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QUALITATIVE ASSESSMENT OF BUBBLE BEHAVIOUR FOR CENTRAL AND ASYMMETRIC INJECTION IN 2D GAS-SOLID FLUIDIZED BED USING IMAGE ANALYSIS TECHINIQUE AND CFD MODELLING

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ABSTRACT

Bubble characteristics such as shape, size, and trajectory control the hydrodynamics and therefore heat transfer in fluidized bed reactors. Thus understanding these characteristics is very important for the design and scale-up of fluidized beds. An earlier developed Eulerian-Eulerian two-fluid model for simulating dense gas–solid two-phase flow has been used to compare the experimental data in a pseudo-two-dimensional (2-D) bed. Bubbles are injected asymmetrically by locating the nozzle at proximity to the wall, thus presenting the effect wall has on asymmetrical injection as compared to symmetrical injection. In this work, a digital image analysis technique was developed to study the bubble behaviour in a two-dimensional bubbling bed.

The high-speed photography reveals an asymmetric wake formation during detachment indicating an early onset of mixing process. The wall forces acts tangentially on the bubble and has a significant impact on the bubble shape, neck formation during detachment and its trajectory through the bed. Larger bubbles drifting away from the centre with longer paths are observed. This qualitative behaviour is well predicted by CFD modelling. Asymmetric injection can significantly influence the heat and mass transfer characteristics.

Keywords: gas-solid fluidisation; wall effect; image analysis, bubble shape; trajectory; CFD

NOMENCLATURE

A_b equivalent bubble area (mm^2)
d_b equivalent bubble diameter (mm)
D bed width (m)
t time (s)
u_b bubble rise velocity (mm/s)
U_{mf} Minimum fluidization velocity (m/s)
ym vertical component of the bubble centroid (mm)

Δt time interval between consecutive frames (s)
ϕ fitted value

INTRODUCTION

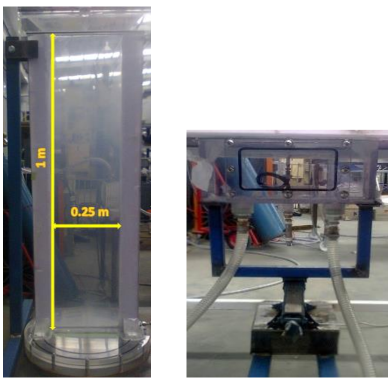
In gas-solid fluidized beds, for Group B particles, when the fluidization velocity exceeds the minimum fluidization, bubble formation takes place. The bubble path inside the bed significantly vary the motion of the emulsion phase improving the mixing process across the different layers of the bed (Davidson and Harrison, 1971). The mixing process maintains temperature uniformity throughout the bed thus enhancing the heat and mass transfer processes in gas-solid fluidized beds (Christensen et al., 2008; Li et al., 2009). Bubbles generally coalesce as they rise along the bed and finally erupts at the surface. Bubbles closer to the wall are significantly affected in their shape and size (Glicksman and McAndrews, 1985; Werther, 1974a). Significant amount of experimental and theoretical research has been done in characterizing the effect of wall on the bubble movement through external injection of bubbles along the center of the bed. VanLare et al. (1997) and Bokkers et al. (2006) reported that bubbles near the wall tend to move toward the center as they rise along the bed. This effect was found to be predominant at higher fluidization velocities. Miyahara et al. (1988) reported spiral flow of bubbles near the wall in solid-liquid fluidized beds. On the other hand, minimal efforts have been put in injecting the bubbles in closer proximity to the wall. Werther (1974 b) reported that bubble injected near the wall was induced by the rotation and translational motion across the bed. Das et al. (2011) showed in their experiments that bubbles near the vertical wall are strongly influenced in their shape, orientations and trajectory.

