Study on gas dispersion characteristics in a Column Flotation using Electrical Resistance Tomography coupled with Pressure transducers

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Abstract

Bubble and solids dispersion characteristics are the key hydrodynamic parameters used for column flotation design and performance evaluation. The gas dispersion characteristics with and without solids presence is studied using electrical resistance tomography (ERT) coupled with pressure transducers (PT) in a 100 mm laboratory column flotation. The effect of superficial gas velocity, feed slurry flowrate, sparger pore density, pulp height and frother dosage on gas dispersion characteristics in the column have been analysed. Experimental results show that ERT coupled with PT is suitable as an online monitoring tool to provide useful information on the two-phase as well as three-phase flow hydrodynamics of the column. Mean gas and solids hold-up values extracted from ERT are critically analysed for the column operating in various flow regimes. The results show that the gas hold-up increases with an increase in the superficial gas velocity. The presence of solids render the bubble rise velocity thereby decreases local gas holdup. Possible mechanisms of solids effect on gas hold-up are discussed and verified in light of current experimental results. It is confirmed that bubble coalescence, bubble wake stabilization due to viscous slurry and change in radial bubble dispersion due to the bubble-particle interactions resulting in increased bubble size, faster rising bubbles lead to a reduction of the gas hold-up.

Keywords: Hydrodynamics, Electrical resistance tomography (ERT), column flotation, gas dispersion, solid hold-up distribution.

1. Introduction

Column flotation is being widely used in mineral processing industries in last few decades. There has been a lot of attention in understanding the various mechanisms that take place during operation. Due to many reasons column flotation has been found to yield better performance than conventional flotation cells, particularly with fine particles (Honaker and Mohanty, 1996). Due to complex flow behavior in nature, the performance of column flotation is influenced by flow characteristics of the process, (Jena et al., 2008). Previously, research is carried out to evaluate the effect of hydrodynamic parameters on the performance of column flotation (Finch and Dobby, 1991).

To characterize the hydrodynamics of column flotation, one need to consider the evaluation of bubble and solids dispersion in column. These parameters are further used in the assessment of column design and performance. Many experimental techniques have been developed to assess the bubble and solids dispersion in column flotation. Tomography techniques are well sound to investigate the hydrodynamics of process equipment. Among that, Electrical resistance tomography (ERT) has been used in various industrial investigations for visualization of the concentration profiles and characteristics of the fluid dynamics in gas–liquid two-phase systems (Wang et al., 1999, Williams and Wang, 2000). ERT is an imaging technique to analyse the internal flow behaviour non-intrusively. Due to its high speed capability, low cost measurement, robust sensors, ERT is considered to be the most powerful tool among other tomography techniques such as positron emission tomography (PET), magnetic resonance imaging (MRI), optical and infrared tomography.

In this paper, column hydrodynamics are explored by studying the flow behaviour in terms of bubble and solids dispersion for design and performance evolution of the column. The distribution gas and solids are measured using ERT coupled with pressure transducers technique in a 100 mm laboratory scale column flotation. The effect of gas and feed slurry superficial velocity, sparger pore density, pulp height and frother dosage in the column on mean gas hold-up and its radial distribution is analysed for three phase flows. Effect of solids on gas dispersion is discussed by analysing the bubble rise velocity and Sauter mean bubble diameter in the column. Possible mechanisms of solids effect on gas hold-up are discussed and attempted to verify in light of current experimental results.

2. Methodology

2.1 Experimental setup

Schematic diagram of column flotation rig used for this study is shown in Fig.1 (a). Experiments are conducted on 0.1 m diameter and 2.5 m length of the column. The laboratory column flotation made with transparent perspex, is shown in Figure 1(b). Experiments are carried out for gas-liquid-solid multiphase system, where the gas phase is air, liquid phase is tap water and solid phase is fine silica. Particles having a mean size of -200 μ of silica material is used in all the experiments. Air is introduced into the column through sintered disc 60,000, 2,00,000 and 4,00,000 pores sparger using an air

compressor. The air flow rate is controlled and measured using rotameter and experiments are conducted within the range of 0.6-1.8 cm/s superficial velocities. Experiments are conducted at 0.3, 0.4 and 0.57 cm/s slurry superficial velocities. MIBC is used as a frother agent in the experiments for controlling bubble size and stabilizing bubble flow in the column. Pressure transducers are used to measure the overall sectional gas hold-up and fitted to the column above gas distributor. The total planned experiments are listed in Table.1.

2.2 ERT Set up

The high speed ERT system, ITS UK, z8000 two planer system was used in experiments. The ERT was designed based on a high performance dual plane system with a data acquisition speed of 1000 frames per second. The ERT setup consists of sensors, DAS (data acquisition system) and computer. Sensors were connected to a cylindrical section of ERT and another part of the sensors was connected to the DAS. Two planes of ERT sensors each composed of 16 electrodes were mounted in the inner wall of 0.1 m diameter cylindrical section of ERT. All these electrodes were connected to DAS via cables.

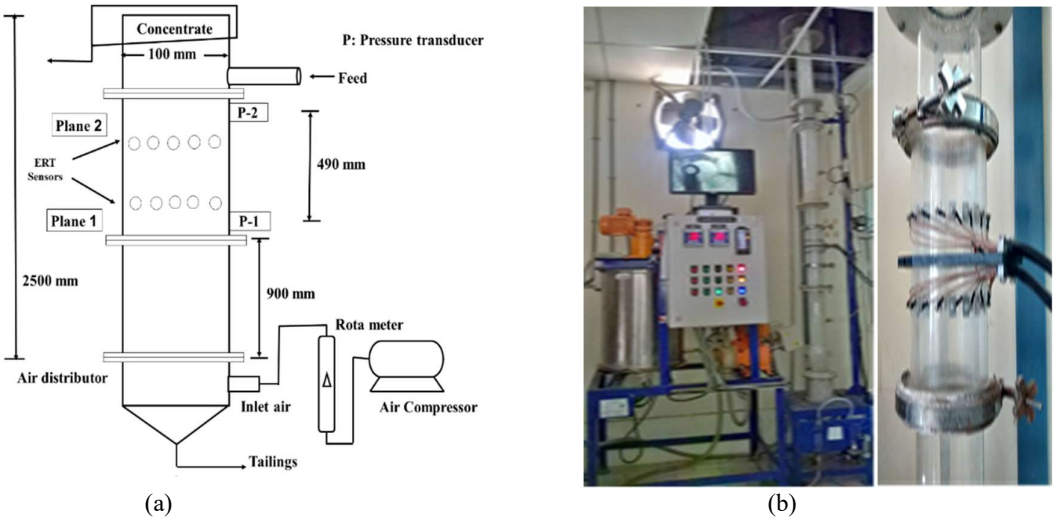


Figure 1: (a) Schematic diagram of Column Flotation, (b) Laboratory Column flotation cell

