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HYDRODYNAMIC STUDY OF TWO PHASE FLOW OF COLUMN FLOTATION USING ELECTRICAL RESISTANCE TOMOGRAPHY AND CFD TECHNIQUES

Balraju VADLAKONDA[1*] and Narasimha MANGADODDY[2]

[1&2] Department of Chemical Engineering, IIT Hyderabad, NH-9,Kandi (V), Sangareddy, Medak (Dist), Telangana, 502285, INDIA
*Corresponding author, E-mail address: ch10p005@iith.ac.in

ABSTRACT

The distribution characteristics of mean gas hold-up and flow field were studied using electrical resistance tomography (ERT) and CFD model in column flotation. The effect of superficial gas velocity and different types of spargers on mean gas hold-up and its radial distribution has been analysed. Experimental results show ERT is suitable as an online monitoring tool to provide useful information on the hydrodynamic parameters of column flotation. The ERT technique facilitates non-invasive and nonintrusive visualization of different parameters in a column flotation. The tomography images, which were generated using a modified sensitivity back projection algorithm, were employed to explore the influence of parameters in two phase flow in column flotation. The mean gas hold-up values from ERT have been validated against pressure transducer data. The measured data is validated against the two-fluid model based CFD data and found them in close agreement.

NOMENCLATURE

A_C Cross sectional area of the column, m^2
DAS Data acquisition system
ERT Electrical resistance tomography
ΔH Vertical distance between two pressure sensor points, m
g Gravitational constant, m/s^2
MOC Material of construction
ΔP Differential pressure between two pressure sensor points, Pa
u_g Gas superficial velocity, m/s
u_l Liquid superficial velocity, m/s
ε_g Gas hold-up
$\sigma 1$ Conductivity of liquid phase, mS/cm
$\sigma 2$ Conductivity of gas phase, mS/cm
σ_{mc} Local mixture conductivity, mS/cm
ρ_l Liquid density, kg/m^3

INTRODUCTION

Column flotation is versatile equipment being used in mineral processing and coal preparation industries. The multiphase behaviour in column flotation is complex, so hydrodynamic study is required to obtain a sound understanding. Column flotation has been found to yield better performance than conventional flotation cells, particularly with fine particles (Honaker and Mohanthy, 1996). Column flotation has been preferred for several reasons: 1) It reduces the number of cells compared to conventional cells, 2) Easy to handle and no moving parts, 3) High aerated volume, and the possibility of air flow rate and bubble size distribution control, 4) Collector requirement is less and better product recovery, 5) The selectivity of the flotation process in a column is higher than in conventional apparatus. The air flow rate, feed rate, wash water rate and reagent dosage relatively affect the flotation column performance (Jena et al., 2008).

Hydrodynamics analysis of column flotation can be pursued by measuring various variables such as mean gas hold-up, mean axial liquid velocity, bubble size distributions, Sauter mean bubble diameter etc. Many techniques have been developed that could be used to experimentally analyse the hydrodynamics of column flotation. 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 analyze the internal phase distribution non-intrusively. ERT provides very useful tools for measuring and monitoring of column flotation process is the on-line monitoring actual already in use. 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. Application of ERT has extended in process systems due to its improved speed of data acquisition, sensitivity, flexibility and noise immunity. On the other hand, Computational fluid dynamics (CFD) is useful tool in analysis of the highly complex fluid flow in Column Flotation. Deng et al. (1996) has attempted to simulate of column flotation two-phase flow behaviour. Chakraborty et al. (2009) provided a basis to adopt the two-fluid model approach for column flotation.

In this paper column dynamics has been analysed by studying the flow behaviour in the terms of mean gas hold-up. Effect of various parameters on the mean gas hold-up has been studied. CFD simulations have been carried out to explain the water-air dispersive flow in column flotation and validated against ERT experimental data in column flotation.