Two-dimensional fluidized beds are great tools for investigating qualitatively the hydrodynamic characteristics of bubble and emulsion phases that are taking place in three-dimensional beds. In recent years, utilization of high-speed photography in experiments with 2D beds have become quite popular to capture and study in detail the dynamic interactions between the bubble and emulsion phase. Currently, CFD methods are quite handy in solving classical Navier-Stokes equations to predict the complex bubbles-emulsion interaction in fluidized beds. The two-fluid model with various closures is widely used to solve such complex problems (Gidaspow, 1994a). In recent years, Eulerian–Eulerian continuum model has been thoroughly evaluated and compared with experimental results. Mougin and Magnaudet (2002) showed that continuum models could predict bubble shape and size quite accurately with experiments. Furthermore, 2D numerical models also predict the general bubble behaviour similar to the 3D models (Wu and Gharib, 2002). Asegehegn et al. (2011) experimentally investigated the behaviour of bubbles in a freely bubbling 2D fluidized bed with immersed horizontal tube bundle. They reported that high-speed imaging and analysis could help in accurately determining the bubble growth and rise velocity. Utikar and Ranade (2007) experimentally studied the bubble characteristics of a centrally injected bubble in a 2D bed using high-speed camera and qualitatively predicted the results with Eulerian-Eulerian two fluid CFD model. They reported some disagreement in their predictions with published literature mentioning the need for further study on comparison between CFD predictions and experimental data.

CFD simulations with single bubble central injection cannot systematically estimate the wall effect because of the symmetric nature of the problem (Patil et al., 2005). Recently Kumar et al. (2013) have utilized the ability of two-fluid model in systematically analysing the effect of wall on the bubble shape and size, neck formation at the inception and bubble trajectory through the bed by asymmetric injection. They reported that asymmetrically injected bubble causes mixing at the inception and stays for longer period inside the bed, which can possibly enhance the heat and mass transfer characteristics in gas-solid fluidized beds. On the other hand, literature also lacks systematic experimental study on the asymmetric injection of the bubbles. Thus, the present work utilizes the digital image technique using high-speed camera in capturing the complex bubble-emulsion interaction. The experimental results are validated with the published literature and are qualitatively assessed with the earlier CFD predictions by Kumar et al. (2013). The objective of the work is to utilize the benefit of CFD simulations and digital image analysis to understand the bubble characteristics in asymmetric injection.

EXPERIMETAL SETUP

A 2D bed of dimension 1 m x 0.25 m x 0.012 m fabricated from polycarbonate material is used as a fluidized bed for all the present experiments (see figure 1). The walls of the bed were glued together with high strength adhesives. A wind box fabricated from acrylic with a flange (30 mm) is connected with the polycarbonate bed. Two sets of O-rings were used to seal the vacuum in the bed. A sintered stainless steel plate was used as a distributor plate. A nozzle/jet of 6 mm diameter is inserted at the bottom with a provision to change its offset from the center. Screw jack at the bottom of the wind box and a stand to hold the column ensured no vibration of the bed while operating with high flow rates. The top of the bed connects to a particle filter and vacuum pump.



(a) (b)

Figure 1: 2D Fluidized bed (a) column, (b) wind box

A high-speed camera (Phantom V711) with a Nikkon 24-85 Macro lens was used to capture the bubbles in the bed. The camera was mounted on a levelled tripod to capture the bubble evolution at 700 frames per second (fps) with 1280x800 pixels with exposure time of 1400 µs, which, according to the calibration used in the present study, yields a resolution of 1.28 mm per pixel (see figure 2). In order to maximise the image contrast, two light sources are placed at a great distance to achieve a diffused and uniform light. The post-processing of the captured image was carried out in Image J software. In our case, we used the default threshold setting for the binary image available in the software.

