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PHASE DISTRIBUTIONS OF AN AIR-SILICONE OIL MIXTURE IN A VERTICAL RISER

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ABSTRACT

This paper reports the results of an experimental study concerned with the phase distributions of gas-liquid multiphase flows experienced in a vertical riser. Scale experiments were carried out using a mixture of air and silicone oil in 6 m long riser pipe with an internal diameter pipe of 67 mm. A series of pipe flow experiments were performed for a range of injected superficial air velocities over the range 0.047 to 2.836 m/ s, whilst maintaining the liquid superficial velocity of 0.047 m/ s. Measurements of radial time averaged void fractions across a pipe section located 5.15 m from the pipe flow injection were obtained using a capacitance wire mesh sensor (WMS). The data were recorded at a frequency of 1000 Hz over an interval of 60 seconds.

A comparison of the experimental data was performed against a published equation presented in [7] and used by [12] to investigate the flow structure of air - water mixtures in a bubble column:

$$\varepsilon_G = \bar{\varepsilon}\left(\frac{n+2}{n+2-2c}\right)\left(1-c\left(\frac{r}{R}\right)^n\right) \qquad (3)$$

It was concluded that the model was able to satisfactorily replicate the observed radial void fraction profile (mean relative error is within 5.7 %) at the higher gas superficial velocities [11]. It was found that the void fraction was strongly affected by the superficial gas velocity, whereby the higher the superficial gas velocity, the higher was the observed average void fraction.

Reasonably symmetric radial void fraction profiles were obtained when the air-silicone oil was fully developed, and the shape of the symmetry profile was strongly dependent on superficial gas velocity.

INTRODUCTION

Nassos and Bankoff [9] studied the slip velocity ratios in an air-water system under steady state and transient conditions. They proposed the following equation for the radial holdup profile

$$\varepsilon_G = \tilde{\varepsilon}\left(\frac{n+2}{n}\right)\left(1-\left(\frac{r}{R}\right)^n\right) \qquad (1)$$

where,
$\tilde{\varepsilon}$ is the radial chordal average gas holdup along the column diameter and the exponent n are parameters and $\frac{r}{R}$ is the dimensionless radial position. The value of n is indicative of the steepness of the holdup profile. When n is large the profile is flat, for small n the profile is steep. The steepness of the holdup profile is reflected in the intensity of liquid circulation. Later, [11] modified equation (1) as follows to include the possibility of finite gas holdup close to the wall

$$\varepsilon_G = \tilde{\varepsilon}\left(\frac{n+2}{n}\right)\left(1-c\left(\frac{r}{R}\right)^n\right) \qquad (2)$$

where,
c is an additional parameter which is indicative of the value of gas holdup near the wall. If c = 1 there is zero holdup close to the wall, if c = 0 holdup is constant with changing $\frac{r}{R}$.

Wu et al. [12] conducted research to study radial gas holdup profiles in bubble column reactions using air and water as the operating fluid, employing gamma ray Computed Tomography (CT). They used the following equation originally proposed by [7] for the radial holdup profile

$$\varepsilon_G = \bar{\varepsilon}\left(\frac{n+2}{n+2-2c}\right)\left(1-c\left(\frac{r}{R}\right)^n\right) \tag{3}$$

Wu et al. [11] conducted correlation exercises to evaluate n and c based on the knowledge of the general operating variables and physical operating variables and physical properties of the system in order to estimate the gas holdup profile by equation (3). They concluded the following empirical relationships

$$n = 2.188\times 10^3 \,\mathrm{Re}_G^{\;-0.598}\, Fr_G^{\;0.146} Mo_L^{\;-0.004} \tag{4}$$

$$c = 4.32\times 10^{-2}\,\mathrm{Re}_G^{\;0.2492} \tag{5}$$

where,

$$\mathrm{Re}_G = \frac{DU_{SG}(\rho_L-\rho_G)}{\mu_L}, Fr_G = \frac{U_{SG}^{\;2}}{gD},$$

$$Mo_L = \frac{g\mu_L^{\;4}}{(\rho_L-\rho_G)\sigma_L^{\;3}}$$

$\bar{\varepsilon}_G$, cross-sectional mean gas holdup was evaluated from the experimental data.

