EXPERIMENTAL STUDY ON BUBBLY FLOW TRANSITION IN VERTICAL ANNULAR GAP BUBBLE COLUMN

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Abstract: Mean and local gas void fractions in vertical upward, two-phase flows contained within the annular gap between two concentric tubes are presented. For a given gas superficial velocity, j_g, the mean void fraction, α, was found to decrease as the diameter ratio of the two tubes approached unity (*i.e.* for narrower gaps). Moreover, α was significantly lower than that obtained in an open tube at the same j_g. Two explanations were proposed: (i) large bubbles, generated in the annular gap, destabilised the flow, and (ii) the drift-flux distribution parameter in an open tube was different to that in an annular gap, which results in a different mean α. It was shown that injection of large bubbles into a homogeneous flow led to an early transition. Furthermore, the void fraction profiles in the annular gaps depended on both j_g and the gap geometry.

Keywords: homogeneous flow, local void fraction, void fraction profile, double-sensor electrical probe.

1. INTRODUCTION

The void fraction, α, is an important variable in two-phase flows, since it is used to distinguish between flow regimes and in the prediction of pressure drops and heat transfer coefficients. Calculation of these quantities is required in the design of industrial processing units, *e.g.* bubble column reactors, aeration tanks, and gas-liquid reactors. In addition, two-phase gas-liquid flows occur in a wide variety of chemical and biochemical industrial applications, *e.g.* in evaporators, condensers, wastewater aeration (Coulson and Richardson, 1999) and gas-liquid multiphase reactors (Vijayan *et al*, 2007) and fermenters. Slow chemical process reactions, such as oxidations, chlorinations and alkylations, commonly use bubble columns as gas-liquid contacting devices. These columns possess numerous advantages in terms of their simplicity, absence of mechanical moving parts and efficient heat and mass transfer characteristics. Thus two-phase liquid-gas flows have great utility, but also exhibit a complexity of flow patterns, even in geometries as simple as a pipe flow. A number of factors, such as internal fittings of the pipe work, fluid physical properties, and flow rates or superficial velocities, exert a considerable influence on the void fraction and on the flow regime.

In bubble columns with no liquid flow, three basic flow regimes occur: the homogeneous, the heterogeneous and the transition regimes (Deckwer, 1992; Kastanek *et al*., 1993; Molerus, 1993; and Zahradnik *et al*., 1997). The homogeneous regime is also known as the dispersed, uniform, bubbly flow regime and occurs at low gas superficial velocities, j_g. With increasing gas superficial velocity, the void fraction increases and hence coalescence of bubbles becomes increasingly likely; this leads to the formation of large, rapidly rising bubbles, surrounded by a dispersion of smaller bubbles. Initially, the effects of coalescence to form large bubbles causes a decrease in void fraction with increasing j_g in the transition regime. At yet higher superficial gas velocities, in the heterogeneous regime, the void fraction continues to increase with increasing j_g. An example of the variation of void fraction with superficial velocity is shown in fig. 1, for a porous plate sparger. The “open tube” or empty bubble column results show the usual flow pattern variations from homogeneous through transition to heterogeneous flows. Here, the transition first starts at a $j_g \approx 0.09$ m/s and a void fraction of $\alpha \approx 0.40$.

The drift-flux approach, proposed by Zuber and Findlay (1964), is a popular model to predict gas void fraction over a range of two-phase flow regimes. It may be written as

$$\alpha = \frac{j_g}{C_0 j_g + v_t} \tag{1}$$

The model contains two adjustable parameters, the single bubble rise velocity, v_t and the distribution coefficient, C_0. The former simply depends on the bubble size and liquid physical properties, whereas the latter depends on the void fraction and liquid velocity profile in the radial direction, across the flow.