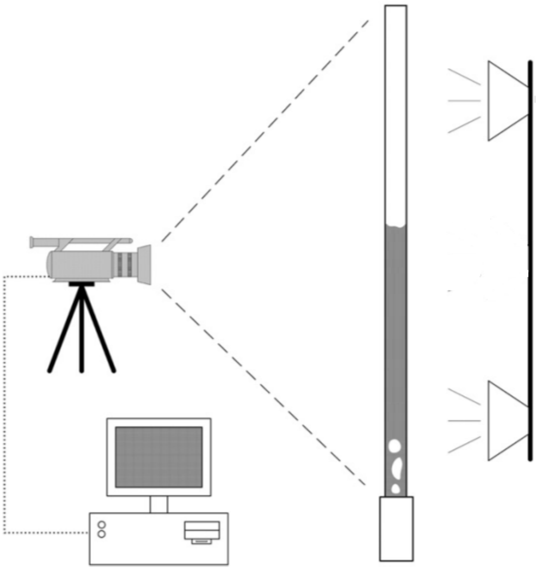


Figure 2: Schematic of the dynamic image capturing method

Experimental method

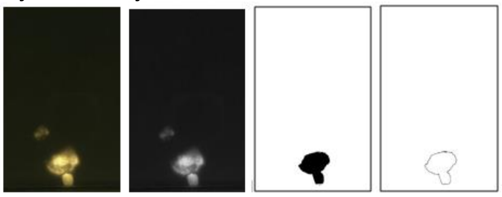
Alumina particles belonging to Group B (mean size: 250 µm, density: 3800 kg/m^3) were used to study the nature of fluidisation in atmospheric conditions. The static bed height was 450 mm.

Variable area flow meters with an accuracy of ±3% were used to measure air flow rate to the chamber and jet separately. To ensure correct mass flow meter readings a pressure of 50 kPa was maintained on entry and exit side of the flow meter using a two-stage needle valve configuration. Pressure transducers with an accuracy of 0.25% were used to measure the pressures at two locations inside the chamber: 5 mm above the distributor plate and 5 mm below the exit of the chamber. In order to maintain consistency in results, similar inlet conditions were used in all experiments. The pressure data were acquired (10 Hz) by using ALMEMO 2590 data logger and were analysed offline by using a personal computer.

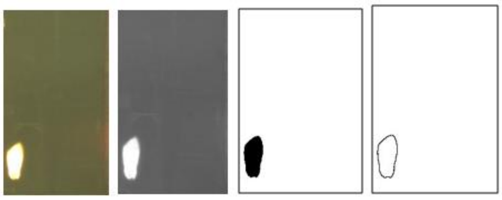
The experiments are performed by initially maintaining the entire bed at minimum fluidization conditions (U_{mf} = 0.104 m/s). Bubbles are injected through the jet at varying velocities from 1.04 m/s to 4.16 m/s corresponding to 10 U_{mf} to 40 U_{mf} respectively. The bubble injection is monitored in pulses at fixed intervals using solenoid valve and timer. Initially the jet is positioned at the centre and is then offset to the proximity of one of the vertical wall of the bed thus enabling to study the bubble characteristics in both central and asymmetric injection.

DIGITAL IMAGE ANALYSIS

The dynamic bubble and emulsion phase movement is captured through the high-speed camera and are automatically monitored through phantom camera control software (PCC 2.6) in personal computer. These video files are converted from .cine to .avi format at 5 fps and then are loaded as grey scale video in Image J software to analyse various bubble characteristics. The movie files are converted into binary image sequence using the default thresholding method. The pseudo bubbles were deleted manually and then the software automatically analyses various characteristics of the bubble in all frames. The results can be viewed in a spreadsheet. The figure 3(a) and 3(b) shows the picture of actual image and its greyscale image, binary image and outline respectively for a fluidized bed with bubble injected centrally and asymmetrically.



(a)



(b)

Figure 3: Image analysis sequence (a) central injection, (b) asymmetric injection (see supplementary animated files)

Calculation of bubble properties

The bubble is treated as sphere and the equivalent bubble diameter can be calculated from the area resulted from Image J software as

$$d_b = \sqrt{4A_b/\pi} \tag{1}$$

The rise velocity is calculated as the difference in the vertical coordinate of the centroid between the consecutive time frames divided by the time interval between the frames.

$$u_b = (ym(t+\Delta t) - ym(t))/\,\Delta t \tag{2}$$

To plot bubble properties with time, the time reported from Image J (at 5fps) is converted into actual time used during recording (i.e., at 700 fps).