Manera et al. [8] compared wire mesh sensor and conductive needle-probe measurements of vertical two-phase flow parameters using an air-water system. They determined that the WMS is capable of delivering a full mapping of the interfacial area density and a full three-dimensional reconstruction of gas bubbles. However, the needle probe was found to be less intrusive and produced fewer disturbances to the downstream flow.

Abdulkadir et al. [1] carried out an experimental investigation to characterise the phase distributions of two-phase air-silicone oil flow in a vertical pipe using WMS. This study concluded that reasonably symmetric profiles were obtained when the air-silicone oil was fully developed and that the shape of the profile was strongly dependent on the superficial gas velocity. They also determined that symmetric parabolic profiles can be represented as spherical cap bubble and slug flows and that flattened symmetric profile can be represented as churn flow.

The objective of the experimental study reported in this paper was to compare the measured experimental radial void fraction with a published equation [12]. Experimental studies were performed on a vertical 67 mm internal diameter vertical riser. A wire-mesh sensor (WMS) was devised for air-silicone oil to measure cross-sectional void fraction and time averaged radial void fraction to provide some information on phase distributions in a quantitative manner. It consists of two planes of 24 stainless steel wires with 0.12 mm diameter, 2.78 mm wire separation within each plane and 2 mm axial plane distance. This determined the spatial/ temporal resolution of the sensor. Since this square mesh sensor is installed in a circular tube, only 440 of the total 576 wire crossing points are within the radius of the tube. During the experiments, the horizontal transmitter lines are pulsed one after another. By measuring the signal of all crossing vertical receiver wires, the local capacitance around the crossing points in the mesh is known. This capacitance signal is a measure for the amount of silicone oil, and thus indicates the local phase composition in the grid cell. The data were taken at a data acquisition frequency of 1000 Hz over an interval of 60 seconds.

NOMENCLATURE

D	[m]	Pipe internal diameter
g	[m/ s^2]	Acceleration due to gravity
ρ	[kg/ m^3]	Density
σ	[N/ m]	Surface tension
μ	[kg/ms]	Viscosity
Re	[ ]	Reynolds number
Fr	[ ]	Froude number
Mo	[ ]	Morton number
U	[m/ s]	Superficial velocity

Special characters

$\bar{\varepsilon}$	[ ]	Cross-sectional average gas holdup
$\tilde{\varepsilon}$	[ ]	Radial chordal average gas holdup
ε	[ ]	Radial gas holdup

Subscripts

SG	Superficial gas
L	Liquid
G	Gas

EXPERIMENTAL ARRANGEMENTS

This section presents an outline of the construction of the experimental rig used to characterise the gas-liquid flow behaviour within a vertical riser. An overview of the experimental facility is given below.

Overview of the experimental facility

All experiments were carried out on an inclined pipe flow rig within the Engineering Laboratories of the Department of Chemical and Environmental Engineering at University of Nottingham. Details about the experimental apparatus have been previously reported [1], [2], [4], [5] and [6]. In brief, the experimental facility consists of a main test pipe section constructed from transparent acrylic glass. The 6 m test pipe section is of a 0.067 m internal diameter. The test pipe section may be rotated on the rig to allow it to incline between -5 ° to

90 ° degree. For the experiments reported in this paper the rig test pipe section was mounted as a vertical riser.
The rig was charged with air-silicone oil mixture to study the flow regimes created by the circulation of various air – silicone oil mixtures created by the controlled pumped circulation of the oil from the reservoir and the compressed injection of air at the base of the inclined riser pipe. The resultant flow regimes created for the range of air-silicone oil injection circulation flow rates studied were recorded using wire mesh sensors (WMS) as shown in Figure 1. This technology, described by [3], [8] and [10], can image the dielectric components in the pipe flow phases by measuring rapidly and continually the capacitances of the passing flow across several crossing points in the mesh.

