Effects of Gas Phase Density on Effervescent Atomization

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Abstract

For scaling considerations in the development of future effervescent nozzle prototypes, the challenge is to minimize the dissimilarities between the real, i.e. hot, operation of the nozzle and the laboratory, i.e. cold flow spray tests. In commercial or hot pilot plant operation of the nozzles, steam is used to atomize bitumen at 350°C. In cold flow spray tests, air is usually used to atomize water at ambient temperatures, ~20°C. To overcome this dissimilarity, this study was attempted to compare two different gas densities (air and mixed gas of 81.4% helium/18.6% nitrogen) at equivalent operating temperatures. Experiments conducted in a nozzle sized to one quarter of the commercial scale using the Dantec 2-D fibre mode Phase-Doppler-Particle-Anemometer, and high speed visualization show no appreciable variation of droplet Sauter Mean Diameter ($D_32$) in the spray and pressure gradient ($dp/dx$) in the upstream two-phase flow for the two ranges of gas density investigated in this study. This study will be a milestone toward energy-efficient technology development for multiphase scaling that would be of very significant value to industries and to the scientific community in general.

Keywords

Scaling, Effervescent atomization, Bubble Size, Droplet Size, Horizontal Nozzle, Stroboscopic Back Scattered Imagery, Phase Doppler Particle Anemometer.

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Introduction

The characterization of multiphase flow and multiphase atomization under in-furnace or in-process conditions are challenging tasks (Fig. 1). Moreover, experimental investigation of the operating conditions such as velocity ($u_m$), pressure ($P_m$), physical properties of fluid (density, $\rho$; surface tension, $\sigma$; viscosity, $\mu$; molecular weight, $M$), gas to liquid mass ratio ($\beta$) and hydrodynamics of a droplet ($D_d$) and a bubble ($D_b$) is difficult in commercial scale due to safety and high temperature restrictions. The majority of the cold flow spray nozzle tests have been performed using air as the atomization gas [1-11]. Very few attempts were previously undertaken to investigate the effects of gas phase molecular weight on the two-phase atomization [12, 13]. In the current study, in order to simulate the atomization performance of the commercial Coker feed nozzles at actual hot operating conditions ($350^\circ$C) under cold flow conditions, the liquid phase, bitumen, is simulated with water [10]; and the small amount of steam ($\sim$1-4 wt %) is simulated with a mixed helium/nitrogen gas instead of air. This mixture of 82 wt% Helium and 18 wt% Nitrogen was used because it’s density or molecular weight at room temperature compares to the density or molecular weight of the atomization steam that is used in the commercial system at operating pressures. Once the scaling of the gas phase density is established, the large volume of experimental data using air and water as the process fluids in the lab scale experiments help to find the effects of upstream flow conditions such as $\beta$ on bubble diameter ($D_b$) or the droplet size ($D_d$) distribution in the downstream spray.

Since gas assisted atomization is becoming increasingly important in many industrial applications such as physical, chemical and petroleum processes, it is critical to understand the fundamental physics behind the upstream two-phase flow transport phenomena (such as $\beta$, $D_b$) and its subsequent effects on the downstream atomization behavior ($D_d$).

Gas Phase Scaling

To overcome the dissimilitude, previous attempts [10] endeavoured to scale the liquid viscosity and surface tension in the cold flow tests with that of bitumen viscosity and surface tension in the hot flow tests. It was also necessary to scale the density of the gas phase. Thus, it was decided to use a mixed helium/nitrogen gas to replace air in the cold flow lab scale spray tests. The commercial feed nozzle operates at $\sim$1651 kPa (225 psig) and $\sim$350°C. By proportioning helium and nitrogen in a gaseous mixture, a nozzle operating at the pressure of 531 kPa and at a room temperature of 15°C, yields a gas density of 1.84 kg/m$^3$ and molecular weight of 8.46. At 1,651 kPa or 225 psig, 350°C and characteristic gas constant of 461 J/kg.K, $\rho_g$ was found to be 5.74 kg/m$^3$ ($0.358 \ lb/ft^3$) and molecular weight of 18. However, at 531 kPa, 15°C and air gas constant of 287 J/kg.K, $\rho_g$ was found to be 6.5 kg/m$^3$ and molecular weight of 29. The equivalent temperature in the lab scale nozzle to work in the operating pressure of steam (1,651 kPa or 225 psig and at a room temperature of 15°C) was found to be 729°C. With a composition of 81.4 vol % helium and 18.6 vol % nitrogen; and a molecular weight of 8.4, the mixed gas was used to scale gas phase molecular weight.