RESULTS

Werther (1983) has given a semi-empirical relation for the variation of bubble rise velocity with bubble diameter for Group B particles as

$$u_b = \emptyset\sqrt{(gd_b)} \tag{3}$$

where ϕ = 0.84 for $D \leq 0.1$ m,
= $1.6\,D^{0.4}$ for $0.1 \leq D \leq 1$m,
= 1.6 for $D > 1$ m

Figure 4 shows a very good validation of the present experimental data with Werther's correlation for centrally injected bubble at 3.12 m/s (30 U_{mf}) with an R^2 value of 0.85.

Effect of gas injection rate on bubble size

Central injection

Experiment

With the variation in gas injection rate from 1.04 m/s to 4.16 m/s (10 U_{mf} to 40 U_{mf}), the bubble size increased. An increase of three times in the equivalent bubble diameter is observed for the same injection time (see figure 5)

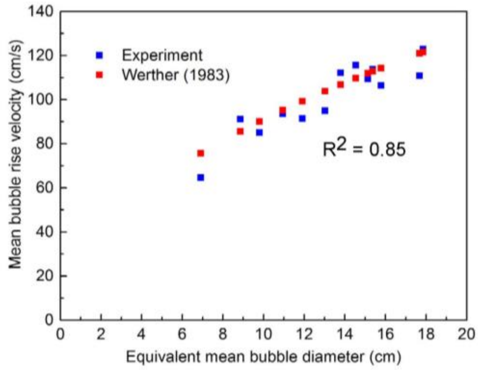
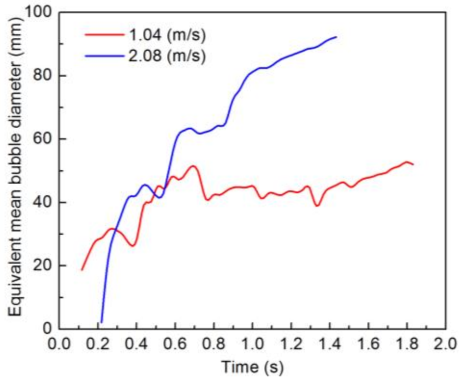
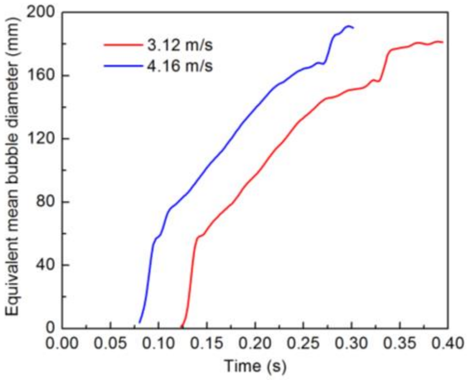


Figure 4: Experimental validation of the bubble characteristics with Werther's correlation



(a)



(b)

Figure 5: Variation of bubble size with gas injection rate for central injection, (a) 1.04m/s to 2.08 m/s, (b) 3.12 m/s to 4.16 m/s

CFD modelling

The results can be qualitatively compared with the work of Kumar et al. (2013) as shown in figure 6. They have used 500 μm alumina particles with superficial velocities ranging from 2 m/s to 10 m/s (10 U_{mf} to 50 U_{mf}) and observed the same trend of increase in bubble size with injection rate through two-fluid Eulerian-Eulerian model in Fluent.

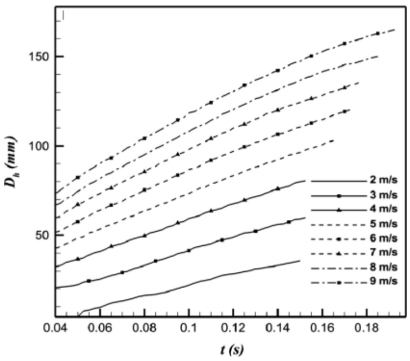


Figure 6: CFD prediction of bubble growth with gas injection rate for central injection (Kumar et al., 2013)

Asymmetric injection

Experiment

For asymmetric injection, the jet is placed at the proximity of the left vertical wall of the bed. Bubbles are injected at a superficial velocity ranging from 1.04 m/s to 4.16 m/s. Figure 7 shows the similarity in the variation of bubble size with rate of injection. An increase of 90 mm to 140 mm in diameter can be seen at 1s for injection rate varying from 1.04 m/s to 3.12 m/s.