PROCESSING OF RESULTS

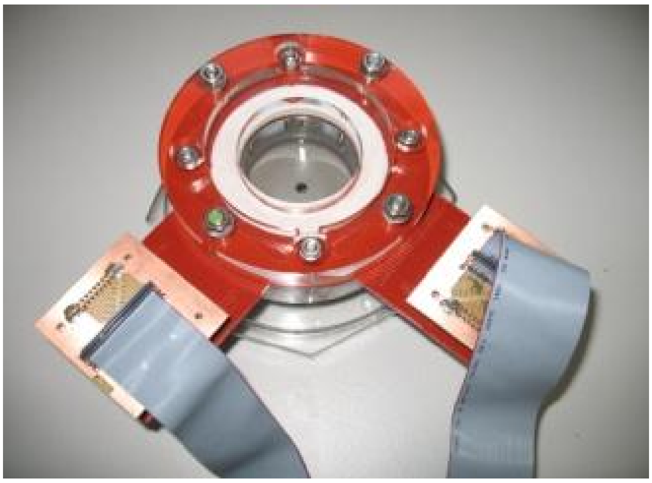


Figure 1 Wire mesh sensor (WMS)

To obtain a quantitative representation of the flow regime, both time and cross-sectional averaging of the void fraction data were used. The weight averaging used was based on coefficients that define the contribution of each crossing point of wires (i, j) in the sensor matrix to the size of the domain, over which the averaging was performed. Details about the definition and methods to obtain the weight coefficients ($a_{i,j}$) may be found in [1].

Radial time averaged void fractions were calculated by averaging the local instantaneous void fractions over the measurement period and over a number of ring-shaped domains (m).

TRENDS AND RESULTS

Comparison of time averaged cross-sectional void fraction distribution with superficial gas velocity

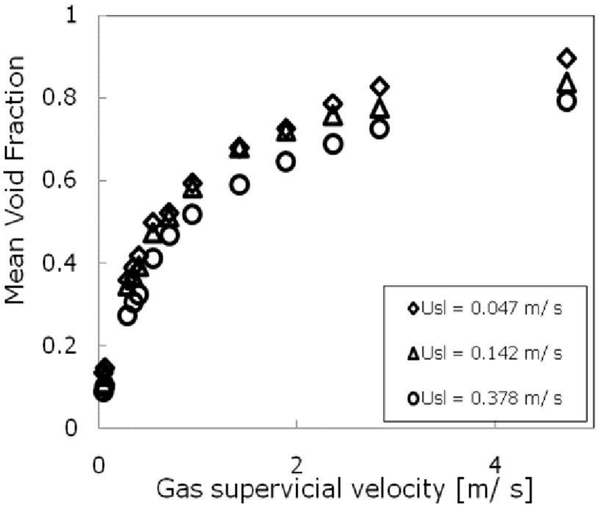


Figure 4 Variation of time averaged cross-sectional void fraction with gas superficial velocity

Figure 4 can be observed to show that all the plots of mean void fraction against superficial gas velocities followed the same trend. It is found that the time averaged cross-sectional void fraction increases with gas superficial velocity with liquid superficial velocity as a parameter. However, the cross-sectional average void fraction increases with a decrease in liquid superficial velocity.

Variation of c-parameter and steepness parameter with superficial gas velocity

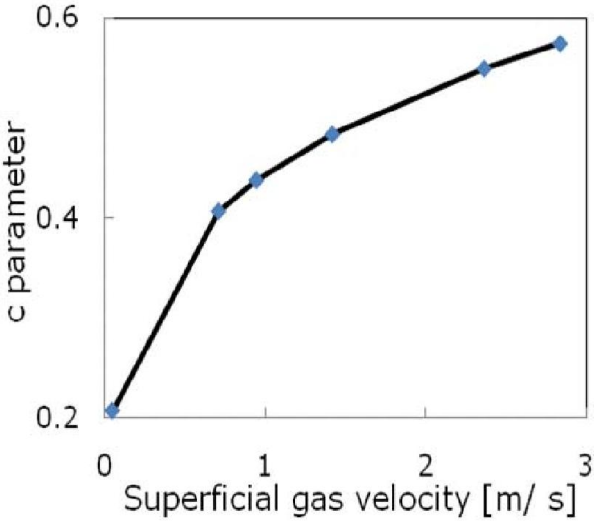


Figure 5 variation of c parameter with superficial gas velocity

The c-parameter is a parameter that defines the amount of gas near the wall. Here the influence of increasing gas flow rate on c parameter will be examined. It was found that that the c parameter increases from 0.207 to 0.575 with an increase in gas superficial velocity as shown in Figure 5. This means the amount of gas near the wall of the riser increases with an increase in gas superficial velocity.