Table 1. Design of experiments

Solid (wt. %)	Feed slurry superficial velocity (cm/s)	Slurry height (mm)	Air superficial velocity (cm/s)	Sparger pore density	Frother concentration (ppm)
5	0.3, 0.4, 0.57	2100, 2300, 2400	0.6, 0.9, 1.2, 1.8	60k, 200k, 400k	0, 5, 10
10	0.3, 0.4, 0.57	2100, 2300, 2400	0.6, 0.9, 1.2, 1.8	60k, 200k, 400k	0, 5, 10
15	0.3, 0.4, 0.57	2100, 2300, 2400	0.6, 0.9, 1.2, 1.8	200k	0, 5, 10

Adjacent electrode strategy is used to get the conductivity measurements. Electric current is applied to between one pair of electrodes and the resultant voltage differences among the remaining 13 electrode pairs are measured by DAS. The 16 electrode sensor gives 104 independent voltage measurements in one measurement of frame. The host computer is used to store and collect the data from the DAS system. After obtaining the voltage measurements from DAS system, the host computer processes data using image reconstruction algorithm.

2.3 ERT data analysis

ERT Data analysis is persuaded using the raw data obtained from 100 mm column flotation. The number of frames collected by using the ERT system is nearly 1500 frames, roughly at about 3-5 seconds of the operation. The 1500 frames are collected from EIT Z8000 system and averaged all collected frames using the ITS tool suite software which is built based on various reconstruction algorithms. Because of averaging of frames, one can minimize the errors in measurements.

3. Equations

The combined mean gas hold-up and solid hold-up of the column flotation from conductivity data is calculated using Maxwell equation (Maxwell, (1892); Kourunen et al., (2011)).

$$\varepsilon_g + \varepsilon_s = \frac{(2\sigma_1 - 2\sigma_{mc})}{(2\sigma_1 + \sigma_{mc})} \tag{1}$$

Where σ_1 is the conductivity of liquid phase, σ_2 is the conductivity of gas phase and σ_{mc} is the mixture conductivity distribution of three phases.

Pressure drop is mainly due to liquid and solid static head, plus frictional and acceleration forces. Since the gas density when compared with liquid density and solid density in column flotation is very small, the frictional and acceleration forces are negligible. So, differential pressure (ΔP) is calculated as,

$$\Delta P = gH\left(\rho_l \varepsilon_l + \rho_g \varepsilon_g + \rho_s \varepsilon_s\right) \tag{2}$$

Where H is the height of the measured section and ΔP is the differential pressure between two pressure sensor points. ε_g, ε_l, ε_s are the gas, liquid and solid phase hold-ups, respectively. Sum of the three-phase hold-up is equal to one.

$$\varepsilon_g + \varepsilon_l + \varepsilon_s = 1 \tag{3}$$

Since the density of air magnitude is very small compare to solid and liquid densities, so the air effect is negligible and ignored in equation (2). The measured pressure drop is obtained as follows

$$\frac{\Delta P}{gH} = \left[1 - \left(\varepsilon_g + \varepsilon_s\right)\right]\rho_l + \varepsilon_s \rho_s \tag{4}$$

Solving the equation (1) and (4), the solid hold-up is calculated from equation (5)

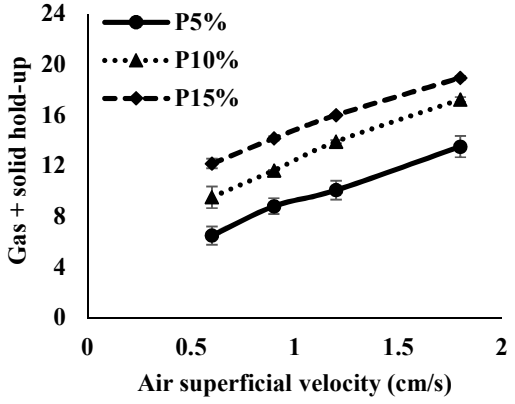
$$\varepsilon_s = \frac{\left(\frac{2\sigma_1 - 2\sigma_{mc}}{2\sigma_1 + \sigma_{mc}}\right)\rho_l - \rho_l + \frac{\Delta P}{gH}}{\rho_s} \quad (5)$$

4. Results and discussion

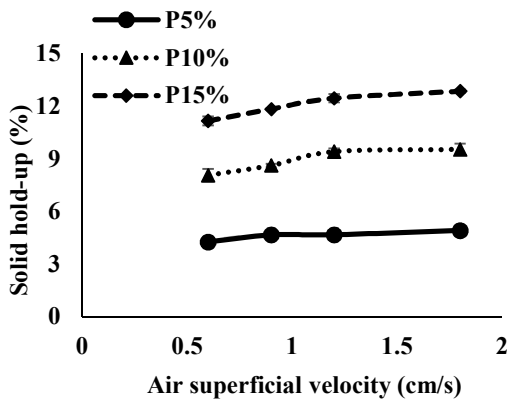
4.1 Phase hold-ups

The estimated combined gas and solid hold-up, solid hold-up and gas hold-up from ERT at different air superficial velocities and varying solids percentages in Figure 2 (a), (b) and (c) are displayed respectively. Experiments are carried out using 200,000 pores sparger at 2300 mm slurry height. Slurry feed superficial velocity of 0.4 cm/s is used in these experiments. The combined hold-up (gas + solid) values are increasing with the air flow rate. The same trend is followed by three kinds of a solid percent of 5%, 10% and 15% (wt. %) slurry solutions. The combined hold-up increase linearly up to 1.2 cm/s air superficial velocity, which comes into homogenous flow regime as described before. Further increase in air flow rate, bubble flow become transitional flow behaviour, where an evolving bubble break-up and coalescence persists. The combined hold-up increases with an increase in solids percentage.

