter mode, and the receiver was set to a scattering angle of 30º (Figure 1) during data collection. Due to manufacturer's specifications, the first order refraction is the most important scattering mode at the angle selected for water droplets in air. Radial velocity profiles were measured at $60D_n$ axial distances downstream of the nozzle. The measurements were taken at different radial positions measured from the nozzle centreline which vary from -30 mm to +30 mm. The working principle of the *PDPA* unit was found in literature [14-18].

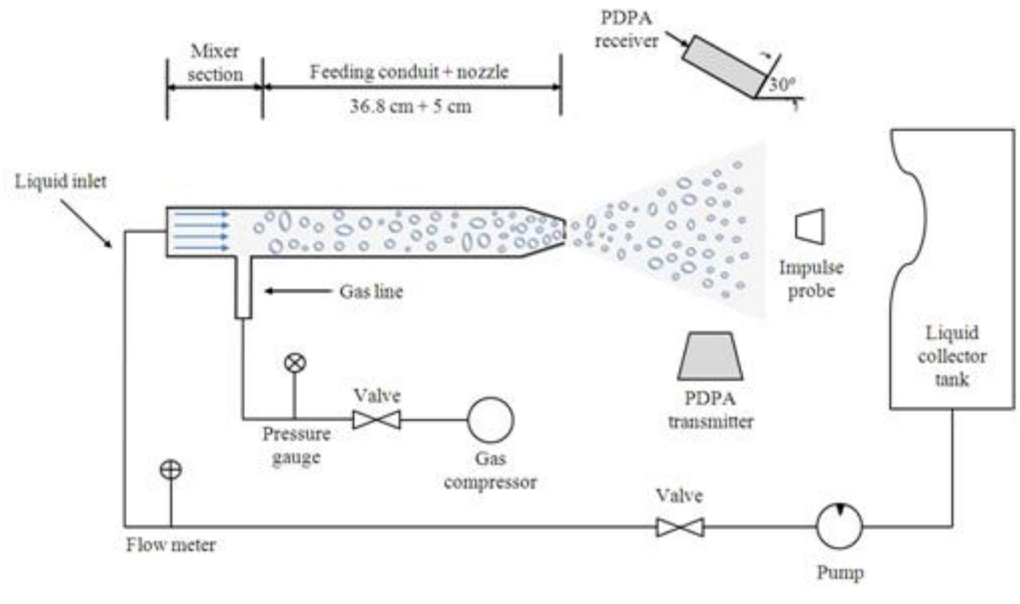

Figure 1. Schematic of the experimental set-up.

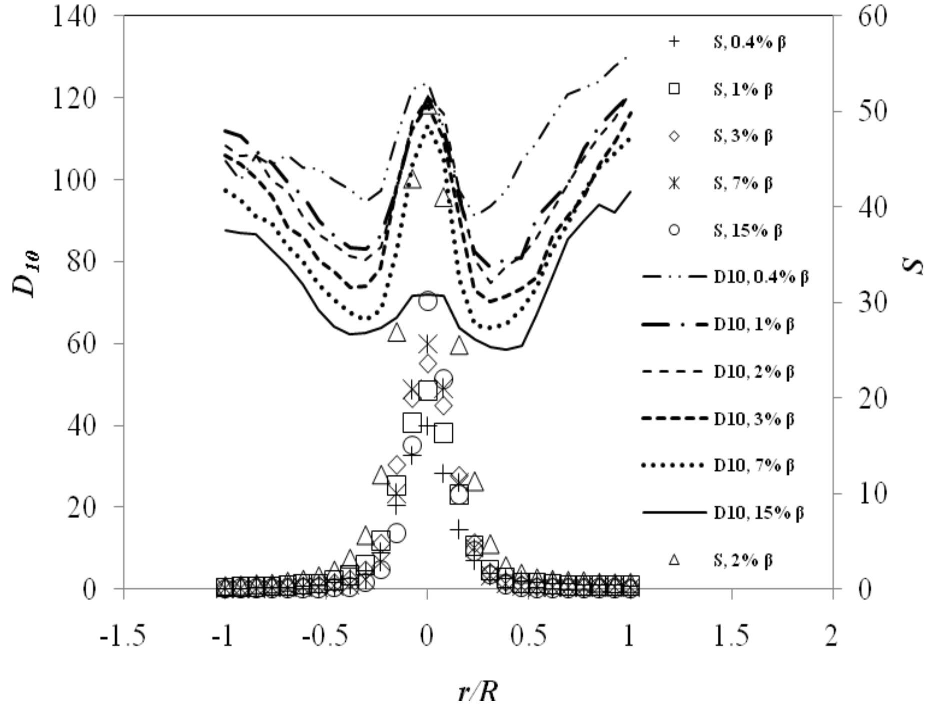

Figure 2. Effects on slip velocity between the phases varying the gas to liquid mass ratio.