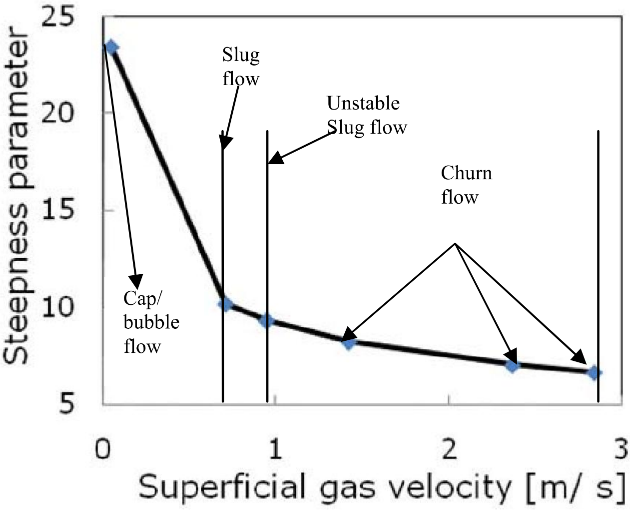


Figure 6 variation of steepness parameter with superficial gas velocity

From an analysis of the variation in steepness parameter with superficial gas velocity (Figure 6), it is concluded that with an increase in gas superficial velocity the steepness parameter decreases from 23.408 to 6.673. This means that higher values of the steepness parameter represent spherical cap bubbles, the intermediate values, slug flow, and the lower values represent churn flow. This therefore shows that the variation of steepness parameter with superficial velocity may be used to classify the flow regimes present.

Figure 7 supports the observations made in figure 3 that as the superficial liquid velocity is maintained at 0.047 m / s and superficial gas velocity increased from 0.047 to 2.836 m/ s, there are observed increases in mean void fraction. This therefore maps the flow regime transition from spherical cap bubble to churn flow regime.

In figure 8 a 2D slice view is shown for the void fractions observed for different gas superficial velocities. At superficial gas velocity of 0.047 m/ s, there are still bubbles of large size, but not as big as the pipe diameter. When the air velocity is increased to 0.709 m/ s, coalescence starts leading to slug flow. At gas superficial velocity of 0.945m / s, the transition to unstable slug flow is complete. When the gas flow rate is further increased, the unstable slug flow transforms into churn flow.

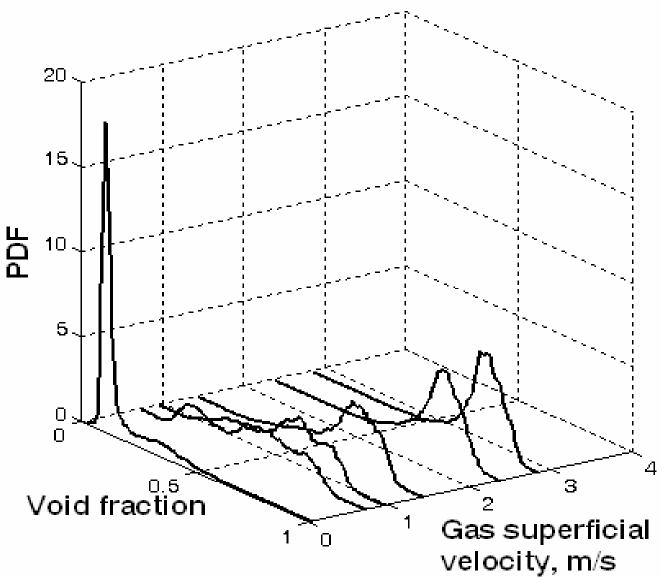


Figure 7 3-D probability density function (PDF) of the void fraction measured by the WMS (U_{SL} = 0.047 and U_{SG} = 0.047-2.836 m/ s)