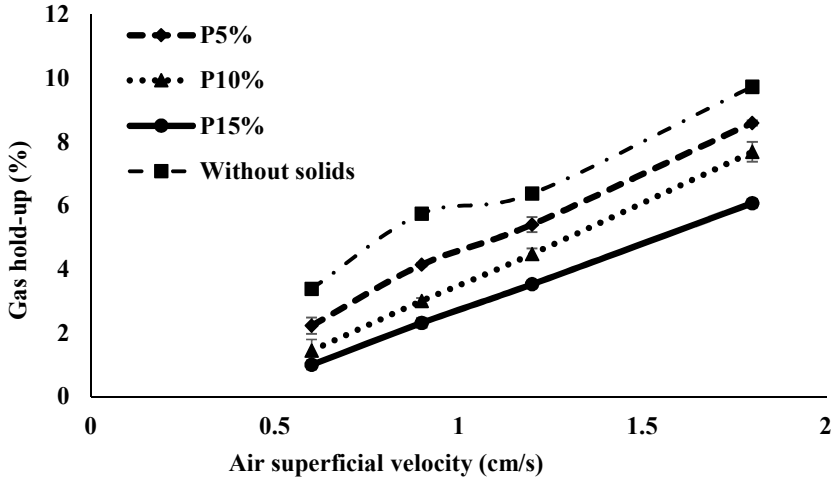
The solid hold-up is slightly increasing with the air superficial velocity. At low air superficial velocity, as the bubble number density is low as a result having low gas hold-up, the dispersion of solid particles due to air phase into the liquid column is somewhat limited. At higher air superficial velocity, the dispersion of solids increases throughout the given cross section, hence a slightly increased solids hold-ups observed. As the slurry solid percent increases, the solid hold-up also increases. The gas dispersion has been presented in the presence of with and without solids. From figure 2 (c), it is observed that cross sectional mean gas hold-up increases with air superficial velocity. Solids content also influence the gas hold-up. The gas hold-up decrease with increase the solids percentage.



(a)



(b)



(c)

Figure 2: Effect of air superficial velocity on (a) Combined gas hold-ups (ε_g) and solid hold-ups (ε_s) (b) solid hold-up (c) gas hold-up

Radial gas and solid hold-up is displayed for various air superficial velocities in Figure 3. Radial profiles are measured for 10 percent of silica solution at 2300 mm slurry height and 0.4 cm/s feed slurry superficial velocity. The combined hold-up difference between centre position and wall region is more in high air superficial velocities, where the flow behaviour is transitional compare with low air superficial velocities, which belongs to homogeneous flow regime. Bubble break-up and coalescence factors influence the increment in the combined hold-up.

Cross sectional tomograms of combined gas and solid hold-up across the column for different solids content at 2300 pulp height, 0.4 cm/s slurry superficial velocity are presented in Figure 4. The different colours represent the gas and solid hold-up ranging from the high concentration (in red and yellow) to low (in blue).

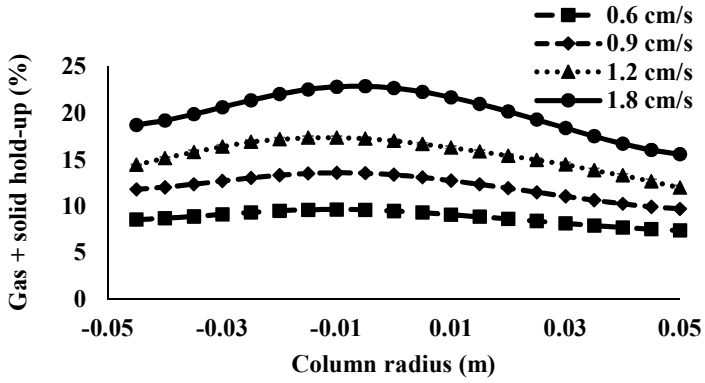


Figure 3: Radial gas and solid hold-up for 10 percentage of silica solution

Tomograms are obtained for three different solid percentages 5, 10 and 15% of slurry solutions. One can clearly observe in the tomograms that the combined hold-up is increasing with solid content. The combined gas and solid hold-up is more at center region of the column compare with wall region as explained earlier.