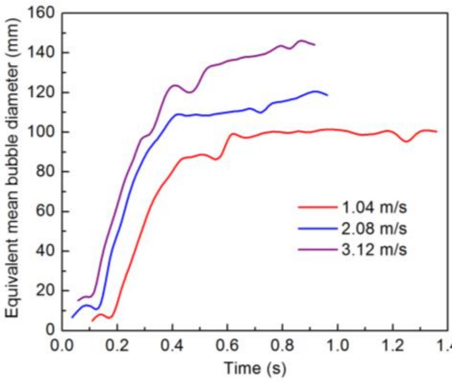


Figure 7: Variation of bubble size with gas injection rate for asymmetric injection

Comparison between central and asymmetric injection

Figure 8 shows the comparison of bubble size evolution with gas injection rate for both central and asymmetric injection. It can be seen that bubbles injected at the proximity of the wall are considerably large for the same injection rate and at the same time. This is due to increase in detachment time for asymmetrically injected bubbles (Kumar et al., 2013). Min et al. (2010) also reported higher gas hold up for bubbles near the wall in their experiments. The reason is due to the nature of the asymmetric velocity field being generated around the bubble creating a misalignment between the buoyancy force and weight of the bubble. This can be seen in next section.

CFD Modelling

Kumar et al. (2013) reported the same qualitative results in their simulations by offsetting the jet position from centre (see figure 9 and 10).

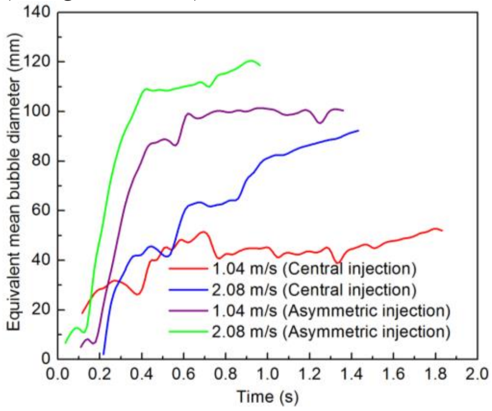


Figure 8: Effect of jet position on the bubble size variation with gas injection rate

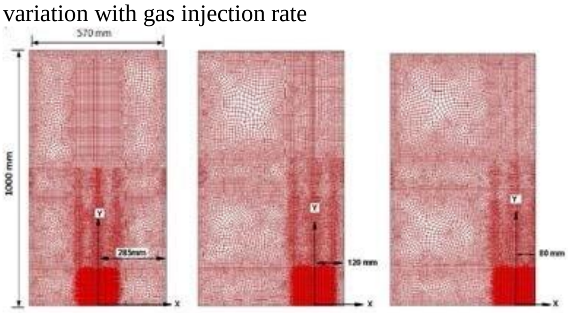


Figure 9: Computation domain (Kumar et al., 2013)

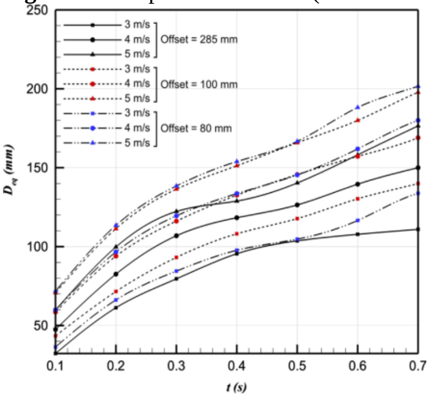


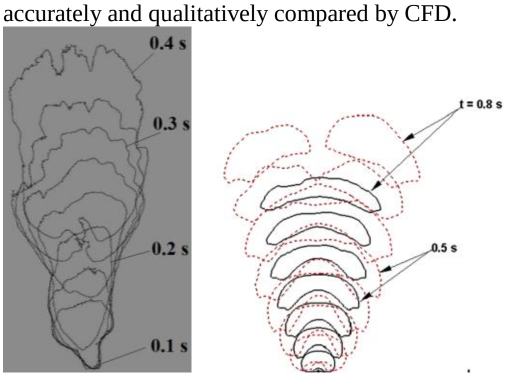
Figure 10: Variation of equivalent bubble diameter with gas injection rate for three different wall offsets (Kumar et al., 2013)

