

Gas hold-up profiles in foaming liquids in bubble columns

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Abstract

Radial variation of gas hold-up was investigated in 0.385 m i.d. bubble column using gamma ray tomography. The gas phase was air and the liquid phase comprised of aqueous solutions of *n*-butanol at different concentrations (0–0.5% v/v). These solutions exhibit foaming behaviour at higher concentrations. Radial profiles were measured at three axial locations ($H_D/D = 0.259, 3$ and 5). The fractional gas hold-up was compared with the air–water system under otherwise identical conditions. Superficial gas velocity was varied from 0.06 to 0.3 m/s. Two perforated sparger plates were used having the same free area (F.A. = 0.42%) and two hole diameters (1 mm (multipoint sparger), and 25 mm (single point sparger)).

The hold-up profiles were found to depend strongly on the sparger design and the concentration of the alcohol. All the results have been correlated on the basis of drift flux model. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Bubble columns; Perforated spargers; Hold-up profiles; Sparger design; Aspect ratio; Tomography

1. Introduction

Bubble columns are widely used for a variety of gas–liquid–solids reactions. The formation of foam layer on the top of the dispersion is common phenomenon for any reaction involved with organic solvents. A foam is a non-equilibrium dispersion of gas bubbles in a relatively small volume of liquid. Froth/foam is exclusively used for the separation of hydrophobic particles in mineral processing in flotation columns which are nothing but bubble columns operated at low superficial gas and liquid velocities. In these equipment, the fractional gas hold-up is very high (50–95%). Such foam columns are also used for foam fractionation and foam reactors for waste water treatment. However, in majority of reactors (including column fermentation), the foam formation is usually undesirable as it reduces the active liquid volume and also loss of liquid. Dilute alcohol solutions simulate reasonably well the liquid phase behaviour of mediums causing foam during the operation (Schugerl et al. [1]; Kelkar et al. [2]; Shah et al. [3]; Bukur and Patel [4]) and extensive literature review on the effect of aqueous alcohol solution on average gas hold-up has been presented by Joshi et al. [5]. Effect of *n*-butanol concentration on average gas hold-up was studied by Dharwadkar [6] and the critical

concentration, the concentration above which there is no change in average gas hold-up was found to be 0.2% v/v.

Gas–liquid dispersions are classified into two regimes: homogeneous and heterogeneous. In the homogeneous regime, the fractional gas hold-up is uniform in the radial direction. On contrast, the hold-up is non-uniform in the heterogeneous regime. For air–water system ($D > 150$ mm, $V_G > 80$ mm/s) the hold-up profile is usually parabolic (with central maxima) in the heterogeneous regime Fig. 1 shows the various shapes of known hold-up profiles in bubble column reactors. In the presence of foaming agents the profiles are saddle type rather than parabolic shape (Xu et al. [7]). They have measured the radial hold-up profiles with conductivity probe which is intrusive and disturbs the flow pattern within the column. The flotation column is characterised by a high frequency of small bubbles ($D < 1$ – 2 mm). Xu et al. [7] used the conductivity probe having needle diameter of 4 mm, which is much higher than the average bubble diameter. This causes problem in signal processing as the probe tip or needle simultaneously gets in touch with bubble as well as liquid surrounded by bubble. They have measured the hold-up profiles in a square (0.91 m \times 0.91 m) floatation column having 13.5 m height. Cominco-type spargers placed at non-dimensional radial locations of (r/R) –0.6, 0 and 0.6, were used for gas sparging. The measurements were carried out with a conductivity probe and at three axial locations viz. H_D/W (ratio of dispersion height to width of the column) = 1.099, 6.6 and 10.99. Dowfroth (15 ppm)

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Nomenclature

A	attenuation
C_0, C_1	drift flux constants as defined by Eqs. (5) and (6), respectively
D	diameter of the column (m)
d_0	hole diameter (mm)
F.A.	free area of sparger (%)
H_D	height of dispersion (m)
I	gamma radiation intensity (counts)
I_0	initial gamma radiation intensity (counts)
I_G	gamma radiation intensity in empty column (counts)
I_L	gamma radiation intensity in column filled with liquid (counts)
I_{TP}	gamma radiation intensity in two phase flow (counts)
r	radial location (mm)
R	radius of the column (m)
t	path length through attenuation medium (m)
T	transmission
V_G	superficial gas velocity (m/s)
W	width of the column (m)

Greek letters

ε_G	local fractional gas hold-up
$\bar{\varepsilon}_G$	average fractional hold-up
$\Delta\varepsilon_G$	difference between the fractional gas hold-up at centre and wall
ε_{GW}	wall hold-up
μ	attenuation (cm^{-1})
ψ	chordal hold-up

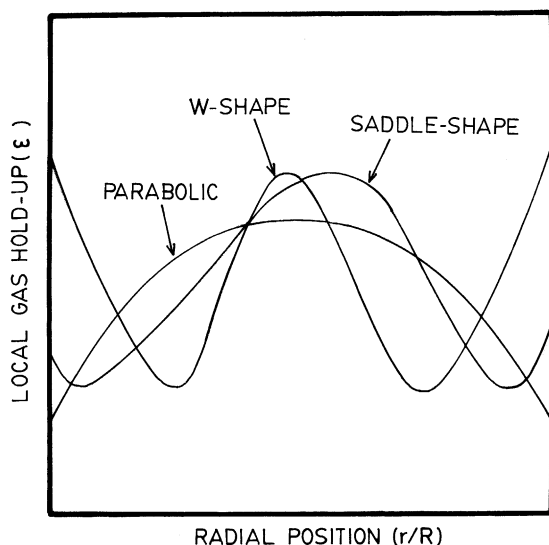


Fig. 1. Various shapes of known radial hold-up profiles in bubble column reactor.