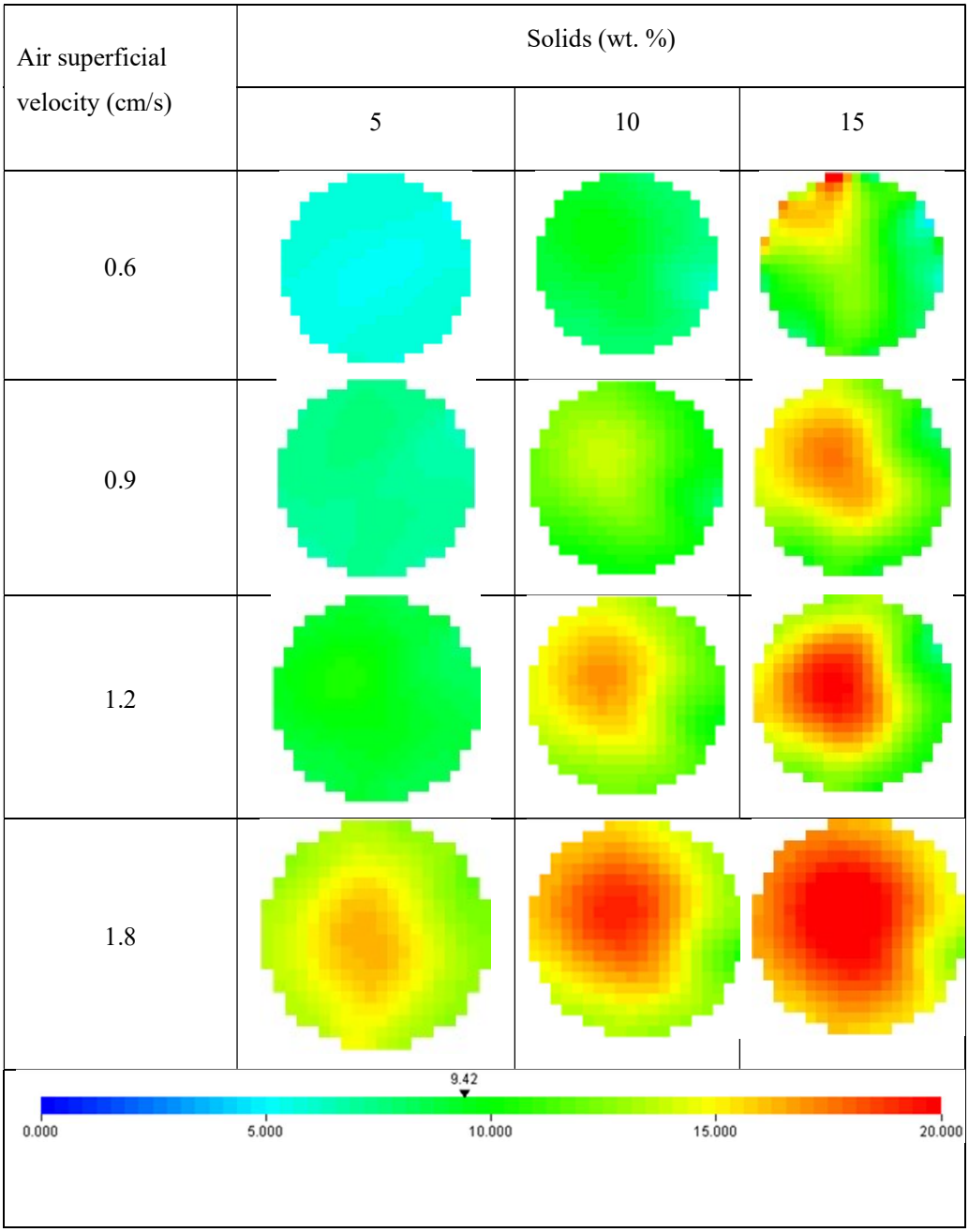


Figure 4: ERT cross-sectional tomograms of solid and gas hold-ups in the column at 2300 mm pulp height, 0.4 cm/s slurry superficial velocity

4.2 Effect of feed slurry superficial velocity

The counter-current flow behaviour of slurry-gas plays a vital role on gas and solid hold-up distribution in the column. The cross sectional mean gas and solid hold-up is explored at three slurry feed superficial

velocities of 0.3, 0.4 and 0.57 cm/s. Experimental analysis of combined and individual phase concentrations are shown in Figure 5 (a), (b) and (c) for 10% solids case. The combined hold-up increase with slurry feed velocity due to increased slurry capacity. The solid hold-up is slightly increasing with slurry feed velocity and change is minimal. The mean gas hold-up increases with slurry velocity. The residence time of bubbles is increased with slurry velocity, so mean gas hold-up increase with slurry velocity.

4.3 Effect of pulp height

Figure 6 displays the effect of pulp height on combined hold-up and in addition to solid and gas hold-up individually. Experiments are carried out with 10 percentage silica solution, 200,000 pores sparger at 0.4 cm/s slurry feed superficial velocity. The combined hold-up and solid hold-up are increase with pulp height for diluted (i.e. < 25% solids) slurry solutions. Solid hold-up increase initially with and reaches constant with air superficial velocity. The gas hold-up increase with slurry height in the column. The silica particles settle down to the column bottom and air bubbles disperse to the column top section. The counter current flow behaviour and hindrance with solid particles, the gas hold-up increase with height.

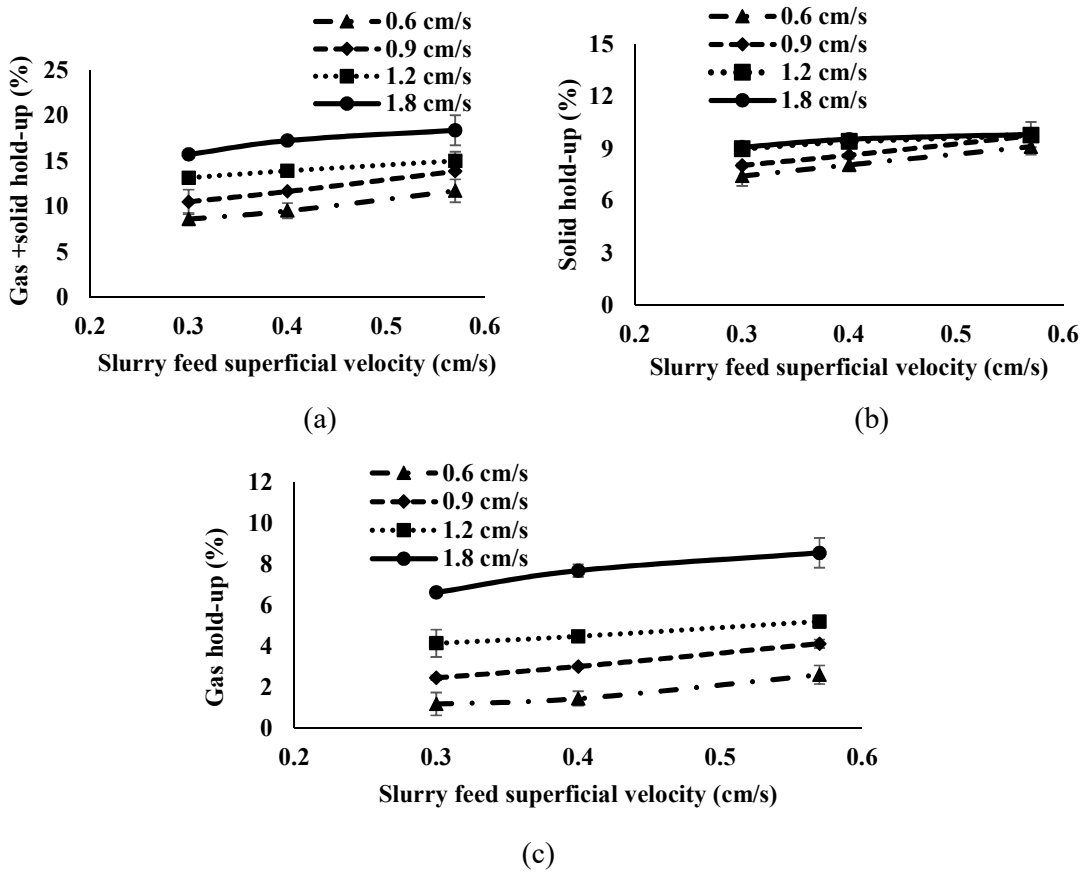


Figure 5: Effect of slurry velocity on (a) combined mean gas and solid hold-up (b) Solid hold-up (c) gas hold-up