The work described here considers the differences in the mean void fraction and void fraction profiles in annular gap columns, compared to simple bubble columns (the annular gap is created between two concentric columns and resembles the flow geometry of an internal loop air-lift bubble column). Figure 1 also shows a comparison between the gas void fraction in an open tube and annular gap column, at the same j_g and both employing a porous plate sparger. In the annular gap bubble column, there is no obvious transition between homogeneous and heterogeneous flow and the mean gas void fraction is considerably lower than for the open tube. The purpose of the present work is to study the differences between these two flow geometries and to propose an explanation of the differences in flow regime and gas void fraction variations. Similar effects have been observed in bubble columns with large orifice gas spargers (*e.g.* Sarrafi *et al.*, 1999); in this case it appears that a heterogeneous distribution of bubbles are produced by the sparger and there is no obvious transition from homogeneous flow. Therefore, a possible explanation of the annular gap results is that the flow geometry produces some large bubbles, which destabilise the homogeneous flow, at low gas superficial velocities. An alternative explanation, may be that there is a different void fraction profile in the annular gap compared to the open tube bubble column. In terms of the drift-flux model, changes in the mean bubble size would affect the v_t parameter, whereas changes in the void fraction profile would affect the distribution parameter, C_0.

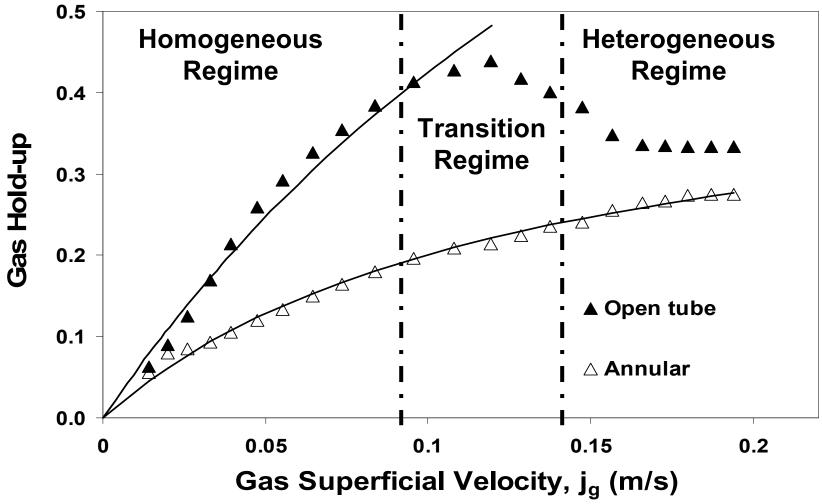

Fig. 1 Gas void fraction behaviour in open tube and annular gap for air – tap-water using a porous plate sparger; in both cases the outer column had a diameter of 0.102 m; for the annular gap column, the inner diameter was 0.051 m diameter. The void fraction α was obtained from the change of level in the bubble column on aeration.

2. EXPERIMENTAL

2.1 Open tube and annual gap rig set up

Experiments were conducted in (i) an open tube bubble column and (ii) an annular gap bubble column, as illustrated in Fig. 2. The outer column consists of a vertical 10.2 cm internal diameter (i.d.) pipe made of transparent QVF® glass with a height of 225 cm. The column is equipped with an appropriate rotameter and digital pressure gauge; a pressure correction was made to the rotameter calibration. Compressed air was injected through a sintered plastic sparger, with a 10 cm diameter and a permeability of 5.3 x 10^{-14} m^2, installed at the bottom of the column. The sparger produced a uniform distribution of bubbles and no large bubbles and slugs were observed moving up the empty column, at low j_g.

Annular gap experiments were conducted by using different inner tube sizes placed concentrically in the column, 2.5, 3.8, 5.1, 7.0 and 7.6 cm (o.d.) tubes denoted as 1, 1.5, 2, 2.75 and 3 inch respectively. The purpose of these experiments was to study the transition (from homogeneous to heterogeneous flow) occurring in air-water systems. The experiments were conducted over the same range of j_g as was used in the open tube experiments. The annular gap has a smaller cross-sectional area than the open tube, and hence the gas flow rates were adjusted appropriately.