Experimental Set-up

In this study, a one-quarter scale of a patented full-scale nozzle, US Patent of 6003789 [53], was used (Fig. 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 located upstream of 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 particles produced by shadowgraph and back-illumination using an infrared diode laser were investigated with a digital image analysis technique [23]. This technique was potentially capable of sizing particles of arbitrary shape and size and with a wide dynamic range. Further studies on advanced photonics measurements can be found in the literature [1, 24-39]. There are also several studies [40-52] found in the literature related to the transport of two-phase, gas/liquid flows through pipelines.
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 mean drop size was measured using a 2-D Phase Doppler Particle Anemometer (PDPA) using Dantec Dynamics specifications [54]. The working principal of the Phase Doppler Particle Analyzer can be found in the literature [55-59]. A round transparent plexiglass pipe was used to visualize the two-phase gas/liquid flow regimes and bubble size distribution inside the nozzle conduit. A 1531-A STROBOTAC electronic stroboscope was used to freeze the bubble motion with back illumination. This device can measure up to 250,000 rpm speed with ±1% accuracy within 0.8 µs flash duration. A D100 high-performance single-lens-reflex (SLR) digital camera was used to capture the back scattered illuminated images. The Micro-Nikkor 55 mm/f: 3.5 micro reverse lens was used with a reversing ring for macrophotography. This highly rated lens can reach a maximum magnification ratio of 1:2 (0.5X) with its internal helical focus mechanism. To obtain even higher magnification, a Bellow unit (Nikon PB-4) was used. With this combination, the magnification ratio reached up to 2X-5X. A Phrotom 1280×1024 monochrome PCI fast cam was implemented to capture the bubble motion using the shadowgraph method. An ARRISUN 12 HMI 1200W lamp-head was used as the light source on the opposite side of the fast cam. Also a built-in blackbody slit was used to concentrate the light in the 6.35 mm (ID) conduit section. For the power source a flicker free ARRRI 575/1200 kW electronic ballast was implemented. Recording rates ranged from full pixel resolution of 500 frames per second to low pixel resolution of 16,000 frames per second. In this study, 4000 frames per second with 640×128 pixel resolution and 2000 frames per second with 1280×256 pixel resolution were used for the air-water and mixed gas-water experiments, respectively. MATLAB 7.1 code was utilized to filter the highly dense bubble population.

Results and Discussions

The Phase Doppler Particle Anemometer (PDPA) measured the droplet velocity very reliably using the Doppler burst. The system also measured the droplet diameter very reliably using phase shift of the two receiving laser beams. However, the application of the PDPA is still a challenge in highly concentrated multiphase spray due to its incapability for reliable mass flux measurement. Form the histogram as presented in Fig. 3, it is evident that the droplets size follow the lognormal distribution. As shown in Fig. 3 both air-water atomization and mixed gas-water atomization follow the lognormal probability distribution indicating no remarkable change in the two range of atomization conditions investigated in this study.

In Fig. 4 the effects of gas phase density and molecular weight on the droplet Sauter mean diameter ($D_{32}$) is depicted. The Sauter mean diameter ($D_{32}$) is the characteristic length scale for a fluid jet [3]. At first glance it is observed in Fig. 4 that the Sauter mean diameter ($D_{32}$) decreases gradually with the β and 120$D_n$ downstream and at a constant mixing pressure ($P_m$) of 483 kPa. Experimental results indicate that at 120$D_n$ downstream of the spray and at 1% β, the $D_{32}$ values are of 145 µm and 146 µm for the mixed gas-water and air-water atomization conditions, respectively. Similarly, at 120$D_n$ downstream of the spray and at 2% β, the $D_{32}$ values of are 129 µm and 130 µm for the mixed gas-water and air-water atomization conditions, respectively. Thus, changing the gas phase density and molecular weight does not significantly affect the droplet length scale. This outcome basically validates the lab scale experiments where air is used as the gas phase at room temperature and pressure conditions, and demonstrates that the results are similar to the commercial scale conditions where steam is used at elevated temperature and pressure conditions.
The frictional pressure gradient \((\frac{dp}{dx})\) in the nozzle conduit can be expressed as follows:

\[
\frac{dp}{dx} = f_{\text{moody}} \left( \frac{\rho_m u_m^2}{2D_c} \right)
\]