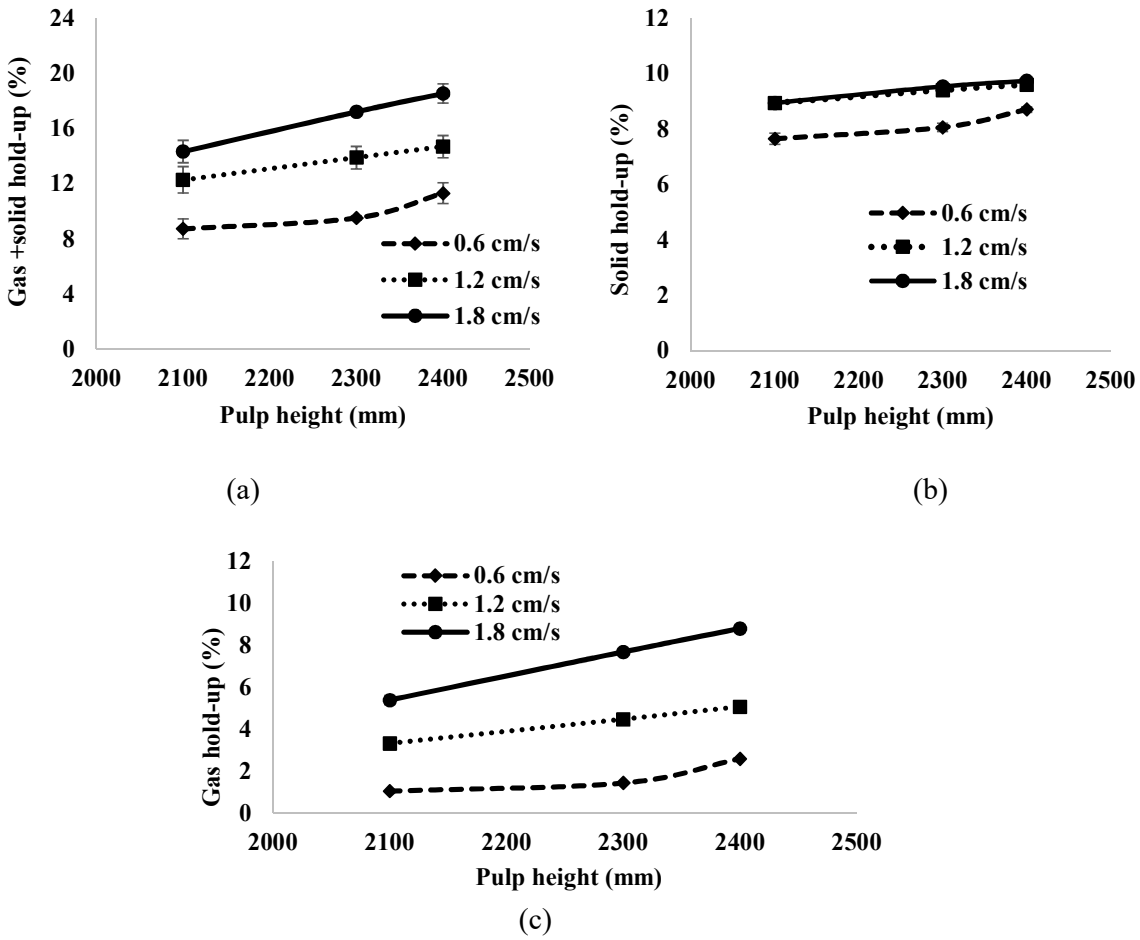


Figure 6: Effect of pulp height on (a) combined hold-up (b) solid hold-up (c) gas hold-up at 10 percentage silica solution and 0.4 slurry feed superficial velocity

4.4 Effect of sparger pore density

Experiments are carried out with 60 k, 200 k and 400 k pores sintered disc spargers. Solid and gas hold-ups are estimated for 10 wt. % solids slurry solution operating with 0.4 cm/s feed slurry superficial velocity. The measured combined hold-up, solids hold-up and gas hold-up are displayed in Figure 7 (a), (b), (c) respectively. The combined hold-up, gas hold-up are increased and the solids hold-up remains constant with the sparger pore number density and air superficial velocity. As the pore number density increases, small size bubbles are generated resulting in more surface to volume ratio of bubbles leading to an increased gas hold-up.

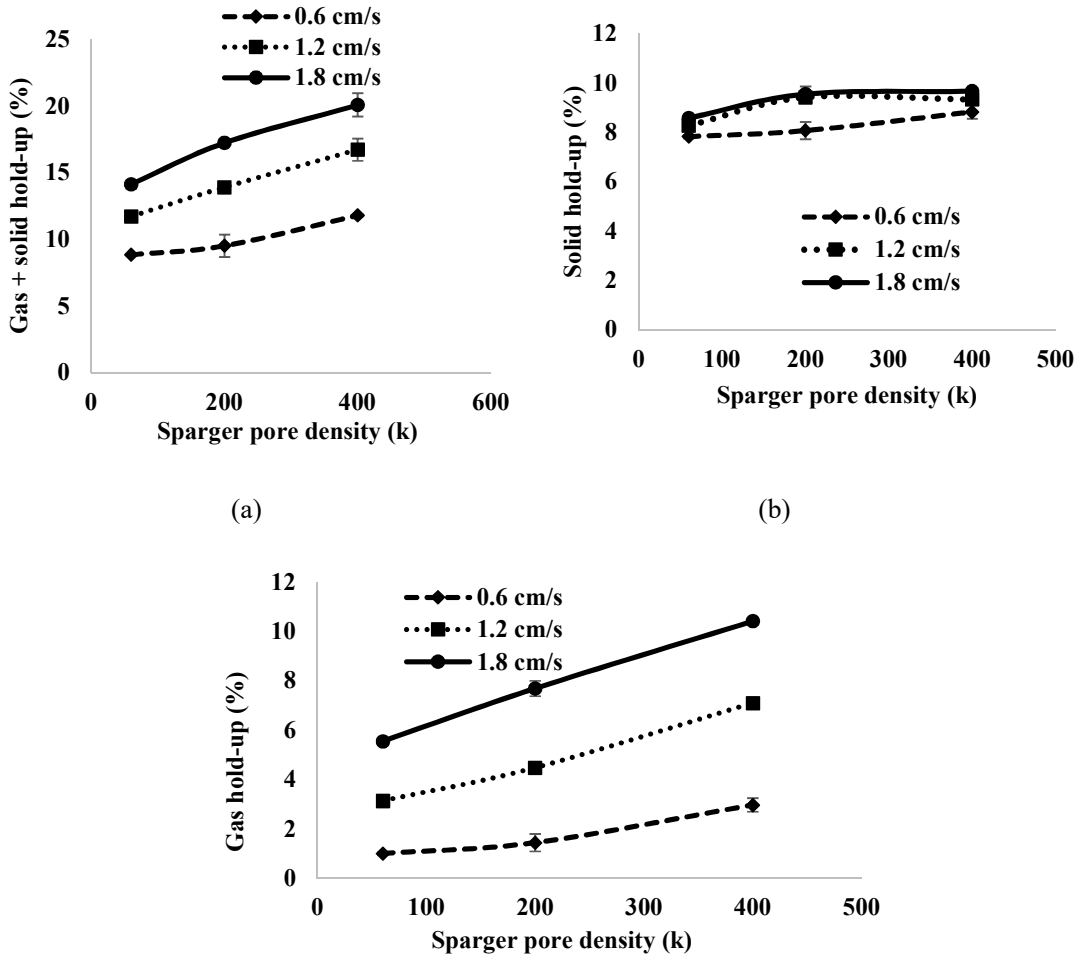


Figure 7: Effect of spargers on (a) combined hold-up (b) solid hold-up (c) gas hold-up for 10 wt. % solids slurry solution

4.5 Effect of frother

The effect of frother on combined hold-up is studied using 0, 5, 10 ppm MIBC solution for 10 wt. % solids slurry case and the same is displayed in Figure 8. Bubble size is an influential factor for estimation of bubble surface area flux and flotation kinetics. Frothers are typically used to improve the generation of fine bubbles and to stabilize froth.