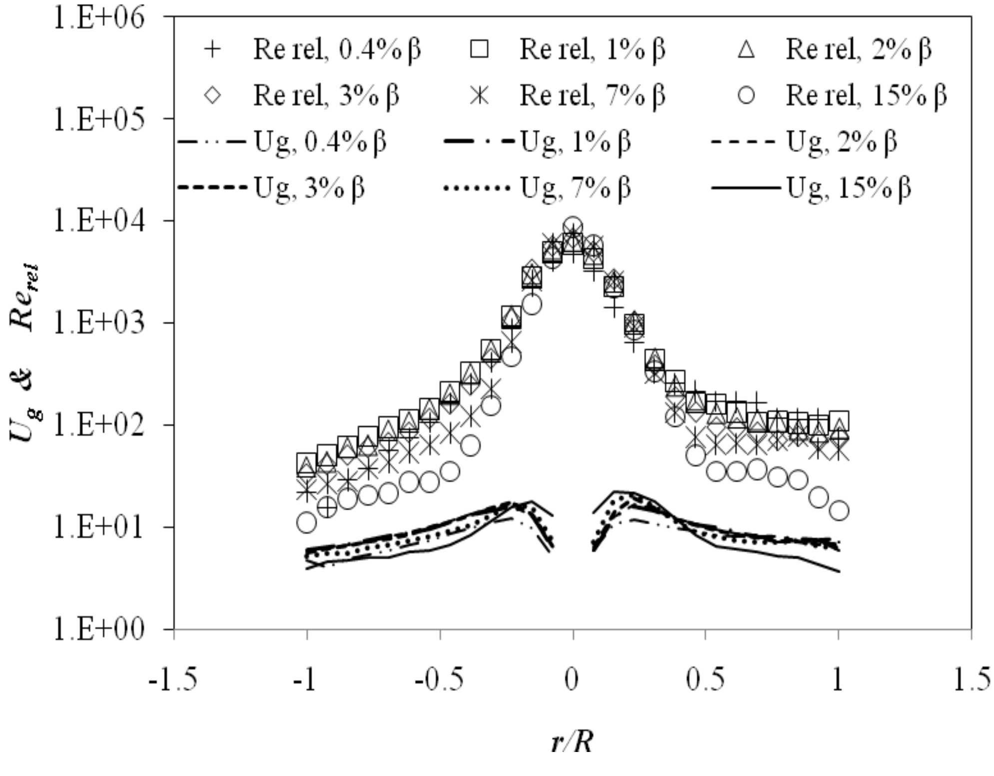

Figure 3. Effects on Re_{rel} and U_g varying the gas to liquid mass ratio.

The values of the D_{32}, droplet diameter (D_{10}) and axial velocity (u_x) were measured changing the values of β and P_m. The droplet size is found by means of detection of the incident droplets on the receiver (Figure 1). The size of the droplet is directly proportional to the phase shift of scattered light in the control volume. The droplet velocity can be found using a similar principle, however in this case the droplets passing through the control volume transmit Doppler frequencies or signals which are proportional to their velocity and are captured by the receiver. Droplet size was measured by detecting the incident droplets on the receiver detectors. These Doppler frequencies are also detected by the receiver.

Results and Discussions

In Figure 2, the effects of changing air to liquid mass ratio on the droplet diameter and slip velocity (S) between the two phases are presented. It is evident that the slip velocity is highest in the centre of the spray. However interestingly, the slip values for all the β cases collapse with each other. Although at 15% β the velocity difference between the two phases is the highest, the slip velocity collapses with other β cases. Interestingly the droplet profile is 'W' shaped at a constant mixing pressure of 482 kPa for the cases shown. Thus, the nozzle geometry and internal two phase flow is responsible for the droplet break up mechanism in this type of atomization. After the radial distance of 0.5 r/R and -0.5 r/R, the slip velocity is negligible and becomes almost zero. Thus, the higher values of the droplet after these radial distances are the consequences of air entrainment effects and improper liquid break-up. However, due to the enhanced shear between the two phases of fluid, the D_{10} values are the smallest for the 15% β case.