EXPERIMENTAL PROCEDURE

The laboratory flotation column was made with transparent perspex. Experiments were carried out for gas-liquid two phase system. Air was introduced into the column through sparger from air compressor. Column was filled with tap water. The air flow rate is controlled by rotameter and experiments were conducted within range of 1-6 lpm. Different types of 60 k, 200 k, and 400 k pores sintered disc spargers are used in experiments. Experiments are carried out at three liquid feed velocities of 0.1296, 0.215 and 0.305 m/sec. Pressure transducers are fitted to the column above the gas distributor. They were

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used to measure the gauge pressure in the column. Appropriate calibration of these pressure transducers is made in the beginning. Schematic diagram of column flotation is shown in Fig.2.

Fig.1 Laboratory column flotation cell

Experiments were conducted on 100 mm diameter and 2500 mm length of column, where ERT system was connected. 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 consist of three parts with sensors, DAS (data acquisition system) and computer. Sensors were connected to cylindrical section of ERT and other 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 100mm diameter cylindrical section of ERT. The electrodes were in rectangular shape and material of construction (MOC) is stainless steel. All these electrodes were connected to DAS via cables. DAS and host computer connected through the probe. A section of the column was replaced the cylindrical section of ERT to perform the experiments. Adjacent electrode strategy used to get the conductivity measurements using electrodes. Electric current was applied between one pair of electrodes and the resultant voltage differences among the remaining 13 electrode pairs were measured by DAS. The 16 electrode sensor gives 104 independent voltage measurements in one measurement of frame. The host computer was used to store and collect the data from the DAS system. After obtaining the voltage measurements from DAS system, the host computer processes data by using image reconstruction algorithm. The reconstruction of conductivity distribution was analyzed by forward and inverse problems. The forward problem predicts the electrical voltage distribution on the surface of the object, when the conductivity distribution and applied current are known. In inverse problem the conductivity distribution is estimated, with known values of electrical voltage and applied current.

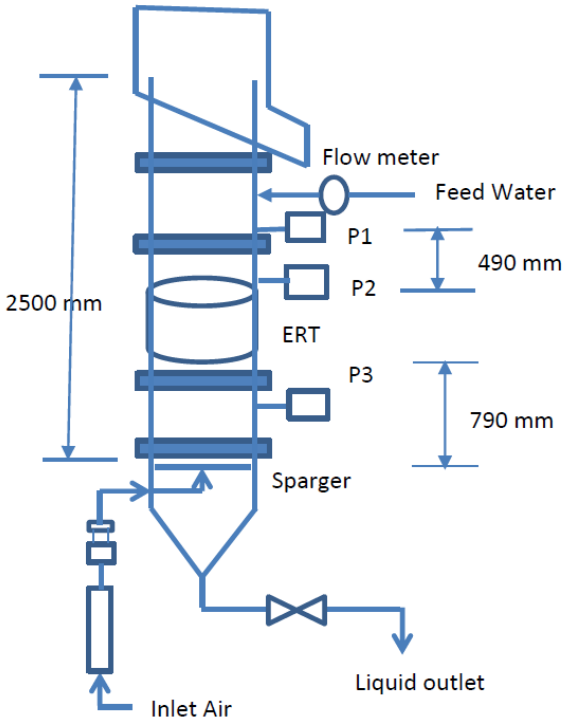

Fig.2 Schematic diagram of Column Flotation

CFD MODELING

The two-phase gas-liquid flow of column flotation is simulated using two-fluid model. The commercial CFD software, FLUENT version 13, with appropriate user defined subroutines has been used in numerical simulations. Standard k-ε turbulence model is used to explore the turbulence in column.

A three-dimensional geometry similar to the experimental setup was created using ICEM-ANSYS software. Grid check has been pursued using different grid numbers between 1, 25,382 and 4, 44,390. Then the predicted gas holdups were didn't change much after 3, 41,838 nodes. So an optimum 3, 41, 838 nodes grid was used in simulations. The transient simulations were performed and the time step 0.001 s was used. Mass and momentum equations were solved using a higher-order discretization schemes, like QUICK. Phase coupled SIMPLE is used for pressure velocity coupling. The gas inlet and feed inlet were taken as a velocity inlet. The average bubble size is 2.5 mm. At the column outlet, a degassing boundary condition was specified. The interphase forces such as Ishii & Zuber drag, lift and virtual mass forces were considered in simulations. Lift coefficient of 0.2 is used.