The bubble size can be controlled by frother addition but the mechanism is still not clear. Cho and Laskowski, (2002), Finch et al., (2008) have described that bubble size is not directly related to controlling the surface tension, but the most common elucidation is the hindrance of coalescence of bubbles. Based on literature review (Lee et al., (2003), Melo and Laskowski, (2006)) small bubbles are generated with the addition of the frother and it has a large surface to volume ratio. Hence, the gas hold-up is more when the frother is added in the column. Due to the possibility of bubble break-up and

coalescence at transitional flow regime (1.8 cm/s J_g), generation of small bubbles is high as compared with the homogeneous flow regime (0.6 cm/s J_g). Hence mean gas hold-up increment is significant at 1.8 cm/s compared to that of 0.6 cm/s air superficial velocity. The frother doesn't show any impact on solids hold-up. Hence, solids hold-up remained constant with increasing the frother concentration, as shown in Figure 8 (b).

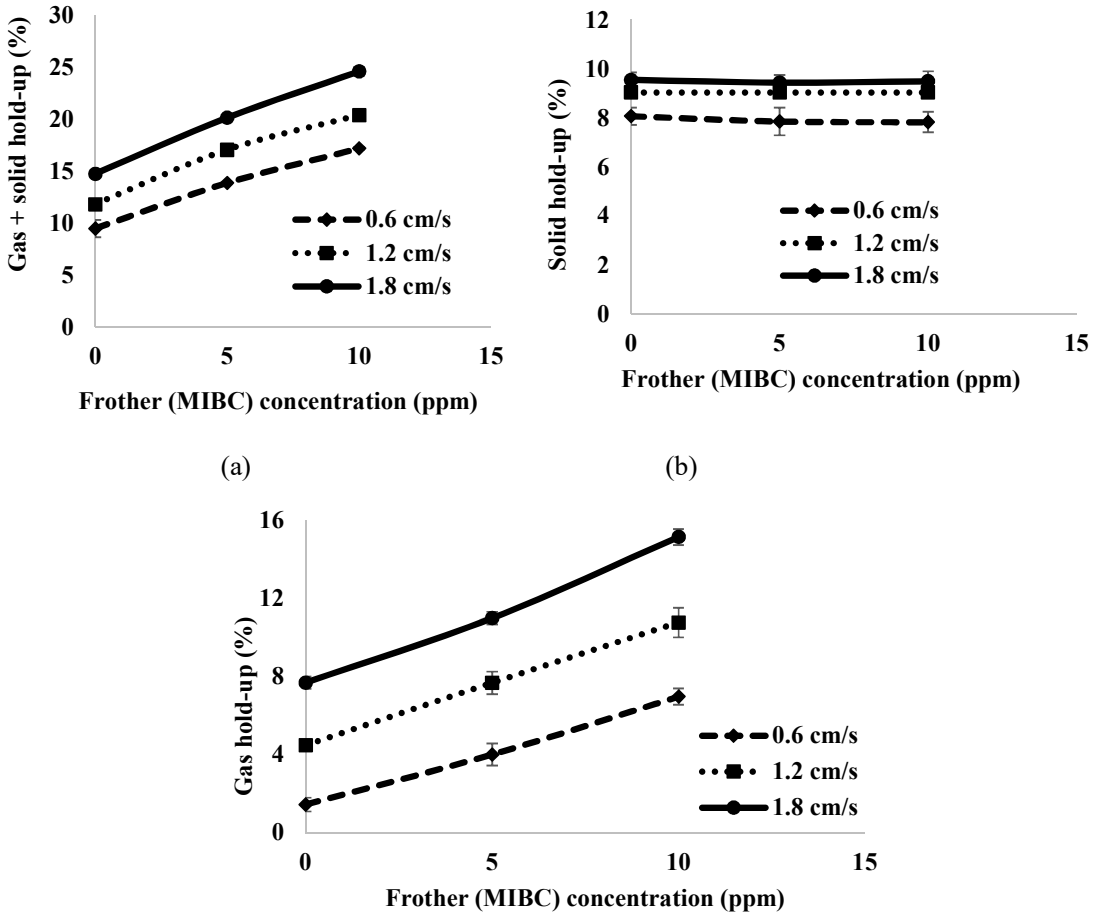


Figure 8: Effect of frother on (a) mean gas hold-up (b) solid hold-up (c) gas hold-up for 10 wt. % solids slurry solution

4.6 Investigation of mechanisms beyond the gas hold-up reduction with solids

Different mechanisms were proposed and assessed in the literature to explain the influence of solid particles mainly on gas hold-up for hydrophobic particles. Nevertheless, the gas hold-up reduction by the presence of hydrophilic particle is still inevitable, and are mainly caused by local hydrodynamics. The effects would be to:

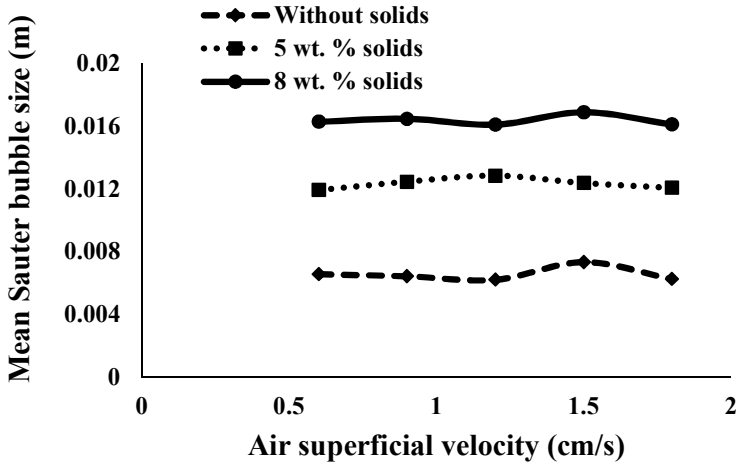
- Bubble coalescence (Banisi et al., 1995; Kuan and Finch, 2010; Vazirizadeh et al. 2016);
- Change in the density and viscosity of the slurry (Finch and Dobby, 1991; Banisi et al., 1995);