was employed as the foaming agent in water (Figs. 2 and 3). The shape of the hold-up profiles was found to be W-shaped rather than saddle shape for low superficial gas velocities, 6 and 9 mm/s. For the higher superficial gas velocity of, 22 mm/s, the profiles were saddle shaped for the same sparger locations. In the case of single Cominco-type sparger placed at the centre of the column, the profiles were found to be saddle shaped even at superficial gas velocity of 6 mm/s as shown in Fig. 3A. But a peculiar observation was, when the sparger was placed off centre, the profiles were found to be non-axisymmetric (Fig. 3B) even at the height of 10 m. It may be emphasised that these authors have used very low superficial gas velocities (6–22 mm/s) and a square column. Under these conditions the profiles may not be fully developed. For a cylindrical bubble column and air–water system, fully developed heterogeneous regime is observed when the value of V_G exceeds 80 mm/s and H_D/D ratio exceeds 5 (Joshi et al. [5]). In the presence of non-coalescing system, higher values of H_D/D are needed for getting fully developed profiles.

In the present work, hold-up profiles have been measured for three different concentrations of *n*-butanol using tomography technique. The effect of superficial gas velocity (60–300 mm/s), sparger design and the effect of concentration was studied at various axial locations.

2. Experimental set-up

2.1. Equipment

Experiments were carried out in a perspex cylindrical bubble column of 385 mm i.d. and 3.2 m height. A schematic diagram is shown in Fig. 4. Sieve plate spargers were placed between the column and distribution chamber (gas chamber) having a drain at the bottom and gas inlet at the side. Further details of the experimental set-up can be obtained from Parasu Veera and Joshi [9]. Two different sieve plate spargers were employed with equal free area of 0.42% and hole diameter of 1 mm (623 holes) and 25 mm (single hole). In all the experiments, liquid phase was aqueous alcohol solution (*n*-butanol) of three concentrations, one above and one below the critical concentration, 0.02, 0.2 and 0.5% v/v and the gas phase was air. For the purpose of comparison experiments were also carried out with only water (0% concentration). The range of superficial gas velocity was from 0.063 to 0.29 m/s. The air flow rate was measured with a pre-calibrated rotameter. The measurements of hold-up profiles were made at three axial locations, one at just above the sparger ($H_D/D = 0.259$) and others at $H_D/D = 3$ and $H_D/D = 5$. At the measurement locations of $H_D/D = 3$ and $H_D/D = 5$, the height of dispersion was maintained constant ($H_D/D = 7$). The average fractional gas hold-up in all the cases was estimated from the knowledge of bed expansion maintaining height of dispersion constant ($H_D/D = 7$). The reproducibility was within 3% when the butanol concentration was less than 0.2%. However, it was within 5% when

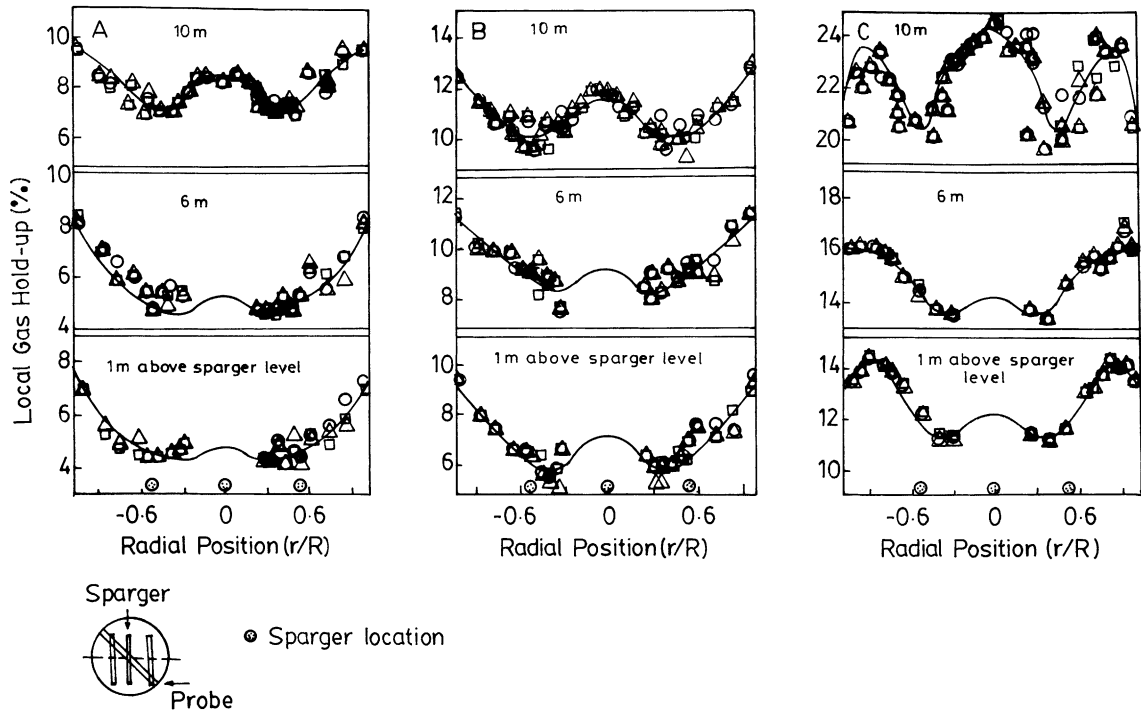


Fig. 2. Radial gas hold-up profiles at three axial locations in flotation column (Xu et al. [7]). (A) $V_G = 6$ mm/s; (B) $V_G = 9$ mm/s; (C) $V_G = 22$ mm/s.