where, the friction factor \(f_{\text{moody}}\) is calculated as a function of the Reynolds number \((Re)\) for laminar flow \((Re<2300)\) \(f_{\text{moody, laminar}}=64/Re\) and for turbulent flow \((Re>2300)\) and Blasius smooth pipes \(f_{\text{moody, turbulent}}=0.18/Re^{0.2}\) and \(Re=U_m D_c/\nu\). Here, \(\rho_m\) is the mixture density \((\text{kg/m}^3)\), \(u_m\) is the mixture velocity \((\text{m/s})\), \(D_c\) is the conduit diameter \((\text{m})\), \(x\) is the axial direction \((\text{m})\), \(p\) is the pressure \((\text{Pa})\), and \(fr\) indicates friction. In reality, it is difficult to keep a dispersed homogeneous flow in a horizontal pipe flow due to the inherent characteristics of two-phase gas/liquid flow. Thus, the homogeneous flow model in calculating the two-phase energy dissipation does not work very well in most of the practical cases. However, the homogeneous flow model is a superior tool to understand the preliminary behaviour of the two-phase flow due to its simplicity to calculate.

In Fig. 5 the change in pressure gradient in the axial direction \((\frac{dP}{dx})\) with gas to liquid mass ratio \((\beta)\) is depicted. Equation (1) was used to calculate the pressure gradient in the axial direction \((\frac{dP}{dx})\). In addition to the effects of \(\beta\), the effects of gas phase molecular weight on the pressure gradient are also depicted in Fig. 5. From Fig. 5 it is found that if the \(\beta\) increases, usually the pressure gradient \((\frac{dP}{dx})\) decreases. However, if the \(\beta\) increases from 1 to 2%, the pressure gradient \((\frac{dP}{dx})\) increases slightly since at a constant mixing pressure of 483 kPa the increased gas phase velocity provides enough momentum to the liquid phase and subsequently increases the pressure gradient in the axial direction \((dP/dx)\). However, if the \(\beta\) increases more than 2%, the liquid volume flow rate decreases and the pressure gradient decreases significantly. If a homogeneous two-phase air/water flow is assumed, a sample calculation indicates that at 10% \(\alpha\), the mixture density \((\rho_m)\) is 898 kg/m\(^3\) and at 90% \(\alpha\), the mixture density \((\rho_m)\) is 100 kg/m\(^3\). Similarly, the mixture viscosity \((\mu_m)\) and mixture velocity \((u_m)\) changes dramatically with the conduit void fraction \((\alpha)\). Experimentally \(\alpha\) increases with \(\beta\). In calculating the pressure gradient in the axial direction \((\frac{dP}{dx})\) using Equation (1), the \(\mu_m, \rho_m\) and \(u_m\) are the important parameters. Thus, although at 1% \(\beta\) the pressure gradient increases, at the greater \(\beta\) values the pressure gradient in the two-phase gas/liquid conduit flow decreases progressively due to higher \(\alpha\) values. Most importantly, from Fig. 5 it is noticeable that there are no significant effects on the axial pressure gradient due to changes in the gas phase density. Experimental results indicate that the pressure gradient in the nozzle conduit at 2% \(\beta\) is 53 kPa/m and 54 kPa/m for the mixed gas-water and air-water experiments, respectively.
Fig. 6. Estimation of the bubble diameter \( (D_b) \) in the conduit from the high-speed image analysis for the air-water experiments. The mean diameter of the droplets \( (D_d) \) in the spray was also calculated from the PDPA measurements or the air-water experiments. The SBSI indicates Stroboscopic Back Scattered Imagery, the HSVS indicates High Speed Video Shadowgraphy, the PDPA indicates Phase Doppler Particle Anemometer.

Conclusions

The relationship between the lab-scale experiments (such as those involving air-water) and real industrial operations (such as those involving steam-bitumen) has never been fully explained for multiphase flows and multiphase atomization. This study will make the development of future generation multiphase transportation models and nozzles much less dependent on trial and error. This research will attempt to establish fundamental scaling relationships for the prediction of multiphase flow and spray behaviour that can be applied directly to full-scale industrial technology. In this effort, a mixed gas of 81.4% helium, and 18.6% nitrogen (on a volumetric basis) was used to compare the density and molecular weight of steam. Experimental results indicate that the mixed gas does not provide a significant change in the multiphase atomization behaviour \( (D_d) \) and multiphase flow characteristics \( (D_b) \) when compared to results obtained with air as the atomization gas. This outcome validates the lab scale experiments using air as the gas phase.

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References