EQUATIONS

The mean gas hold-up of column flotation from ERT was calculated using the equation due to Maxwell:

$$\varepsilon_g = \frac{(2\sigma_1 + \sigma_2 - \sigma_{mc}\sigma_2/\sigma_1)}{\left(\sigma_{mc} - \frac{\sigma_2}{\sigma_1} + 2(\sigma_1 - \sigma_2)\right)} \qquad (1)$$

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 two phases. Here considering the gas phase as a non-conductive material, the above equation reduces to

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$\varepsilon_g = (2\sigma_1 - 2\sigma_{mc})/(2\sigma_1 + \sigma_{mc})$ (2)

The local mixture conductivity $\sigma_{mc,}$ was determined from the pixel conductivity of ERT image. So, the average value of mixture conductivity over the column cross-sectional area (A_C) is given by

$$\bar{\sigma}_{mc} = \frac{\int_{A_C} \sigma_{mc}\, dA_C}{A_C} \quad (3)$$

The average gas holdup (ε_g) can be obtained from Eq. (4),

$$\bar{\varepsilon_g} = \frac{2\sigma_1 - 2\bar{\sigma}_{mc}}{2\sigma_1 + 2\bar{\sigma}_{mc}} \quad (4)$$

The axial gas hold-up can be measured from the two differential pressure values. It was calculated by equation (5). The liquid acceleration and wall friction are assumed as small and could be neglected.

$$\varepsilon_g = 1 - (\Delta P/(\rho_l\ g\ \Delta H)) \quad (5)$$

where ΔP is the differential pressure between two pressure sensor points, ΔH the vertical distance between two pressure sensor points, and ρ_l liquid density.

RESULTS AND DISCUSSION

Calibration of ERT system

Fig.3 shows the calibration of ERT system against the standard conductivity meter. To prove that ERT is giving correct values of conductivity, we have compared the readings of ERT with the readings of conductivity probe at different concentrations of salt solutions of 0%, 1%, 3% and 5% (wt/vol). The measurements of conductivity are almost same in both the ERT and Conductivity probe. ERT slightly over predict due to its inherent diffusive nature and the adopted reconstruction algorithms.

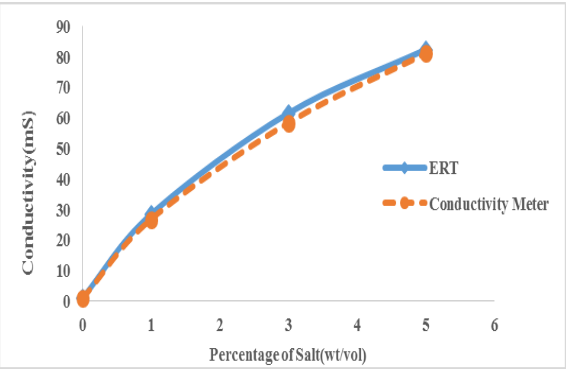

Fig.3 Calibration of ERT

ERT Data analysis

Voltage measurements were recorded for each operating condition by collecting tomograms at the rate of 1000-1500 frames. Fig.4 shows the obtained ERT voltage measurements, reference voltage measurements and relative changes between the reference and actual measurements. The conductivity of inside flotation cell equals to tap water conductivity, when the reference measurement was conducted. The vertical axis indicates voltage measurements (mv) and horizontal axis has the pair of different electrode measurements from 1 to 13. With the help of voltage measurements based on standard deviation values, one can know whether the system is operating with minimal noise or not. The graph indicating about measurement of two planes. The 1500 frames are collected from EIT Z8000 system with actual frame rate 1000 frames per second for dual planes and averaged all collected frames using the ITS tool suite software in order to minimize the errors in measurements.