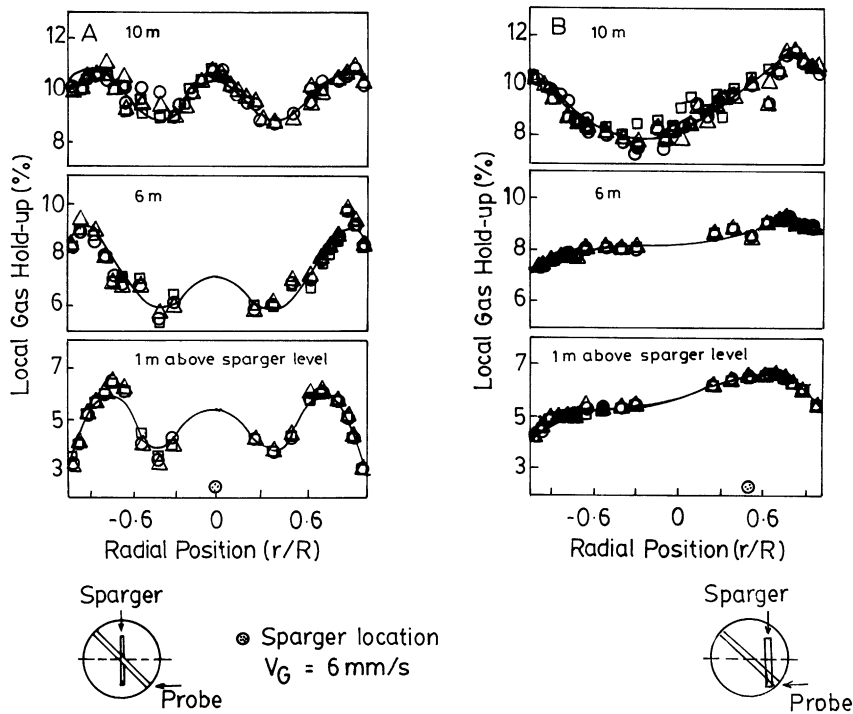


Fig. 3. Radial gas hold-up profiles at three axial locations in flotation column (Xu et al. [7]): $V_G = 6$ mm/s. (A) Sparger at centre; (B) sparger at off centre

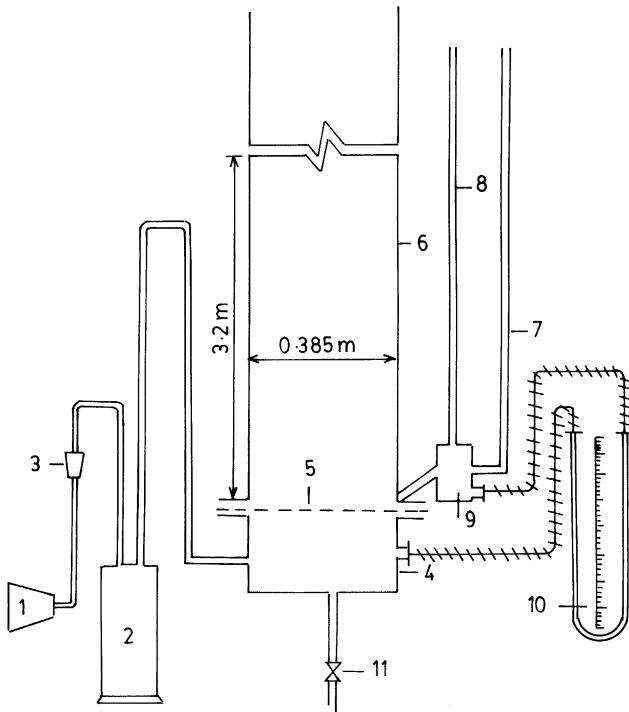


Fig. 4. Schematic of Experimental set-up. (1) Air compressor; (2) surge vessel; (3) rotameter; (4) distribution chamber; (5) sparger; (6) bubble column; (7) clear liquid tube; (8) vent; (9) disengagement chamber; (10) manometer; (11) drain valve.

the butanol concentration was 0.5%. This was because of foamy nature of 0.5% butanol solution.

2.2. Tomography

The Gamma ray tomography system for the measurement of radial voidage profiles and its related electronic components was explained in detail by Parasu Veera [8] and Parasu Veera and Joshi [9]. The source (^{137}Cs) was collimated in a lead brick with a central slit of 35 mm \times 8 mm \times 30 mm which provides a fan beam with a subtending angle of 30° in the horizontal plane. Detectors were collimated in lead bricks having vertical slit of 6 mm \times 18 mm and 30 mm thickness. So the resultant emerging beam from the source detected by the detectors has the thickness of 6 mm, i.e. equal to the thickness of the vertical slit of the detector. The dwell time was optimised to 60 s for this given source strength. These dimensions of the collimators were found to give least sample variance, in the number of photons detected by the detector for a given dwell time. Though the scanning times are very high for this large dwell times, reliable and reproducible profiles were observed.

Experimental methodology adopted for scanning measurements was partly fan beam scanning and partly pencil beam scanning. The detectors were moved in an arc equal to the outer diameter of column with angles equal to the 0, 6, 12, 18, 24, 30, 37.5 and 44.5° from the axis of the source

(Parasu Veera and Joshi [9]). These angles cut the diameter at the r/R positions of 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7, respectively. After this normalised radial position of 0.7, the pencil beam scanning was done at r/R locations of 0.8, 0.9 and 0.95. In Compton scattering, the incoming gamma ray photon deflects through an angle with respect to its original direction. This process leads to the partial or complete transfer of the gamma ray photon energy to electron energy. This results in sudden and abrupt changes in gamma ray photons existence, either disappearing completely or scattering through a large average angle as low energy photon. The distance between source and detector is less in fan beam scanning near the wall region, there is possibility to detect the low energy scattered photons by detectors. For a fan beam scanning a standard counted photons due to scattering was 5% of the total counted photons and this can even go high (up to 50%) as the distance between source and detector decreases resulting into introduction of more error (Hermann [10]). So for this reason, a pencil beam scanning was adopted after the r/R (normalised radius) of 0.7 (Parasu Veera [8]). During the fan beam scanning, source was kept fixed at the centre of column and detectors were moved in an arc of radius 39 cm. And during the pencil beam scanning, both the source and the detector were moved simultaneously in parallel to the diameter.