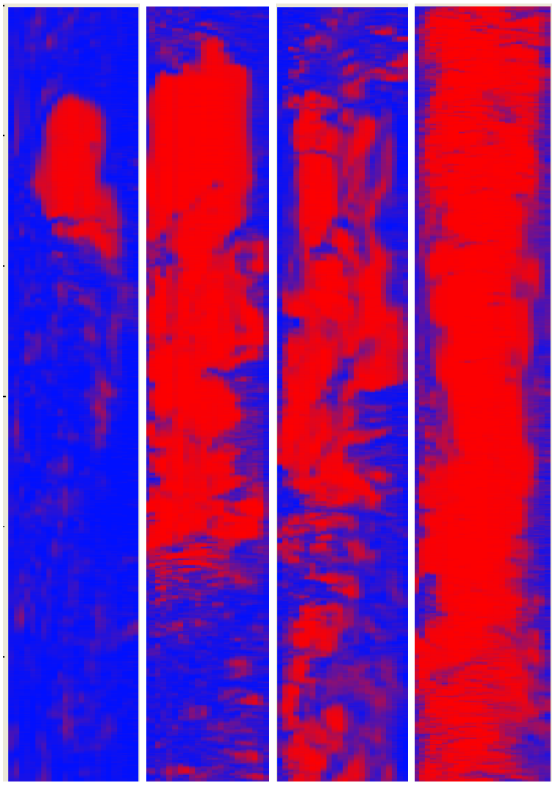
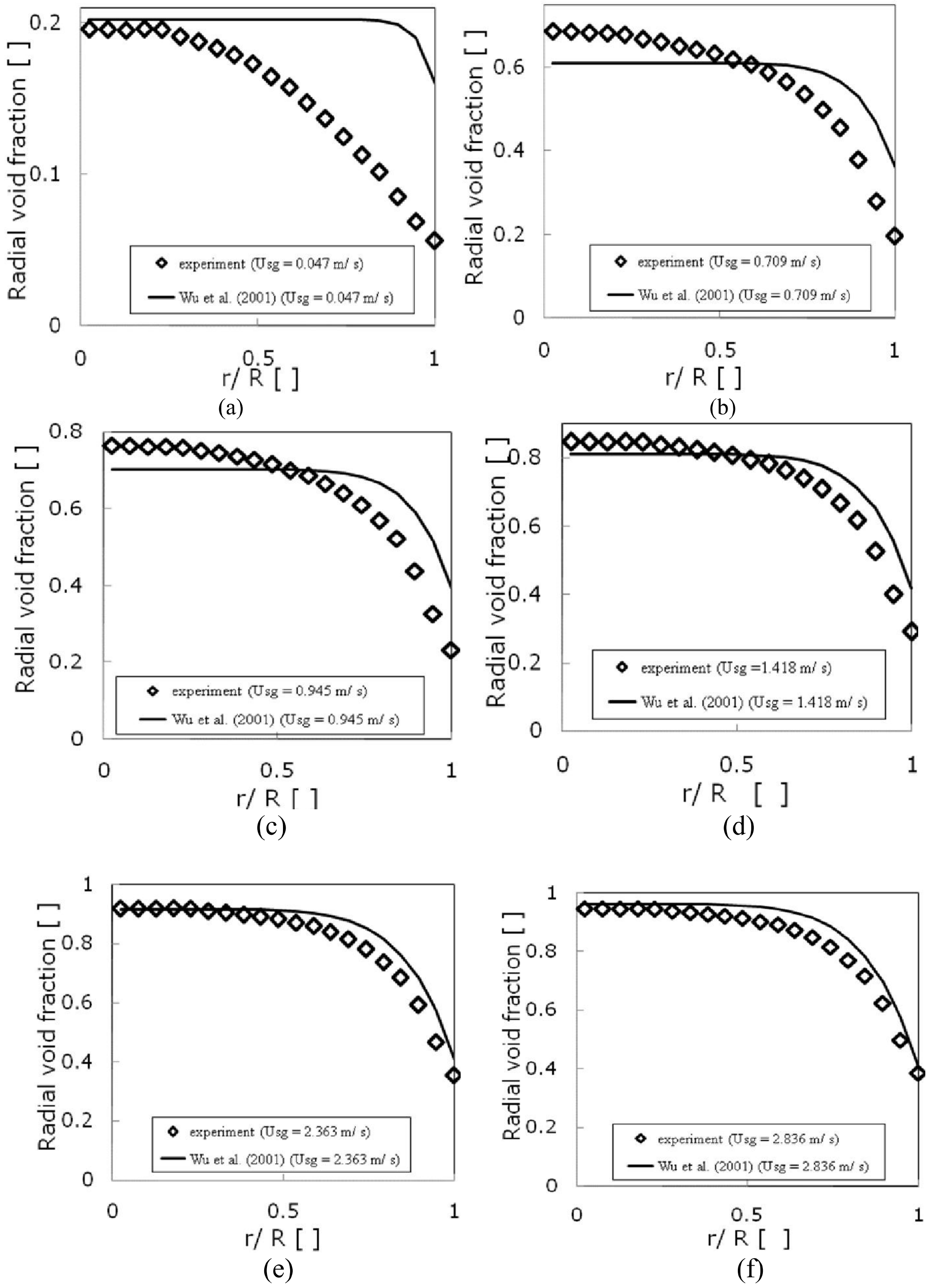