Conductivity Tomogram across the column

The mean conductivity tomogram is extracted by averaging 1000 conductivity reconstructions across the column. Fig.5 shows the mean conductivity at different air flow rates. The tomograms were generated by ERT system using modified sensitivity back projection (MSBP) algorithm. As air flow rate increase, the overall conductivity of the plane slowly decreases. Based on Maxwell equation, the gas hold-up is extracted

Gas hold-up comparison using pressure method and ERT

Gas hold-up is an important parameter for analysing the column flotation performance. The gas hold-up is function of gas velocity. ERT and differential pressure methods are used in measuring the gas hold-up in column. The gas hold-up compared between ERT and pressure difference method has shown in Fig.6. Sinter disc sparger was used in laboratory column flotation. 400k sparger is used for the comparison. The results obtained by two methods are matching well. The gas hold-up obtained by pressure transducers is slightly higher than that obtained with ERT. The slight discrepancy is most likely due to use different measurement principles (Jin. et.al, 2007). The mean gas hold-up is increased with air flow rate. As air flow rate increases, due to bubble break-up and coalescence there is no linear relationship between gas flow rate and gas hold-up.

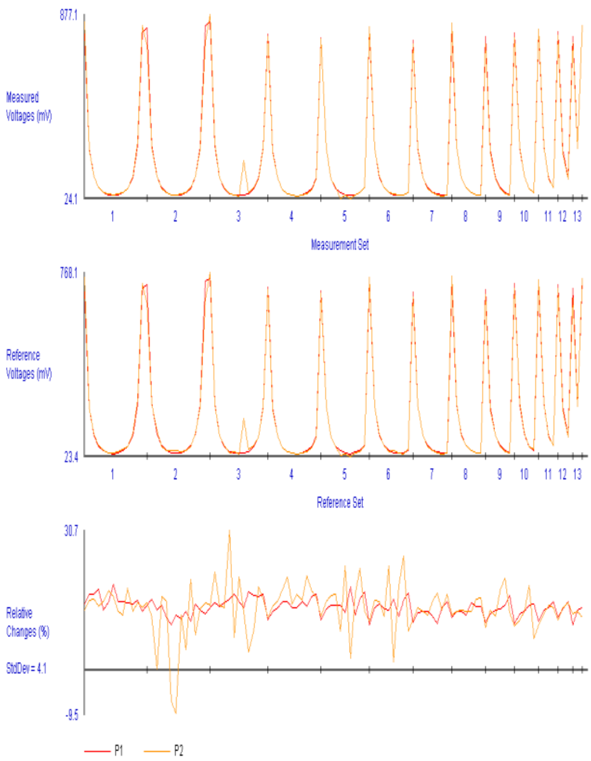

Fig.4 ERT Voltage measurement at two planes in the column

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Effect of liquid velocity on mean gas hold-up

Fig.7 shows the variation in gas hold-up with gas rate for three different liquid velocities. The counter-current flow behaviour of liquid-gas plays a vital role in gas hold-up distribution of the column. Gas hold-up increases with liquid velocity rapidly in the beginning, but at higher liquid velocity it decreases again. The bubble rise velocity increases with liquid velocity and the residence time of bubble reduces in heterogeneous regime. So the mean gas hold-up dips in heterogeneous regime (Jin.et.al, 2007).

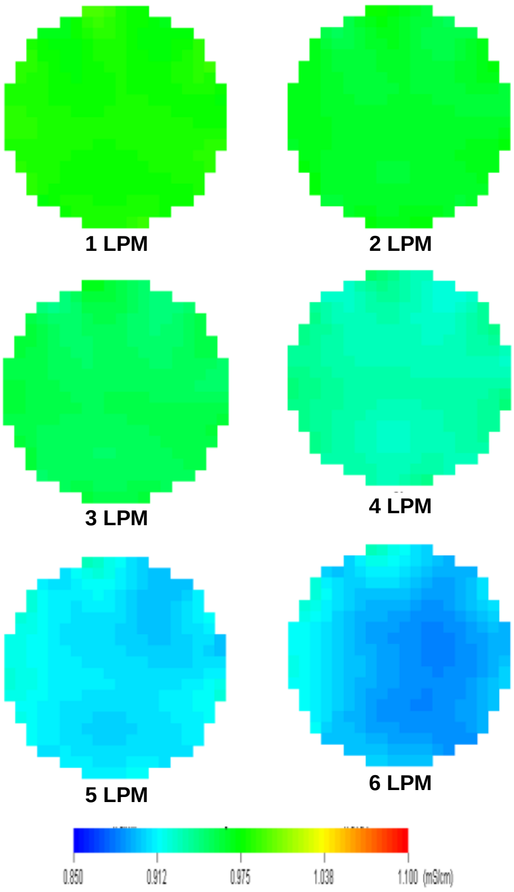

Fig.5 Conductivity tomograms across the column at different air flow rates at plane 2