2.3. Estimation of hold-up profiles

If the measured intensity of a monoenergetic radiation beam is I , after passing through a length of attenuating medium ' t ', then the transmission is given by Beer-Lambert's law, expressed as

$$T = \frac{I}{I_0} = \exp(-\mu t) \quad (1)$$

where I_0 is the incident radiation intensity, μ the attenuation coefficient. The attenuation is given by

$$A = -\ln\left(\frac{I}{I_0}\right) = \mu t \quad (2)$$

Attenuation coefficient can be reconstructed if the spatial variation of the attenuation is known as both of them are linearly related.

The projections (chords) of different lengths across the column diameter were measured. The chordal hold-ups were calculated using the perpendicular formula given by:

$$\psi_i = \varepsilon_{\text{chord}} = \frac{\ln(I_{\text{TP}}/I_{\text{L}})}{\ln(I_{\text{G}}/I_{\text{L}})} \quad (3)$$

where I_{TP} , I_{L} and I_{G} are gamma ray intensities in two phase, column filled with liquid only and empty column, respectively. Chordal hold-ups were measured at 11 different chordal lengths of 385, 382.8, 376.5, 366.15, 351.7, 333.4, 307.4, 276.0, 230.6, 167.5, and 120.2 mm from centre to the wall. The actual counts for all these calculations were obtained by subtracting the back ground counts. Back

ground counts are averaged over a set of six independent measurements. These chordal hold-up were reconstructed to get the local hold-up profiles. The reconstruction of the profiles were done by Abel inversion. The measured chordal hold-ups at different normalised radius were fit with even powers of r/R and various constants were evaluated to estimate the profile. All these details were explained in detail by Parasu Veera and Joshi [9].

3. Results and discussion

3.1. Average gas hold-up

For the multipoint and single point spargers studied, the fractional gas hold-up increases with an increase in the concentration of *n*-butanol. A very dense foamy layer was observed at the top of dispersion for the aqueous solution of alcohol and this foam layer was not observed in air–water system. As the concentration increases the gas–liquid mixture becomes milky white and frothy thereby increasing the average gas hold-up. It is known that the presence of small amount of aliphatic alcohol in water acts as a surface active agent and reduces the dynamic surface tension making liquid mixture non-coalescing (Zahradnik et al. [11], Oolman and Blanch [12]). The average bubble size and bubble rise velocity decreases in non-coalescing liquid mixtures, and as a consequence, the average fractional gas hold-up increases. Figs. 5 and 6 show the effect of concentration of *n*-butanol on the average gas hold-up for multipoint and single point spargers, respectively. It can be seen that the hold-up increases with an increase in the *n*-butanol concentration. There exists a concentration above which there is no change in the average hold-up, called critical concentration. For instance, at a given V_G , 0.02% butanol solution has approximately 20% (average) higher hold-up than water

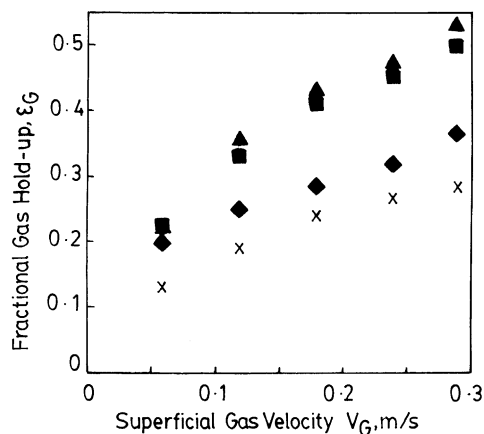


Fig. 5. Effect of *n*-butanol concentration on average gas hold-up for the multipoint sparger: $d_0 = 1$ mm, F.A. = 0.42%, $H_D/D = 7$. (x) Concentration 0% (water); (◆) concentration 0.02%; (■) concentration 0.2%; (▲) concentration 0.5%.

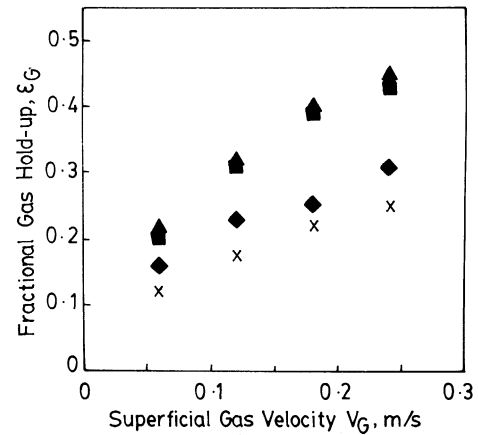


Fig. 6. Effect of *n*-butanol concentration on average gas hold-up for the single point sparger: $d_0 = 25$ mm, F.A. = 0.42%, $H_D/D = 7$. (x) Concentration 0% (water); (◆) concentration 0.02%; (■) concentration 0.2%; (▲) concentration 0.5%.

and 0.2% solution has approximately 40% (average) higher hold-up than 0.02% butanol solution. Further, 0.5% solution gives higher hold-up than 0.2% butanol concentration by 5% (average). Since, the experimental accuracy at 0.5% butanol concentration is within 5%, we have concluded that the 0.2% solution is the critical concentration. This observation is in agreement with Dharwardkar [6]. Zahradnik et al. [11] recently reported the transition concentration for a variety of alcohols (C_1 to C_8) and observed 0.16% v/v as critical concentration for *n*-butanol. Oolman and Blanch [12] also observed the transition concentration at 0.16% v/v which is in line with the observations of Zahradnik et al. [11]. Meissner and Michales [13] found the critical concentration to be 0.23% (v/v). All these observations give a range of critical concentrations of 0.16–0.23% (v/v).