Effect of gas injection rate on bubble shape and trajectory

Central injection

Experiment and CFD modelling

With the help of high-speed camera images and digital image technique as discussed earlier, the bubble movement can be easily captured and its path can be tracked at all time frames. It can be seen that bubbles generally follow the symmetric path during central injection as it rises along the bed. Although the shape of the bubble is distorted near the wall, but overall symmetry of the circular shape is maintained. It is especially seen at higher gas injection rate. Kumar et al. (2013) made similar predictions through CFD study. The bubble motion is mainly caused by the wake forces generated by the entrained particles behind the bubble and the inertial forces generated by superficial velocity. They reported through the stream tracers that identical vortices are formed at symmetrical locations. This emulsion phase movement around the rising bubble is the main reason for particle mixing (Tsuchiya et al., 1990). It is observed that bubble shapes are more flattened at the upper part, which is also observed by Miyahara et al. (1988) and well predicted by Kumar et al. (2013). More flattened the bubble shape, the weaker the interfacial forces that holds the bubble to a single unit. Thus, bubble starts splitting into smaller bubbles (Tsuchiya et al., 1989). Figure 11 shows that the present experimental observation is quite accurately and qualitatively compared by CFD.



(a) (b)

Figure 11: Bubble trajectory with time for central injection, (a) experiment for 3.12 m/s (b) CFD predictions for 2 and 3 m/s

Asymmetric injection

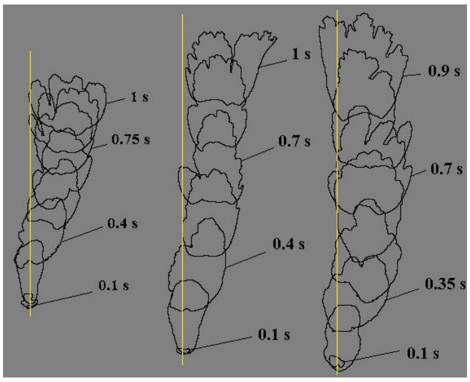
Experiment and CFD modelling

It is observed from the experiments that the bubbles when injected asymmetrically are larger in size, more elongated and are moving away from the wall. It is due to the dense phase movement in the bubble-wall gap that forces the bubble to move tangentially. These tangential forces cause significant oscillation in the bubble movement even before its detachment (Kumar et al., 2013). It is also seen that due to asymmetric wake formation, the flow field is non-uniform making the bubble to deviate from the vertical axis resulting in a trajectory path. This qualitative behaviour is well predicted by CFD simulations (Kumar et al, 2013). It is observed from the present experiments that at low injection rate (1.04 m/s), the bubble oscillates periodically and as injection rates are increased beyond 2.08 m/s, the bubble movement takes a trajectory path. This is predicted due to the effect of oscillatory vortex shedding at wake regions for smaller bubbles or at low injection rates. This effect is not observed at high flow rates due to increase in bubble size and the bubble is always being accompanied up to the surface by vortices on either side making it to take spiral trajectory path. This accurate qualitative prediction of CFD modelling is assessed by the present experiments (see figure 12). Effect of gas injection rate on bubble rise velocity

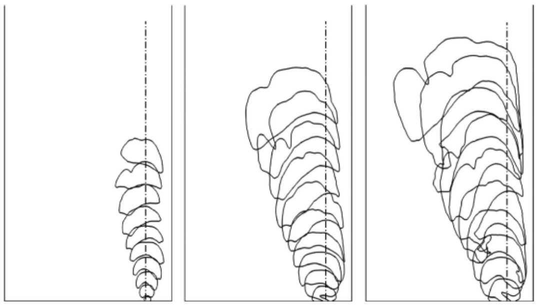
Experiment

Central injection

The bubble rise velocity is found to increase with increase in gas injection rate. It is due to inertial forces affecting the bubble movement as discussed earlier. As injection rate is increased from 3.12 m/s (30 U_{mf}) to 4.16 m/s (40 U_{mf}), a maximum increase of 600 mm/s in rise velocity is observed at around 0.3 s of bubble travel (see figure 13).