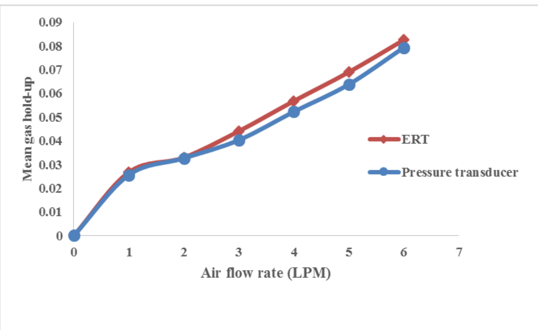

Fig.6 Comparison of gas hold-up between ERT and differential pressure method for sparger 400 k

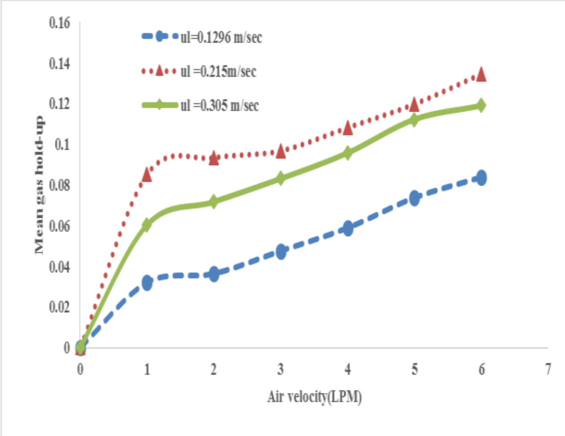

Fig.7 Variation of gas hold-up with liquid velocity

Radial gas hold-up distribution across the column

Radial distribution of gas hold-up across the column is an important parameter. Fig.8 shows the cross sectional tomograms in the column at different air flow rates. The different colours represent the gas hold-up ranging from the high concentration (in red and yellow) to low (in blue). Experimentally using high speed camera, it is observed the adopted porous spargers are generating small size bubbles, hence at low gas flow rates say 1 & 2 L~~l~~pm cases, the distribution of gas hold-up appears to be uniform. At high gas flow rates, there is a variation of radial gas hold-up profiles, which is believed due to increased rate of bubble break-up and coalescence. This can be seen from the significantly different BSD at high gas flow rates (6 Lpm) compared to low gas flow rate (1 L~~L~~pm) conditions, which is shown in fig.9. The gas hold-up increases gradually at the centre of the column with air flow rate.

The quantitative radial distribution of gas hold-up has been plotted across the column in fig.10 and 11 at the plane 1 and 2 respectively. The radial gas hold-up peeks at the centre of the column with increase the air flow rate. The radial distribution is analysed for both planes in ERT at 0.1296 m/sec feed liquid velocity. The gas hold-up is uniform at low air flow rates across the column. The bubbles are uniformly distributed at low flow rates in the column. From the radial gas hold-up distributions at plane 1 & 2, it is observed that there is slight differences in local gas hold-up due to local liquid recirculation typically observed in general bubble columns.

Effect of sparger on gas hold-up in the column

Gas hold-up is analysed for two different spargers of 200,000 and 400,000 pores sintered disc spargers. Fig.12 displays the effect of sparger on gas hold-up in column. With increase is the number of pores of sparger the gas hold-up is increased. When the number of pores are increased, the pore diameter is reduced so smaller bubbles are generated and the surface to volume ratio of bubbles is increased. Detailed investigation of different spargers and liquid flow rates studies in progress.