3.2. Drift flux model

The drift flux model of Zuber and Findlay [14] is given by the following equation:

$$\frac{V_G}{\varepsilon_G} = C_0 V_G + C_1 \quad (4)$$

where C_0 and C_1 are the drift flux constants and for the stationary liquid phase ($V_L = 0$), the constants are given by the following equation:

$$C_0 = \frac{\langle \varepsilon_G V_G \rangle}{\langle \varepsilon_G \rangle \langle V_G \rangle} \quad (5)$$

$$C_1 = \frac{\langle \varepsilon_G \varepsilon_L V_S \rangle}{\langle \varepsilon_G \rangle} \quad (6)$$

Zuber and Findlay [14] have given the following physical significance to the values of C_0 and C_1 . C_0 represents the nature of the hold-up profiles and C_1 represents the bubble velocity. All the hold-up data was analysed using Eq. (4).

Table 1
The values of C_0 and C_1 for various n -butanol concentrations

n -Butanol–water system ($D = 0.385$ m, $d_0 = 1$ mm)				n -Butanol–water system ($D = 0.385$ m, $d_0 = 25$ mm)			
Concentration (vol.%)	C_0	C_1	R^2	Concentration (vol.%)	C_0	C_1	R^2
0	2.4	0.3257	0.9675	0	2.5	0.3648	0.9924
0.02	2.1	0.204	0.9974	0.02	2.31	0.252	0.9642
0.2	1.34	1.34	0.998	0.2	1.41	0.214	0.9797
0.5	1.237	1.237	0.9935	0.5	1.4	0.199	0.9927

Table 1 shows the values of C_0 and C_1 for air–water (0% alcohol) and all the concentrations of aqueous solutions of n -butanol. From Table 1 it can be seen that, in all the cases, the constant C_0 gradually decreases as the alcohol concentration increases. The value of C_1 decreases with an increase in the concentration. This indicates that the bubble rise velocity decreases with an increase in butanol concentration.

3.3. Radial hold-up profiles at axial location of $H_D/D = 0.259$

Profiles were measured at the location of H_D/D of 0.259 which was just above the sparger for aqueous solutions of alcohol of concentrations (0, 0.02, 0.2 and 0.5%). The H_D/D ratio was 7 for all the measurements. Figs. 7 and 8

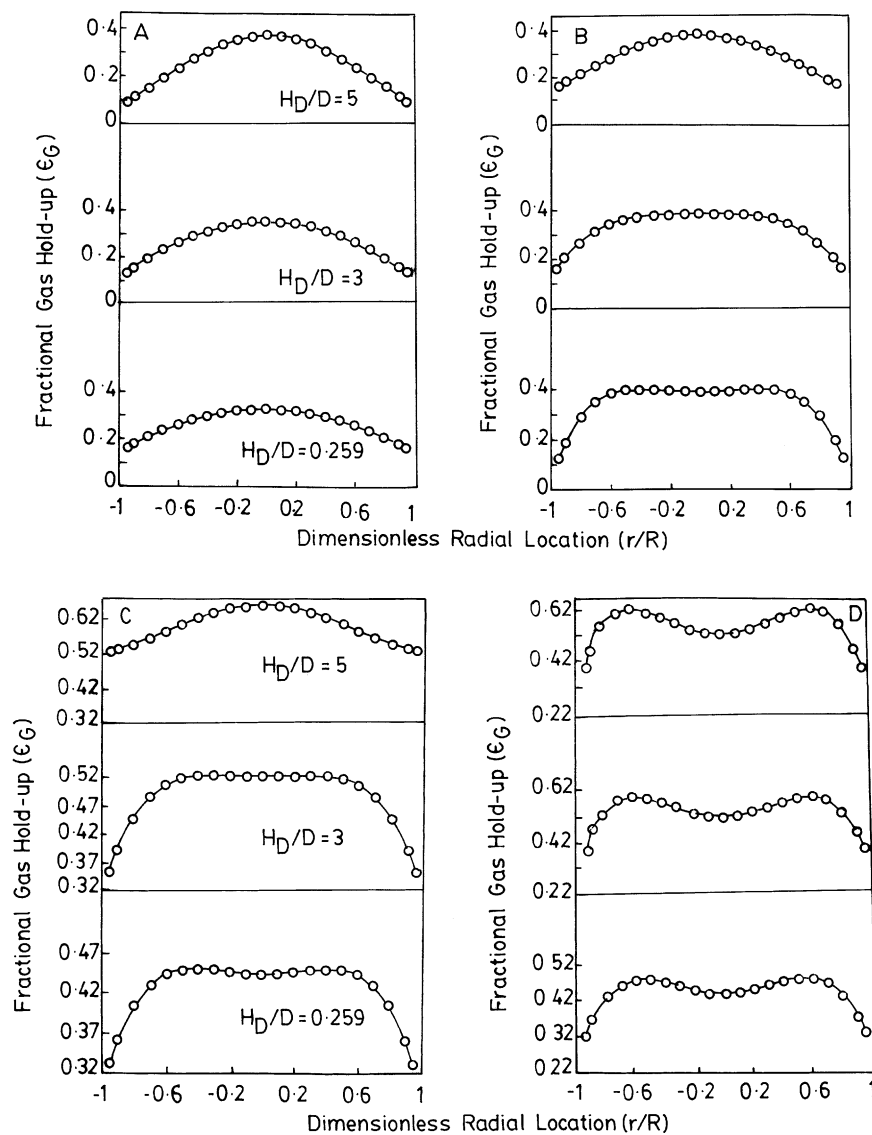


Fig. 7. Radial gas hold-up profiles at three axial locations ($H_D/D = 0.259, 3$ and 5) for the multipoint sparger: $d_0 = 1$ mm, F.A. = 0.42%, $V_G = 0.18$ m/s. (A) 0% (Water); (B) 0.02%; (C) 0.2%; (D) 0.5%.