Figure 8 Side view of the two-phase flow transition from spherical cap bubble to churn flow. Superficial liquid velocity of 0.047 m/ s and superficial gas velocity a) 0.047 m/ s b) 0.709 m/ s c) 0.945 m/ s and d) 2.836 m/ s. Sensor: Wire mesh, 24×24 sensitive points; time resolution: 1000Hz.

A comparison of experimental time averaged radial void fraction with a published equation [12]



(a) (b) (c) (d) (e) (f)

Figure 7 Comparison of experimental time averaged radial void fraction distribution with [12] published equation at superficial liquid and gas velocities of 0.047 m/ s and ($0.047 < U_{sg} < 2.836$ m/ s), respectively. The [12] published equation was recalculated using the physical properties of air and silicone oil. r/ R represent normalised pipe radius, r/ R = 0.5 represents centre of the pipe radius, r/ R = 1 represents pipe wall and r/ R = 0 is the radius of the pipe.

This section presents the results of a comparative analysis of the experimental data with a published equation [12]. From an examination of the experimental data plotted on Figure 7 it is concluded that the radial void fraction increases with gas superficial velocity and that the shape of the profile is dependent on the gas superficial velocity.

It is interesting however, to note that contrary to the results obtained by [12], the profiles for bubble and slug flows are parabolic and semi- flat parabolic whilst for churn flow flat parabolic as earlier reported by [1]. It can be observed that the [12] model is not suitable for replicating the observed radial void fraction at low superficial velocity.

The comparison between experiment and [12] published equation is very poor at superficial liquid and gas velocities of 0.047 and 0.047 m/ s respectively as shown in Figure 7a. The mean relative error is very high, about 47.3%. The experiment predicts the profile as parabolic while the [12] published equation predicts it as flat. The wide deviation could be as a result of this discrepancy.

For Figures 7b to 7f, the radial void fraction presents a semi-flat parabolic profile. Very good agreement is found for Figure 7f, with a mean relative error of 5.7 % while for Figure 7b a mean relative error of about 8.5 % is obtained between experiments and [12] published equation. For slug flow (Figures 7b and 7c) it has been found that the [12] equation under predicts and over predicts void fraction before and after the centre of the radius of the pipe respectively. The effects disappearing with an increase in gas superficial velocity for churn flow as shown in Figures 7d to 7f. The under prediction and over prediction of the void fraction could be due to the fact that the equation was originally developed for air-water systems.

CONCLUSION

The phase distribution of an air-silicone oil mixture in a vertical riser has been successfully determined. An analysis of the results shows that:

- The cross-sectional void fraction was strongly affected by the superficial gas velocity, whereby the higher the superficial gas velocity, the higher was the observed average void fraction.
- The steepness parameter decreases with an increase in gas superficial velocity whilst the c-parameter increases with an increase in gas superficial velocity. The steepness parameter can be used to classify flow regimes; high steepness values represent cap/ bubble flow, intermediate values, slug flow and low values represent churn flow.
- The radial void fraction increases with gas superficial velocity and that shape of the profile is dependent on the gas superficial velocity. The profiles for cap/ bubble, slug and churn flows are parabolic, semi-flat parabolic, and flat parabolic profiles, respectively based on the radial void fraction distribution.
- The published equation [12] is most suitable for satisfactorily replicating radial void fraction profile at high gas superficial velocities (churn flow).

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