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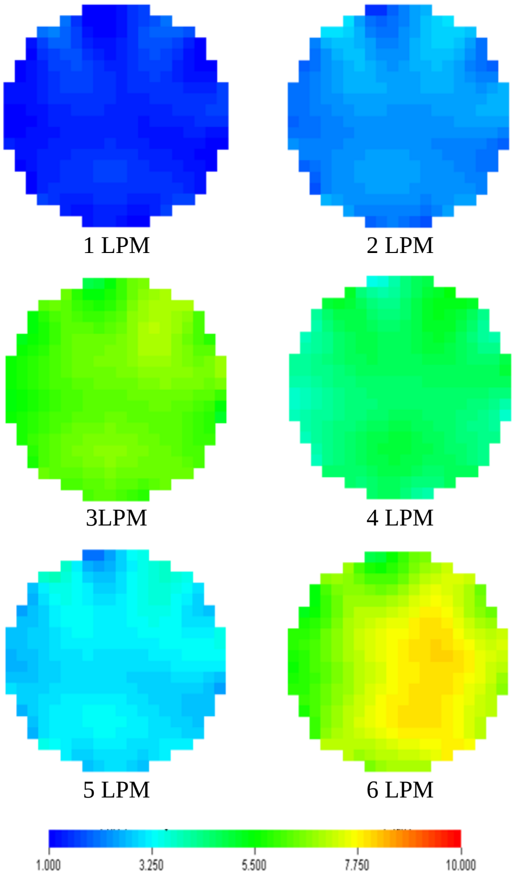