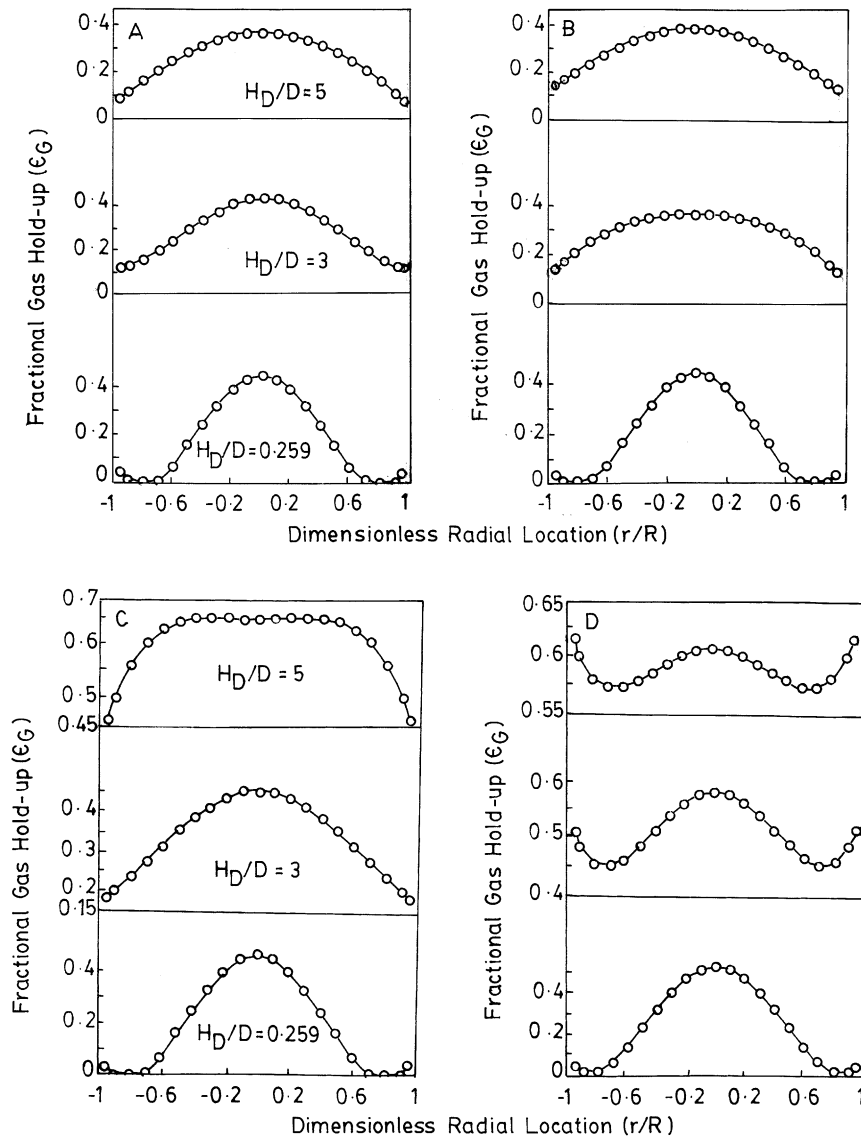


Fig. 8. Radial gas hold-up profiles at three axial locations ($H_D/D = 0.259, 3$ and 5) for the single point sparger $d_0 = 25$ mm, F.A. = 0.42% , $V_G = 0.18$ m/s. (A) 0% (Water); (B) 0.02% ; (C) 0.2% ; (D) 0.5% .

(A–D bottom graphs) show the profiles at this axial location for both the sparger designs. For the multipoint sparger, it can be seen from Fig. 7(A–D) that, there is a distinct change in the profile nature as the concentration increases. As shown in Fig. 7A, the profile is steep even at this location for air–water system. As the concentration increases from 0 to 0.5% v/v the profile progressively changes to a saddle type shape. In Fig. 7C, the dip in the central portion is clear and this increases further in Fig. 7D for the concentration of 0.5% v/v.

For the single point sparger (Fig. 8), practically no variation was observed in the profile nature up to a concentration of 0.2% v/v. The profiles can be seen to be very steep at the centre and the gas hold-up becomes practically zero in the r/R range of $0.7–0.9$. However, near the wall ($0.9 <$

$r/R < 1.0$), ϵ_G was found to have finite value, probably due to the recirculating bubbles. In the case of 0.5% v/v concentration, finite hold-up was observed at the radial location in the range of $0.7–0.9$ (less than 2% of the average hold-up).

The cross-sectional average gas hold-up was calculated using the following expression.

$$\bar{\epsilon}_G = \frac{1}{\pi R^2} \int_0^R 2\pi \epsilon(r) r dr \quad (7)$$

Table 2 shows the comparison of the column average gas hold-up with the cross-sectional average at this axial location. For all the superficial gas velocities studied, a good agreement was observed for the multipoint sparger. These trends are also shown in Figs. 9 and 10 for multipoint and single point sparger, respectively.