Overall mean gas void fractions (averages for the whole column) were obtained by recording the volume change on aeration at a given j_g, from the change in volume (or height) on aeration:

$$<\alpha> = \frac{\text{volume of gas}}{\text{volume of gas} + \text{liquid}} \tag{2}$$

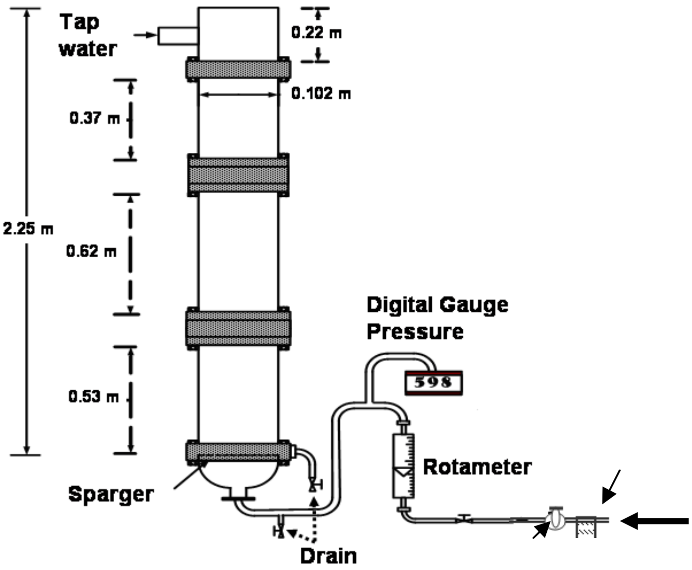

Fig. 2 Experimental set-up

2.2 Measurement of local void fractions and profiles

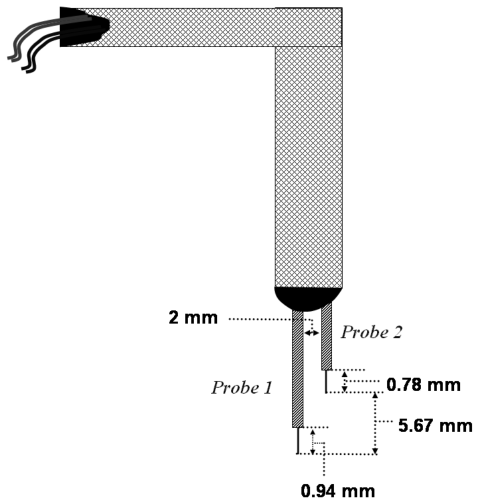

Fig. 3 Design and geometry of the two-point conductivity probe (not to scale)

The impedance method, using one or more electrodes, is a popular method that has been used for void fraction measurement by many researchers (*e.g.* Angeli & Hewitt, 1999; Julia *et al,.* 2005). The electrical conductance of the gas-liquid region surrounding the electrodes is measured. The relationship between α and the difference in impedance between the gases and liquids in two-phase flow, as measured by the electrodes, is exploited in this method. Furthermore, the bubble velocity, α and bubble size in two-phase experiments may also be measured using a double sensor probe, as shown in Fig. 3. The probe consists of a pair electrodes that measure the resistance of the solution to the passing of an ac current (to prevent electrolysis). The sensing stainless steel needle of the probe was electrically insulated and made non-wetting and non-conductive by the application of a varnish except at the needle tip. This needle tip was able to pierce, with minimum deformation, the fast-moving small bubbles at the point of impact, leading to a fast signal response to sense a local bubble interface. The probe operated like an electrical switch: when the tip was in contact with the liquid phase—closed circuit—and gas phase—open circuit. The tip reacts as live (+ve) current and the case as earth (-ve) in this circuit. Depending on the bubble sizes in a two-phase flow system, a suitable axial distance, around 5 mm, between the two needle tips was selected to measure the size and velocity of bubbles with reasonable accuracy.

The conductivity probe signals were digitally recorded using LabView and then processed using Matlab script files to yield the local α measurements (the fraction of time in the gas phase); the distribution of α was obtained by traversing the probe across the column diameter, or radially along the annular gap. Mean void fractions were obtained by volume-averaging the local α profiles.

3. RESULTS AND DISCUSSION

3.1 Mean void fraction, α

A comparison between the gas void fraction in the open tube and in different annular gap geometries is shown in Fig. 4. Both measurement methods confirm that the mean α in the open tube is high compared to that in annular gap. This is either because large bubbles have been generated in the annular gap, which led to heterogeneous flow, or the radial α profile has changed — the latter would affect the distribution parameter, C_0, in Zuber and Findlay's (1965) drift-flux model. The geometry of the annular gap also affects the mean α: Fig. 4 shows that when the inner tube size increases, then a lower mean α results.