Fig.8 Gas hold-up distribution tomograms at plane 2

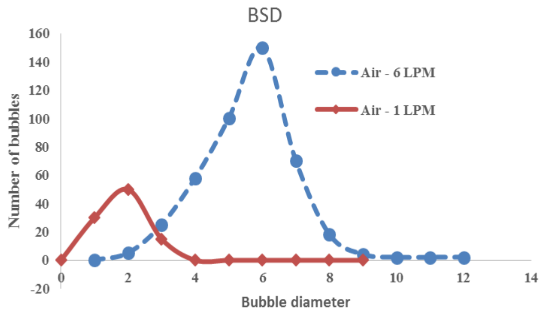


Fig.9 Bubble size distribution in low and high air flow rates

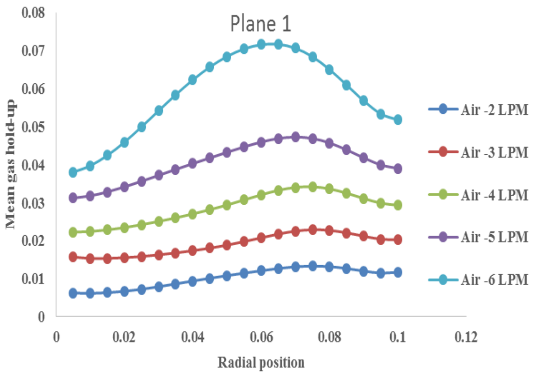


Fig.10 Radial gas hold-up across the column at plane 1

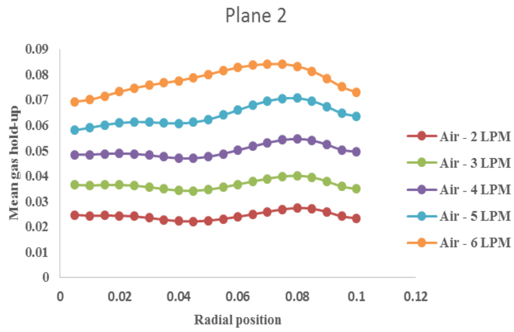


Fig.11 Radial gas hold-up across the column at plane 2

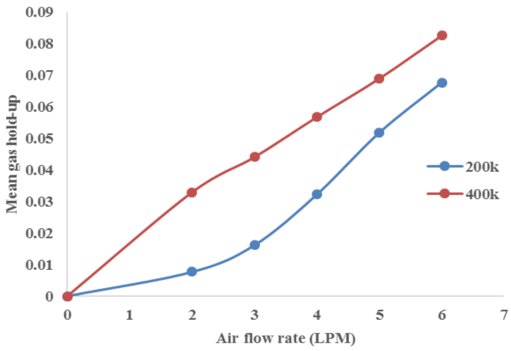
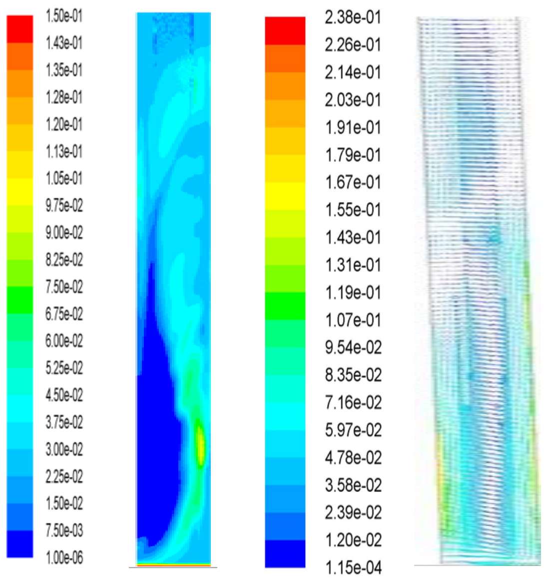


Fig.12 Effect of sparger on gas hold-up

Simulation results

Column flotation simulations are carried out in transient manner. Fig.13 explains about instantaneous gas hold-up and liquid velocity vectors in the column flotation at an air flow rate of 3lpm. The vortexes are observed in the liquid velocity flow field of the column, due to the influence of recirculation. The liquid moves upward in centre and downwards at the wall region. Meandering motion of bubble plume is observed in Fig.13 (a) as a result of local gas hold-up distribution varies across the column.



(a) Instantaneous gas hold-up

(b) Liquid velocity vectors

Fig.13 Instantaneous gas hold-up and liquid velocity flow field for flotation column

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The comparison of ERT experimental measured values and predicted time averaged gas hold-up profiles are shown Fig.14. Simulations are carried out for 400k sparger and 1-5lpm air flow rates. The simulations values are predicted at 0.9m height from bottom of the column and matching with experimental values at high air flow rates and following trend at low air flow rates.

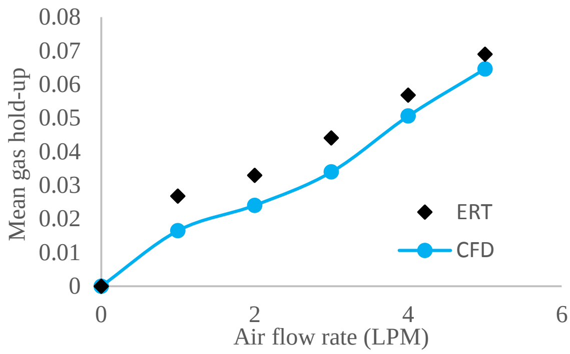

Fig.14. Validation of simulated mean gas hold-up values with ERT experimental data.

CONCLUSION

Experiments were conducted to measure the mean gas hold-up and bubble size distribution in the column flotation using high speed camera and ERT. Time averaged gas hold-up increases with air superficial velocity. Radial profiles of gas hold-up were analysed at different air flow rates. Effect of different spargers was analysed. At high gas flow rates the gas hold-up varies radially, where at the centre it is showing maximum and near wall it is minimum. The gas hold-up increases with air flow rate. At low gas flow rates, gas hold-up is uniformly distributed. Highly porous spargers provide an increased gas hold-up due to increased surface to volume ratio. Measured gas hold-up profiles by ERT were validated against pressure transducer data and the gas superficial velocity influence is supported with help of bubble size distribution estimated by high speed camera. CFD simulations are carried out to analyse the mean gas hold-up and liquid velocity in the column. Conducting ERT experiments are always challenging task in real flotation column, where the flow behaviour is multi-phase and evolving transitional/turbulence nature. Solid hold-up distribution across the column is quite interesting. Widespread CFD studies with enhanced capabilities will be attempted in the future in order to analyse the hydrodynamic behaviour of column flotation.

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