Table 2
Comparison of cross-section average to column average fractional gas hold-up

V_G (m/s)	d_0 (mm)	H_D/D	Air–water		Air–alcohol (0.02%)		Air–alcohol (0.2%)		Air–alcohol (0.5%)	
			Column average	Cross-section average	Column average	Cross-section average	Column average	Cross-section average	Column average	Cross-section average
0.29	1	0.259	0.283	0.289	0.364	0.3674	0.498	0.483	0.53	0.551
0.24	1	0.259	0.267	0.261	0.318	0.327	0.452	0.453	0.474	0.473
0.18	1	0.259	0.24	0.238	0.285	0.3	0.411	0.408	0.43	0.429
0.12	1	0.259	0.19	0.21	0.249	0.251	0.33	0.349	0.355	0.354
0.06	1	0.259	0.13	0.155	0.1987	0.182	0.225	0.19	0.24	0.225
0.29	1	3	0.283	0.281	0.364	0.354	0.498	0.535	0.53	0.652
0.24	1	3	0.267	0.246	0.318	0.318	0.452	0.491	0.474	0.57
0.18	1	3	0.24	0.229	0.285	0.2902	0.411	0.469	0.43	0.527
0.12	1	3	0.19	0.2	0.249	0.257	0.33	0.448	0.355	0.509
0.06	1	3	0.13	0.14	0.1987	0.194	0.225	0.27	0.24	0.301
0.29	1	5	0.283	0.275	0.364	0.3629	0.498	0.67	0.53	0.664
0.24	1	5	0.267	0.241	0.318	0.311	0.452	0.609	0.474	0.5917
0.18	1	5	0.24	0.228	0.285	0.28	0.411	0.581	0.43	0.55
0.12	1	5	0.19	0.178	0.249	0.243	0.33	0.55	0.355	0.513
0.06	1	5	0.13	0.123	0.1987	0.2	0.225	0.325	0.24	0.33
0.24	25	0.259	0.251	0.113	0.309	0.118	0.4317	0.124	0.45	0.24
0.18	25	0.259	0.22	0.1042	0.252	0.1035	0.3916	0.093	0.4012	0.143
0.12	25	0.259	0.175	0.0898	0.228	0.0823	0.31	0.087	0.321	0.132
0.06	25	0.259	0.12	0.065	0.159	0.055	0.201	0.0504	0.215	0.069
0.24	25	3	0.251	0.249	0.309	0.312	0.4317	0.3456	0.45	0.634
0.18	25	3	0.22	0.215	0.252	0.26	0.3916	0.286	0.4012	0.488
0.12	25	3	0.175	0.1798	0.228	0.226	0.31	0.233	0.321	0.3725
0.06	25	3	0.12	0.121	0.159	0.162	0.201	0.148	0.215	0.278
0.24	25	5	0.251	0.236	0.309	0.313	0.4317	0.664	0.45	0.652
0.18	25	5	0.22	0.214	0.252	0.2598	0.3916	0.577	0.4012	0.589
0.12	25	5	0.175	0.1785	0.228	0.223	0.31	0.471	0.321	0.478
0.06	25	5	0.12	0.136	0.159	0.163	0.201	0.255	0.215	0.31

3.4. Radial hold-up profiles at axial location of $H_D/D = 3$

For the multipoint sparger, the profiles at this axial location were practically similar in nature to the profiles at the axial location of 0.259 for aqueous *n*-butanol solutions of all

concentrations (Fig. 7(A–D)). For the single point sparger, the profiles were found to become flatter with an increase in distance from the sparger for the concentration up to 0.2% v/v (Fig. 8(A–C)). Whereas, for the higher concentration the profile turns to W-shape (Fig. 8D). The change in the centreline and wall hold-up for single point sparger can

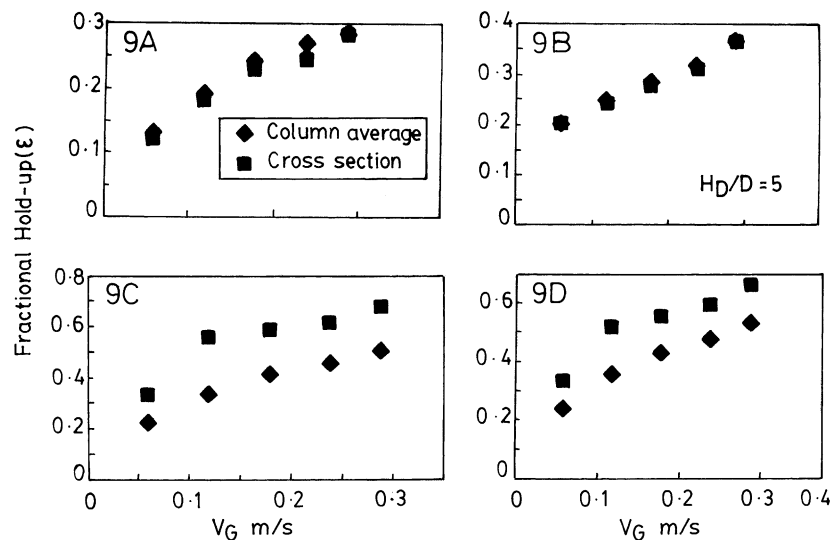


Fig. 9. Comparison of column average and cross-sectional average hold-up as function of superficial gas velocity for multipoint sparger: $d_0 = 1$ mm, F.A. = 0.42% at $H_D/D = 5$ for different concentration of alcohol. (A) 0% (Water); (B) 0.02%; (C) 0.2%; (D) 0.5% butanol.