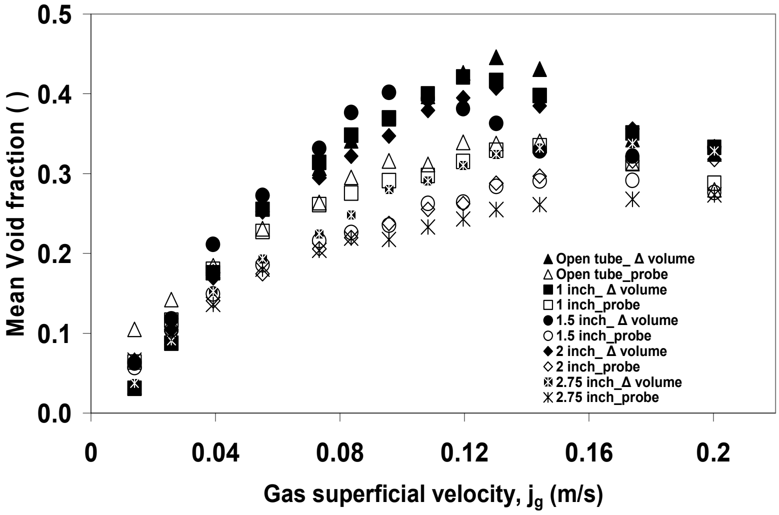

Fig. 4 Mean α in an annular gap for various geomtries, compared to the open tube results (Δ volume = mean α from differences in aerated height and probe = mean void fractions from volume integration of α profiles).

The first mechanism by which the mean α might be lowered in an annular gap column was investigated, namely that the formation of large bubbles might destabilise the flow and force an early transition to the heterogeneous regime. To test this out, a single orifice with various diameters between 0.6 – 3 mm was drilled in the centre of the porous sparger, generating a stream of large bubbles in the open tube bubble column geometry. Fig. 5 (a) and (b) present the results obtained from the volume change and conductivity methods, respectively. From Fig. 5, the conductivity probe mean α values agree fairly well with the volume variation results; discrepancies are due to (i) the volume change method measures a mean α for the whole bed, whilst the conductivity probe averages over a horizontal plane, assuming axisymmetry and (ii) some small bubbles may bypass the conductivity probe, without being pierced. In the open tube with the normal sparger (NS, *i.e.* with no orifice), it was observed that at low j_g, small, uniform-sized bubbles in homogeneous flow, were generated. When the sintered plastic sparger was drilled with a small hole *e.g.* with a diameter 0.6 mm, large bubbles were not generated and hence both homogeneous flow and heterogeneous flow regimes were observed (data not shown). The literature suggests that the orifice size has to be greater than 1 mm to generate heterogeneous flow at all j_g. The effects of large bubble generation from the orifice starts to take place at a diameter of 2 mm; these bubbles should rise much faster than the smaller spherical bubbles produced by the sintered sparger. The results in Fig. 5 for large orifice size generates large bubbles, are consistent with a destabilisation of the homogeneous flow at low j_g, leading to the disappearance of the transition regime of decreasing void fraction..