- Change the radial gas hold-up and flow profiles (Banisi et al., 1995);
- Bubble wake effects (Banisi et al., 1995);

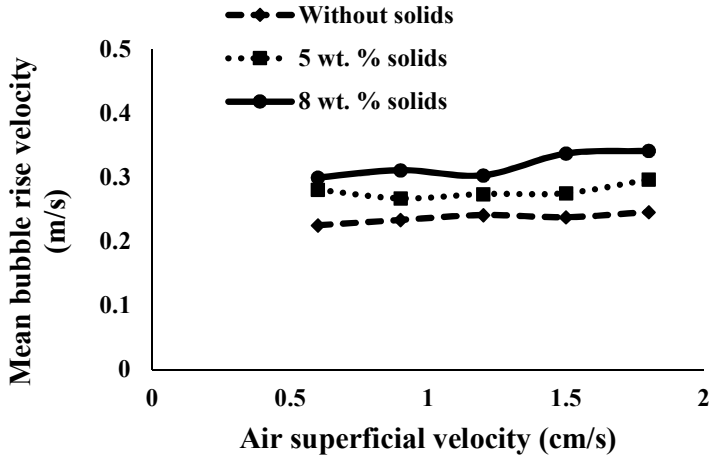
Each of these proposed hypotheses is examined in the light of measured data in the present work

4.6.1. Bubble coalescence and break-up

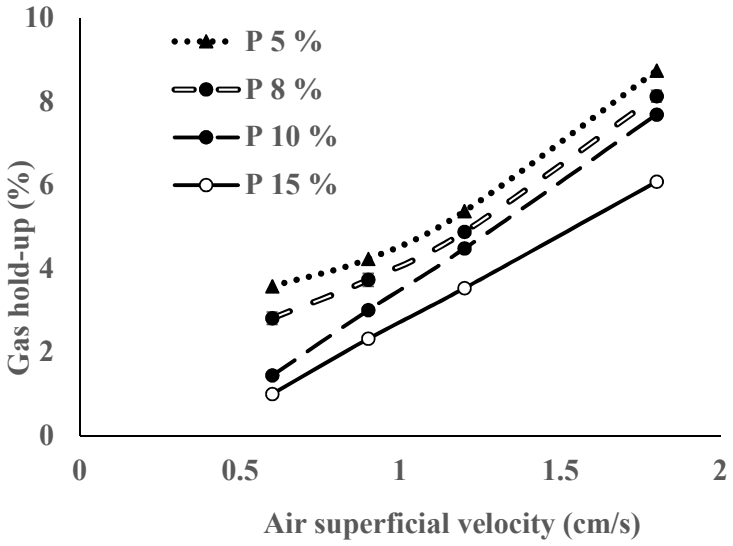
Bubble coalescence occurs due to the bubble interactions resulting an increased bubble size, faster rising bubbles. This would eventually lead to a reduction of the gas hold-up. The bubble coalescence induced by solid particles could occur during the counter-current flow of bubble-solids progressively along the column.



(a)



(b)



(c)

Fig. 9 Sauter mean bubble size and bubble rise velocity at the column flotation for 2300 mm liquid height, 200 k sparger

In the present study, by assuming that radial solids holdup is invariant in the axial direction of the column from the feed port to sparger section, since all the silica particles are hydrophilic nature would eventually get separated mainly as the tailing, one could adopt the dynamic gas disengagement (DGD) technique. Similar to two-phase flow measurements, the Sauter mean bubble size and bubble rise velocity in the presence of solids have been calculated with the help of DGD method. Experiments are carried out for two phase gas-liquid system and 5 %, 8 wt. % silica slurry solution at 2300 mm pulp height, 200 k sparger using the ERT. The Sauter mean bubble size and bubble rise velocity of bubble swarm are calculated by similar approach to Balraju and Narasimha (2017). Estimated Sauter mean bubble size and bubble rise velocity are shown in Fig.9. It is observed that Sauter mean bubble diameter as well as the mean bubble rise velocity increases with solids content compared to pure air-water system. It is believed that due to the associated bubble interaction via coalescence phenomena, the Sauter bubble size is expected to increase with solids, which further reflects the increase in bubble rise velocity (See Fig 9 (b)) as well as the reduction mean gas hold-up with increase the solids in the slurry solution (see Fig 9(c)). This clearly indicating that bubble coalescence is a possible mechanism beyond gas hold-up reduction with hydrophilic nature solids. Similar observation was also reported earlier by Vazirizadeh et al. 2016.

4.6.2. Change in the density and viscosity of the slurry

The presence of solid particles in the size range of treatable by flotation process usually increases both the pulp density and slurry viscosity. The change in increased viscosity and pulp density have strong impact on bubble dynamics especially the bubble rise velocity and gas hold-up.

Based on the equation of Narasimha et al (2016) adopted for slurry classification through a hydrocyclone separator, the slurry viscosity (μ_m) can be calculated as

$$\frac{\mu_m}{\mu_w} = \left[1 - \frac{\alpha_p}{0.62}\right]^{-1.55} \left(F_{-38\,\mu m}\right)^{0.39} \qquad \text{---------- (6)}$$

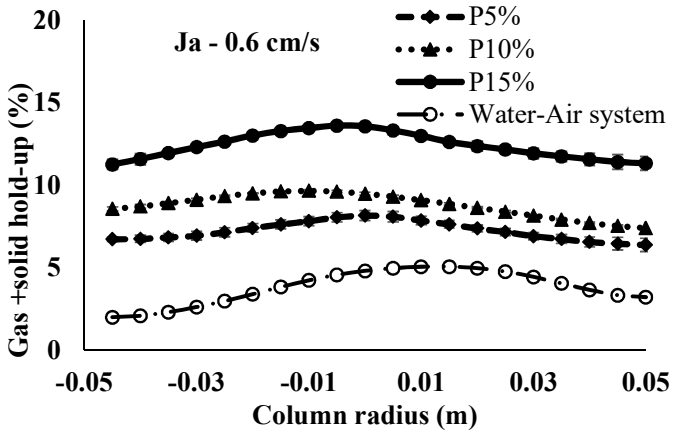
where μ_m, μ_w are the mixture and water viscosity respectively, $F_{-38\mu m}$ is the fine fraction below 38 µm and α_p is the solids volume fraction in the slurry.