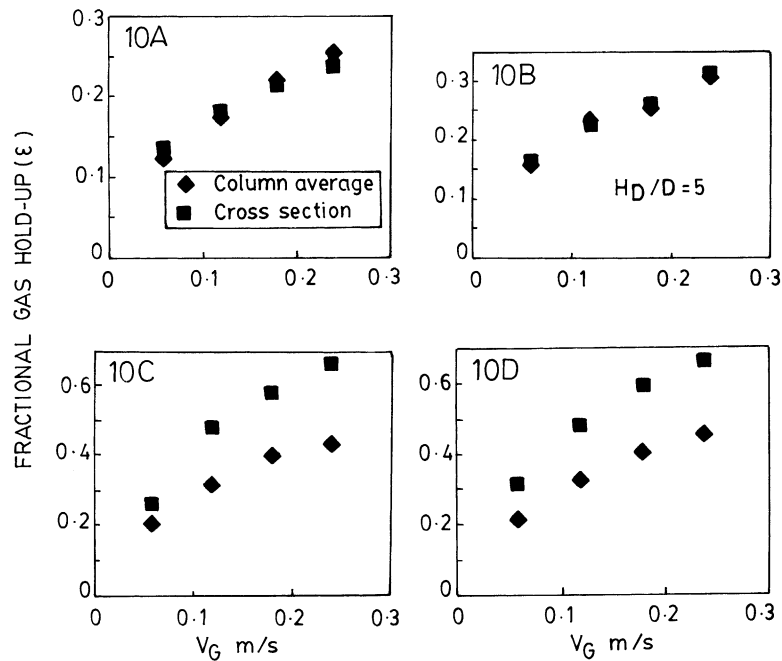


Fig. 10. Comparison of column average and cross-sectional average hold-up as function of superficial gas velocity for single point sparger: $d_0 = 25$ mm, F.A. = 0.42% at $H_D/D = 5$ for different concentration of alcohol. (A) 0% (Water); (B) 0.02%; (C) 0.2%; (D) 0.5% butanol.

be seen to be significant with an increase in the concentration of the *n*-butanol. Similar results were observed for the range of the superficial gas velocities studied.

A good agreement between cross-sectional average hold-up and column average hold-up was observed for water and *n*-butanol concentration of 0.02% (Table 2) for the multipoint sparger. For the higher concentrations, there is no agreement between the cross-sectional and column average hold-up (Fig. 9B). This is because of the existence of high hold-up (due to foaming nature) region at the top of the column and measurements were difficult in this region.

3.5. Radial hold-up profiles at axial location of $H_D/D = 5$

At this axial location for water and aqueous solutions of *n*-butanol up to concentration of 0.02%, the profiles become steep as against very flat profiles for the other two axial locations and for the multipoint sparger (Fig. 7A and B). For the higher concentrations (0.2 and 0.5%) the profiles seem to behave differently. For 0.2% concentration, the hold-up profile at this axial location, is relatively flat with high values of wall hold-ups. For 0.5% concentration, profile transforms to saddle type, with peak at the radial location of 0.5–0.7. This clearly shows the contribution of foam that is formed at these concentrations. In the case of single point sparger, the profile flattens at this axial location for water and *n*-butanol concentration of 0.02%. For the concentration of 0.2% at all the axial locations, the flatness increases further, and for 0.5% concentration the profiles turn to W-shaped. The

variation in profiles for the concentration of 0.5% and for both the spargers is seen clearly from Figs. 7D and 8D. For multipoint sparger there is dip at the central hold-up making the profile saddle type and for single point there is dip at the r/R locations of 0.5–0.8 making the profile W-shaped. This clearly shows the effect of sparger design on the hold-up profile with the concentration. As the concentration increases the sparger (the height up to the sparger design affects ε_G . Beyond such a critical height the value of ε_G is independent of the sparger design) influencing region increases to the greater heights. Xu et al. [7] found the effect of sparger region even up to the height of measurement location, 10 m from the sparger for the range of superficial gas velocities studied.

The comparison between column average and the cross-sectional average hold-ups is given in Table 2 which can be seen to be reasonably good for water and 0.02% *n*-butanol concentration. This may be due to formation of the foam at these higher axial locations. At the bottom location ($H_D/D = 0.259$) the agreement between cross-sectional hold-up and column average hold-up may be due to the prevailing of the high velocities (hole velocities) which are responsible for the foam breaking. As the distance increases, the foam breaking capacity for the gas velocity decreases causing an increase in the cross-sectional average. However, for single point sparger there is no agreement at all the axial locations and as the distance increases the cross-sectional average increases. Hold-up profiles were not correlated with parabolic equation due to the change of profile nature with increase in concentration.

4. Conclusions

1. For both, the multipoint and single point spargers, the average gas hold-up increases with an increase in the concentration of *n*-butanol.
2. The variation in average hold-up was found to be nominal beyond the critical concentration of *n*-butanol and the critical concentration was found to be 0.2% v/v.
3. For the multipoint sparger, the hold-up profiles become parabolic as the distance increases from the sparger. However, for the higher concentrations of *n*-butanol, the hold-up profiles turn to saddle type.
4. For single point sparger, the hold-up profile becomes flat as the distance increases from the spargers. At higher concentration of *n*-butanol, the hold-up profiles turn to W-shaped as the distance increases from the sparger. At H_D/D of 0.259, the hold-up profiles are independent of concentration.
5. At all the three axial locations, the column average is in good agreement with cross-sectional average value up to concentration of 0.02% v/v. However, for higher concentration of *n*-butanol, column average is in good agreement with cross-sectional average value at the axial location of $H_D/D = 0.259$ only. At higher axial locations, the cross-sectional average is higher than the column average. This variation may be due to the increase in the stability of foam with an increase in the distance increases from the sparger (refer Table 2, Figs. 9 and 10).

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