In Figure 3 the gas phase velocity (U_g) and relative Reynolds number (Re_{rel}) values with changing β cases are depicted at $60D_n$ nozzle downstream and a 482 kPa constant mixing pressure. The U_g is highest between the centre (r = 0) and 0.5 r/R radial distances. Thus, although apparently the velocity differences between the liquid and gas phases are greater at the centre of the spray due to the greater values of Re_{rel} at the centre of the spray, the U_g values are not highest at the centre of the spray. Thus, by observing the Re_{rel} and S values, one cannot fully predict the droplet mechanism. That is why it is essential to determine U_g values to ensure droplet diameter is the smallest near the radial distance of $\pm$ 0.5 r/R.

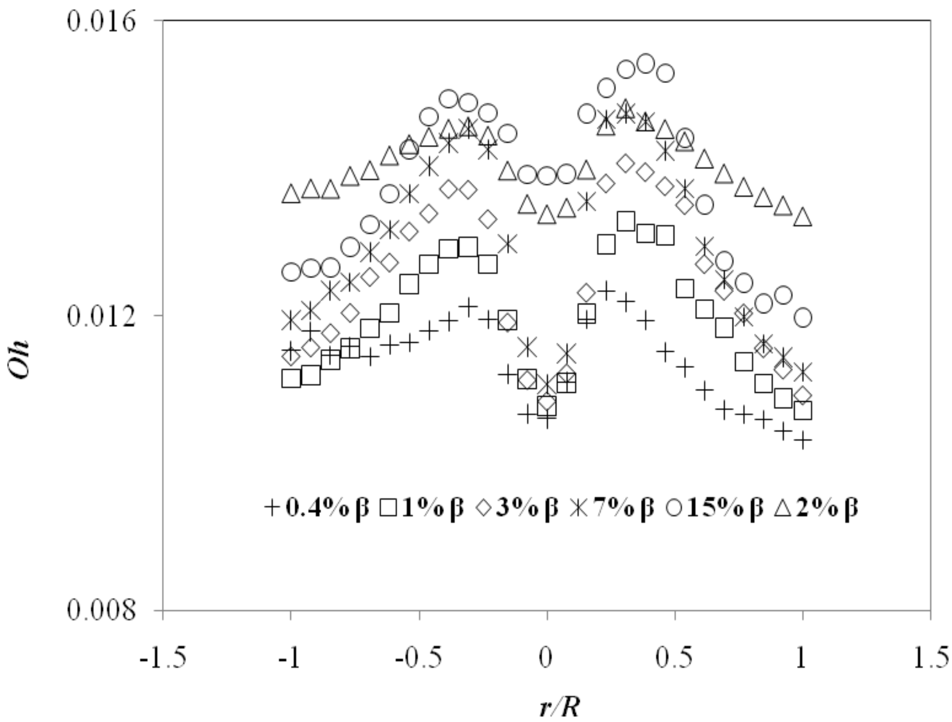

Figure 4. Effects on the *Oh* number varying the gas to liquid mass ratio.