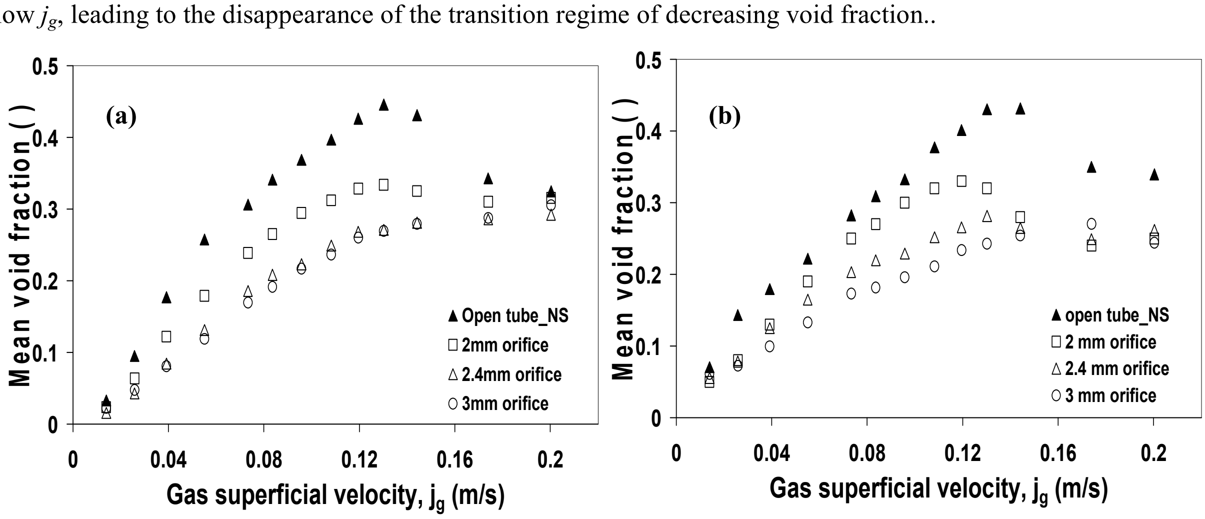

Fig. 5 Mean α with respect to j_g, comparison between plastic sparger “no orifice” (NS) and plastic sparger with different orifice sizes; a) Δ volume method, b) conductivity probe method.

Zuber and Hench (1962) carried out experiments over a range of gas superficial velocities, using a number of perforated plates as air dispersers; see table 1. From their experiments, as the hole size in the gas distributor plate decreased, higher gas void fractions were generated, forming a homogeneous regime. So the orifice diameter plays an important role in determining the gas void fraction, by destabilization of the homogeneous regime. The results in Fig. 5 are consistent with Zuber and Hench's (1962) findings: the NS sintered plastic sparger generated small and uniform bubbles (homogeneous regime) with high gas void fraction, behaving in the same way as the minimum orifice diameter of 0.41 mm, used by Zuber and Hench (1962). As the orifice diameter increased, the flow tends to form a heterogeneous regime. Figure 6 compares the current study results compared with those by Zuber and Hench's (1962). Large orifices would generate large bubbles, which rose much faster than the smaller spherical bubbles produced by the sintered sparger. These large bubbles would sweep the smaller bubbles into their wake, causing coalescence and a early transition to heterogeneous flow.

Table 1 Gas distributor configurations used by Zuber and Hench (1962)

No. of orifices	Diameter (mm)	Square array spacing (mm)
1	4.06	-
49	4.06	6.25
100	1.52	9.5
289	0.41	6.25

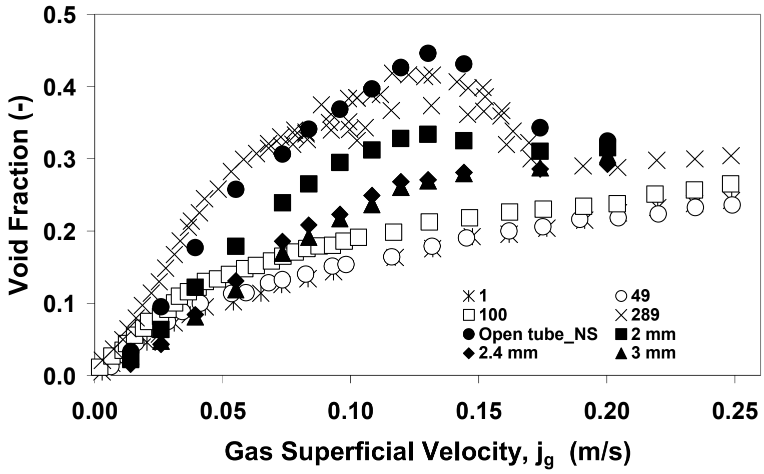

Fig. 6. Mean α for normal sparger (NS) and spargers with different orifice hole sizes; comparisons with Zuber and Hench's (1962) results (see table 1)

3.2 *Void fraction Profile*

Fig. 7 represents the relationship between the local α and position across in the column for the open tube (NS). At low j_g the results show almost uniform and axisymmetric α distributions across the column. Most of the bubbles tend to travel in the centre of the column at high j_g and relatively few bubbles travel close to the wall.