(a)



(b)

Figure 12: Bubble trajectory with time for asymmetric injection, (a) experiments for 1.04 m/s, 2.08 m/s and 3.12 m/s (b) CFD predictions for 80 mm offset at 2, 4 and 6 m/s

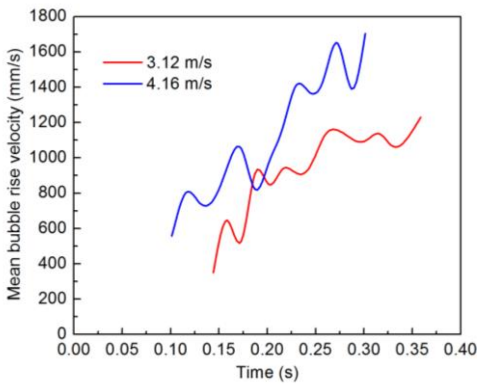


Figure 13: Effect of gas injection rate on bubble rise velocity for central injection

Asymmetric injection

A similar trend is observed even when the bubbles are injected at the proximity of the wall. Although bubble rise velocity is increasing with time as gas injection rate increases, it is observed that this effect is less pronounced when compared to centrally injected bubble. This phenomena is due to the repeated oscillations and trajectory path encountered by the bubble as discussed earlier. Thus it is understood that bubble stays for longer period in asymmetric flow field due to longer path coverage. This effect can significantly influence the heat transfer characteristics. A similar point is made by Kuipers et al. (1992a) that heat transfer characteristics are higher in the wake region if the bubbles are injected asymmetrically. Figure 14 shows that for the injection rate of 3.12 m/s (30 U_{mf}), the centrally injected bubble rises much quicker than the asymmetrically injected bubble.

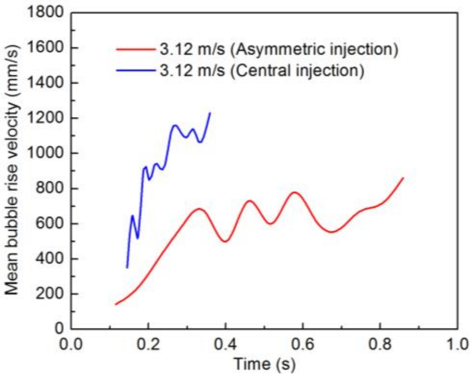


Figure 14: Effect of jet position on the variation of bubble rise velocity with gas injection rate

CONCLUSION

Digital image analysis was employed in the present study to understand the bubbling behaviour in both central and asymmetrically injected bubble for alumina particles (mean size: 250 µm). A high speed jet was used to inject bubbles at 10 U_{mf} to 40 U_{mf} and dynamic bubble-emulsion interaction was captured using high speed camera and the results were quantified using Image J. The CFD simulation developed earlier was employed to qualitatively assess the experimental results. It was found that CFD could qualitatively predict the bubble size, shape and trajectory with the present experimental data. The following conclusions were derived from the present work.

1. The bubble size and rise velocity were found to increase with gas injection rate for central and asymmetric injection.
2. Bubble in proximity to the wall was found to be larger in size, and elongated in shape and moving towards the centre due to the non-uniform wake forces acting behind the bubble.
3. Bubbles tend to move in periodic oscillatory motion at low gas injection rates while taking a trajectory path at higher injection rates.
4. The long bubble holdup in asymmetric flow field allows the bubble to take longer paths. This enhances the particle mixing, which could improve the heat and mass transfer characteristics.

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