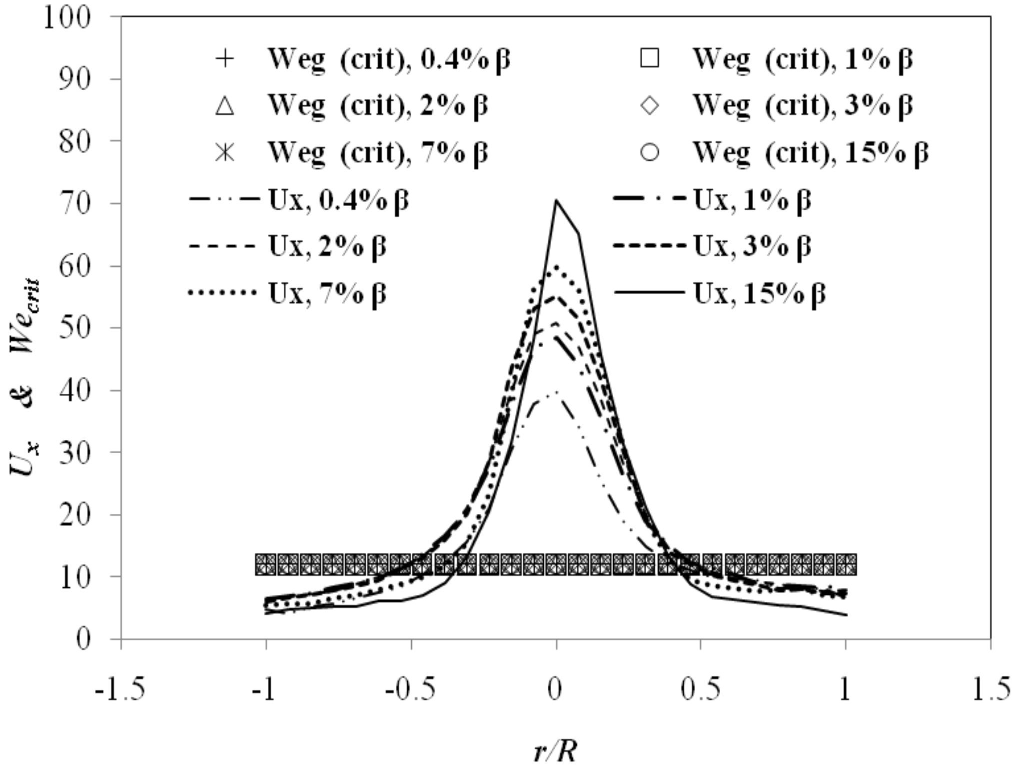

Figure 5. Effects on the We_{crit} and U_x number varying the gas to liquid mass ratio.

In Figure 4, the effects of the β on the Ohnesorge number (*Oh*) are presented. The *Oh* number is the ratio of viscosity effects over the surface tension effect. From the values of the *Oh* numbers, which are in the range of 10^{-3} range, it is evident that the viscosity effects are negligible compared to the surface tension effects. However, if the

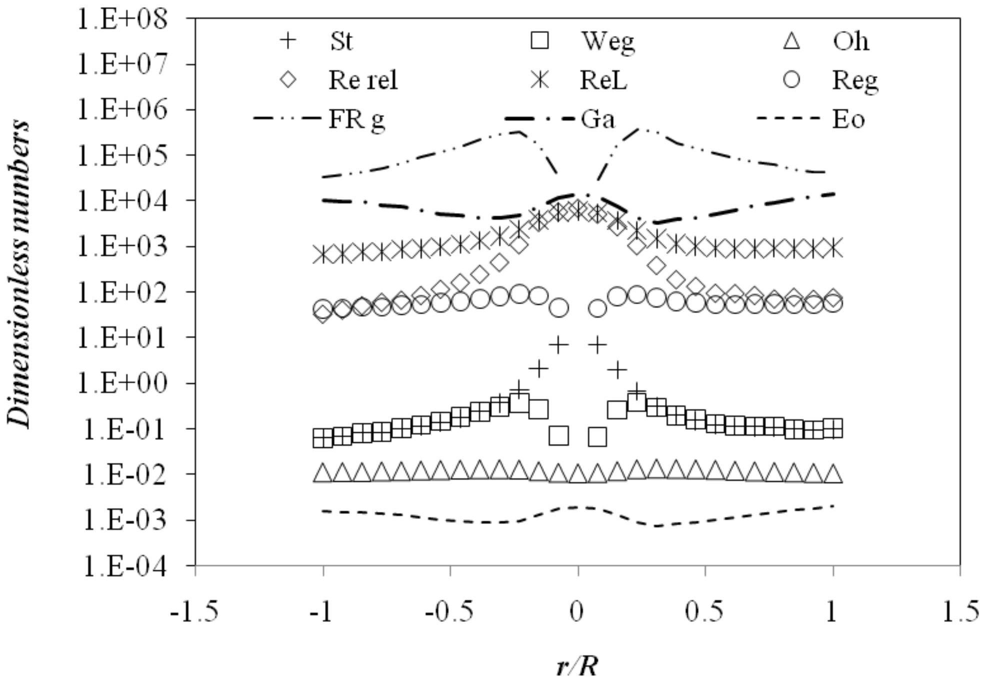

Figure 6. Effects various dimensionless numbers of the spray beak up mechanism at 2% gas to liquid mass ratio.