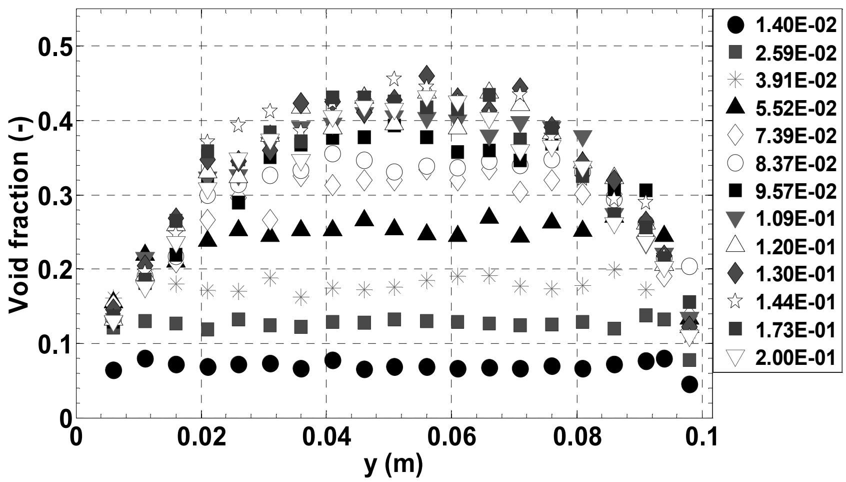

Fig. 7. α profile for open tube-NS at different j_g (legend shows values of j_g in m/s).

The void fraction profiles with respect to electrode radial position in an annular gap column are represented in Fig. 8. The void fraction profile in the annular gap behaves slightly different to that in open tube, since an inner tube is placed at the centre of the column. The maximum α value is not on the centre-line of the gap; bubbles have a higher void fraction at around r = 0.03 m). As before, in the open tube, the void fraction profiles become more uniform at lower j_g, indicating that the distribution coefficient C_0 in eq.(1), may not be a constant under these conditions. Quite clearly the void fraction profiles change their shape, with the geometry of the annular gap and with the gas superficial velocity.

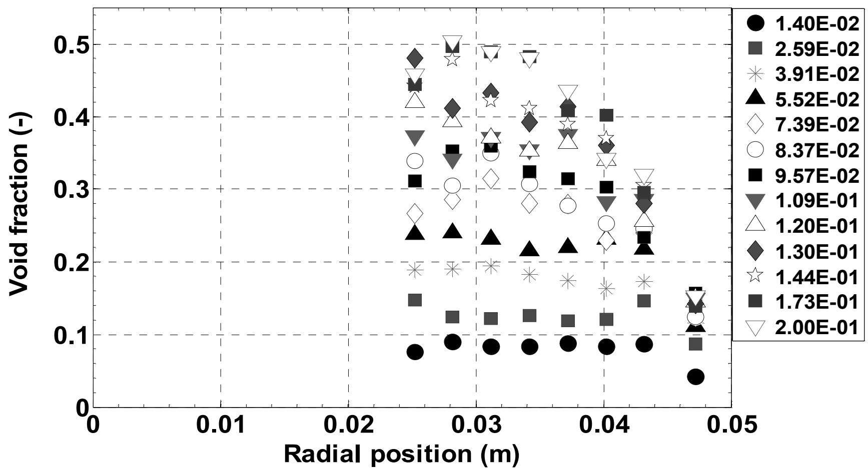

Fig. 8 Void fraction profile respect to radial position for annular gap ,2 inch inner tube (legend shows values of j_g in m/s).

4. CONCLUSIONS

Two main effects have been considered in this study, which reduce α in annular gap columns compared to (open tube) empty bubble columns, at the same j_g , resulting in destabilisation of the homogeneous flow by large, fast rising bubbles and changes to α profile, which affects the distribution parameter C_0 in the drift-flux model. Separate experiments confirm that bubbles formed from a large diameter orifice (> 2 mm) orifice reduce the mean α by destabilising the homogeneous flow. The present results also agreed with Zuber and Hench's (1962) findings, who found lower mean α when using large orifice diameter spargers. Mean void fraction and local α distribution results also showed that the profile shape was not constant and varied with both j_g and the annular gap geometry.

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