According to equation (6), the slurry viscosity increases with solids content and more importantly when the fines fraction below 38 microns increases, the slurry viscosity increases significantly to large values The increased slurry viscosity can stabilize bubble wake (Bhaga and Weber, 1980). This, in turn leads to an increase of the bubble rise velocity, and thus a reduction of the gas hold-up (Banisi et al., 1995 and Vazirizadeh et al. 2016).

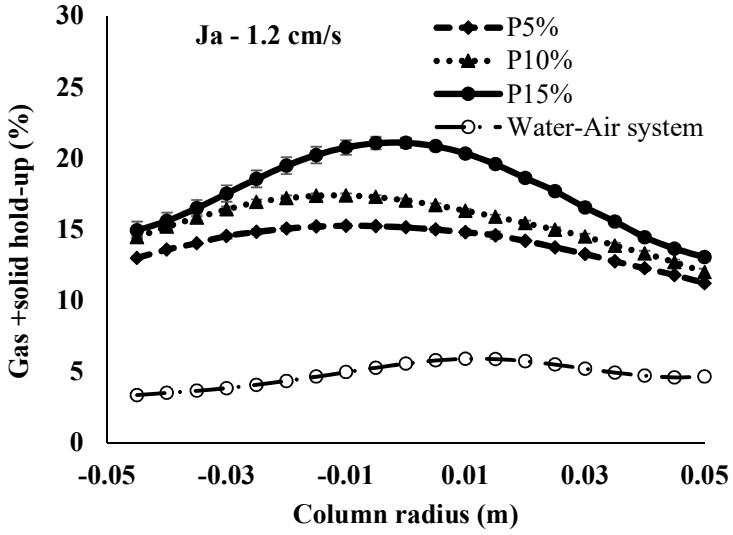
In the present work the solids contents have been tested for 5, 8, 10 & 15 % by weight, which is equivalent in terms of α_p are 1.95, 3.18, 4.02, 6.24 %. The estimated slurry viscosities and pulp densities are shown in Table 2. The pulp density seems to varying slightly over 3 % to 10% compared to water case, but the effective slurry viscosity varies significantly from 1 cP of water-air system to 6.25 cP. These high viscosity values reflected here are mainly due to the dominant fines fraction (up to 72 %) below 38 microns of silica particles in the flotation feed. As reported by Banisi et al 1995, the higher viscosity would certainly affect the bubble stability leading to increase in bubble wake stability (Bhaga and Weber, 1980; Tsuchiya et al., 1990). This, in turn may leads to an increase of the bubble rise velocity. Hence a net reduction of gas hold-up is inevitable for this kind very fine particulate flotation systems even for hydrophilic particles.

Table 2: The estimated slurry viscosities and pulp densities at different solids content

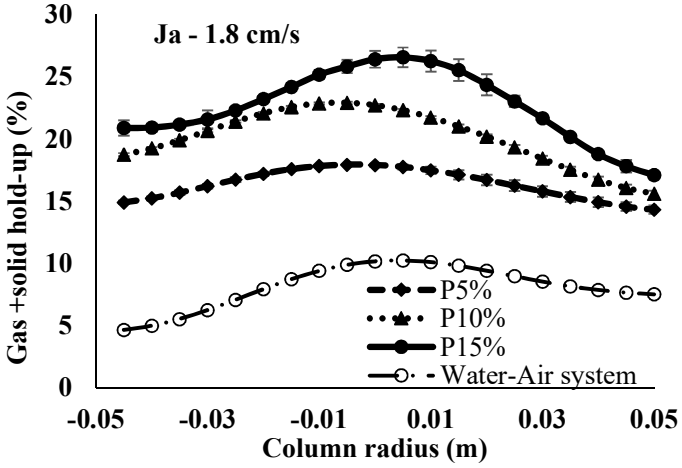
Solids content (wt%)	α_p	μ_m / μ_w	$\rho_{sl,}$
5	1.94742	5.56984	1.032132
8	3.177125	5.751354	1.052423
10	4.024145	5.882117	1.066398
15	6.243496	6.248974	1.103018



(a)



(b)



(c)

Fig. 10 Sauter mean bubble size and bubble rise velocity at the column flotation for 2300 mm liquid height, 200k sparger

4.6.3: Change in the radial hold-up and flow profiles

Radial combined hold-up profiles have been obtained from ERT are compared for different solids contents along with pure water-air system displayed in Fig 10 (a) to (c). From Fig 10 (a), it was observed that at low air superficial velocity of 0.6 cm/s, the phase hold-up in the water-air system seems to be asymmetric and it is believed due to the bubble plume oscillations and associated with its dynamic behaviour. The presence of solids up to 10 wt% in the column, makes combined radial hold-up profiles slightly flat and uniform compared to water-air system, of course at elevated hold-up values. In case of 15 wt% solids, the radial hold-up profiles become non-uniform. At higher superficial air velocities, say 1.2 & 1.8 cm/s, the phase hold-up in the water-air system seems to be flat and is changes to non-uniform profiles in the presence of solids. This might be an indication of counter flow of water along with the hydrophilic particle near the wall region whereas the column central zone is occupied rich in bubbles. This influence would be inevitable as proven in the previous section that hydrophilic solids presence enhances the bubble coalescence and enhanced bubble wake stability within the laminar to transitional bubbly flows in columns. There is some theoretical evidence as proposed using the drift flux analysis by Banisi et al. (1995), where it was reported as the change in radial gas hold-up profiles from flat shape to non-uniform nature when operated from water-air system to slurry systems. It is, therefore, postulated here that solids influence the local flow field and followed by a shift in radial hold-ups from flat in the water-air system to non-uniform in the slurry-air systems.

5. Conclusions

The bubble and solid dispersion characteristics are successfully explored using an advanced non-invasive technique such as ERT coupled with pressure transducers. Combined hold-up, solid and gas hold-up are assessed at both homogeneous and transitional flow regime. Experiments are conducted for three different solid percentages of slurry solutions and effect of various air and slurry feed superficial velocities, pulp height, frother dosage and sparger pore density on mean gas and solid profiles are investigated. Combined mean gas and solid hold-up is increases with air superficial velocity, slurry superficial velocity and pulp height. The variation in gas hold-up in the presence of solids content has been explained by bubble rise velocity and Sauter mean bubble diameter in the silica slurry solution. The gas hold-up is reduced by the addition of solids. Possible mechanisms introduced from the literature on solids effect on gas hold-up are discussed and verified in light of current experimental results. It is confirmed that bubble coalescence, bubble wake stabilization due to viscus slurry and change in radial bubble dispersion due to the bubble-particle interactions resulting an increased bubble size, faster rising bubbles lead to a reduction of the gas hold-up.

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