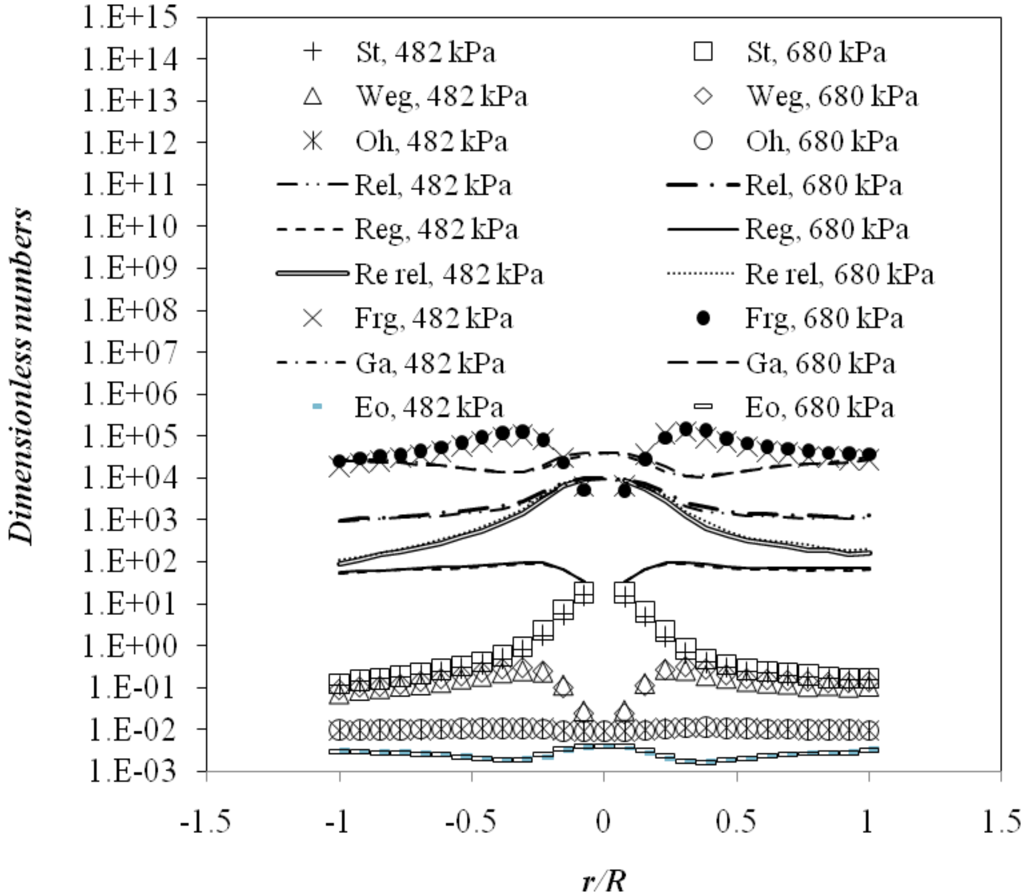

Figure 7. Effects various dimensionless numbers of the spray beak up mechanism at 3% gas to liquid mass ratio and different mixing pressure**.**

β increases, the viscosity effects become more important compared to the lower β cases. In Figure 5 the effects of the β on the axial velocity (U_x) and critical Weber number (We_{crit}) are presented. The U_x is highest at the centre of the spray and decreases with axial distances. Moreover, U_x increases with the β values. The droplet break-up completes at the We_{crit}. Thus, regardless of the β values, the droplet break-up achieves We_{crit} values of 12 in all the cases.

In Figure 6 the behaviour of different dimensionless numbers with varying spray radial distances is depicted. It is evident that *Oh*, *Eo*, *St*, We_g dimensionless numbers are not important due to their small values compared to other dimensionless numbers. It also evident that the important dimensionless numbers are the Fr_g and *Ga* numbers. The Re_g, Re_L and Re_{rel} values show that these dimensionless numbers have moderate significance.

In Figure 7, the behaviour of different dimensionless numbers with varying mixing pressure is depicted. It is evident that the mixing pressure does not have any remarkable effects on the spray break up mechanism. As indicated in the previous section, the Fr_g and *Ga* numbers have significant effects on spray droplet size in both ranges of mixing pressure investigated.

Conclusions

The available standard dimensionless numbers are effective tools to describe the break-up mechanism of two-phase gas/liquid atomization. From this study, it is evident that the Froude number and the Galileo number are the important numbers that demonstrate the dominant forces acting on the atomization. Thus, the gravity force, inertia force, and the drag force are the dominant forces in the droplet formation from a nozzle which has a hybrid design of an effervescence nozzle and twin fluid nozzle. Gravity forces try to stabilize the system, thus inhibiting further break-up of droplets. On the contrary, the inertia force and drag force disrupt the system, thus enhancing further break-up of droplets. When there is equilibrium between these forces the droplet break up completes. Moreover, from this study is it evident that the gas phase velocity has an important role on the break up mechanism while the mixing pressure has less effect on the atomization.

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