SIZE DISTRIBUTION OF BUBBLES GENERATED BY FINE-PORE SPARGERS

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Introduction

Gas dispersion in bubble columns is brought about by forcing the gas through porous spargers or through orifices of assorted configurations. The size distribution of bubbles that results from the sparging is the single most important parameter that determines the gas holdup and interfacial area for mass transfer, and also influences the liquid phase mixing and level of circulation.

Gas dispersion by various types of spargers has been reviewed by Heijnen and van't Riet (1984). Orifice pipes usually produce bubbles larger than 4 mm in diameter irrespective of the type of liquid used, while porous spargers are used when bubbles smaller than 1 mm are desired. Such bubbles provide large gas-liquid interfacial areas for efficient mass and heat transfer. Although a considerable amount of literature is available on the use of porous spargers for generating gas bubbles, there is confusion regarding the average size and size distribution of bubbles generated by them. Koide *et al.* (1968) found that the average size of bubble size distribution produced by a porous sparger increases with gas flow rate in coalescing media, while detecting very little effect in non-coalescing systems. Akita and Yoshida (1974) observed that the bubble size distributions produced by different porous plates in a bubble column were approximated by a log-normal distribution function, while Deckwer (1977) found them to be nearly normal. Solanki *et al.* (1992) have reported that the bubble size distribution generated by a filter cloth was unimodal in air-water system and bimodal in aqueous electrolyte solutions, especially at the upper ranges of the gas flow rates used by them. In non-Newtonian liquids, Buchholz *et al.* (1978) found the size distribution of porous sparger bubbles in viscous fluids to change from unimodal to bimodal, and/or trimodal, with increasing distance from the sparger surface. More recently, Miyahara and Hayashino (1995) used perforated plates (hole

diameters 0.7 to 1.5 mm) and found the bubbles to have a logarithmic-normal probability distribution in both Newtonian and non-Newtonian liquids, with little changes with increase in distance from the perforated plate.

The differing, and in some cases contradictory, observations made in the above studies may be due to the fact that most of the measurements were made at various locations away from the sparger surface. The liquid phase properties and other variables like turbulence influence coalescence and re-dispersion. In a coalescing medium, bubbles generated by the sparger coalesce as they rise, and the mean size and size distribution of the bubbles in the bulk is not necessarily the same as those at the sparger surface. In order to understand the effects of coalescence due to liquid phase properties and turbulence, the size distribution of bubbles generated at the spargers would need to be known. This paper reports a study in which this requirement is met for bubble produced by spargers with very fine pores. The experiments are carried out such that the effects of coalescence and gas flow induced turbulence on bubble size distribution is minimised. It is therefore expected that the observed size distribution corresponds to that actually generated on the sparger surface.

1. Experimental

To obtain bubbles of different sizes, a range of sintered discs were used. Such discs have been used by a number of investigators in the past (De Vivo and Karger, 1970; Reay and Ratcliff, 1975). To avoid ambiguity and to facilitate future work, standard discs of pyrex glass were used. The discs are designated as Sparger 0 to 4 following the classification numbers provided by the manufacturer (Pyrex). The discs meet or exceed the requirements set down by BS 1752 in terms of the spread of the pore sizes. The details are given in **Table 1**. The diameter and thickness of the discs were 90 and 5 mm respectively. Each sintered glass disc was fixed onto a perspex base to form a sparger unit. The sparger units were fixed interchangeably to the bottom of a circular perspex tank of diameter 0.195 m (**Fig. 1**), and the liquid height in the tank was also maintained at 0.195 m.

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Table 1 Average pore sizes of the sintered glass discs used for generating bubbles

Sparger No.	Pore size (μm)	
	British standard 1752 requirement	Manufacturer's standard
0	150 – 250	150 – 250
1	90 – 150	100 – 120
2	40 – 90	40 – 60
3	15 – 40	20 – 30
4	5 – 15	5 – 15

Fig. 1 Schematic of the bubble photography set-up

As the aim of the study was to determine the size distribution of the bubbles generated at the sparger without coalescence effects, the experiments were conducted under non-coalescing conditions. The liquid medium (water) was made non-coalescing by adding 50 ppm v/v of methyl isobutyl carbinol, which is a common industrial frother. The surface tension of the liquid phase was determined to be 71.3 mN/m. The air superficial velocity U_g , based on the cross sectional area of the tank, was varied between 0.25 and 1.25 mm/s.

Bubble size was measured by photography. A stream of liquid containing a dispersion of bubbles was drawn through a specially-made perspex photographic cell placed above the tank (Fig. 1). This was made possible due to the non-coalescing nature of the medium. The cell had two flat transparent windows between which the dispersion was drawn while being

photographed. The funnel-shaped section below the windows ensured a smooth entry of the gas-liquid dispersion into the gap between the windows. In general, at least 300 bubbles were sized for each specific condition. To check for non-coalescence, bubble size distribution was measured at various heights in the tank, and no statistically significant variation in either the average bubble size or the bubble size distribution was observed.

2. Results and Discussion

2.1 Frequency size distribution of bubbles

In absence of the coalescence inhibiting agent, the bubbles were seen to coalesce as they ascended through the liquid column in the vessel. Reliable measurements of bubble size distribution, as generated at the sparger surface, could not therefore be obtained in coalescing conditions. However, the average bubble sizes generated at the sparger surface were estimated by visual observations to be about 200 – 300 μm , 300 – 400 μm , 600 – 700 μm , 1.2 – 1.5 mm and 2 – 3 mm for the Spargers 4, 3, 2, 1, 0, respectively. Closer to the liquid surface, the bubble sizes were estimated to be considerably larger than those at the sparger surface.

In non-coalescing conditions, the bubbles formed on the sparger surface were observed to be smaller than in the coalescing environment, probably representing the actual sizes being formed on the surface. As mentioned earlier, in the non-coalescing media, the size of bubbles generated at the spargers was preserved throughout the bulk of the vessel. The minimum, maximum and arithmetic average bubble sizes obtained for the spargers, in non-coalescing conditions, are shown in **Table 2** for a superficial gas velocity of 1.0 mm/s. The size distribution of bubbles generated were nearly unimodal for all the spargers, deviating from a “normal distribution”, with a skewness towards the larger bubble sizes. As an example, the size distribution generated by Spargers 3 at a superficial gas velocity of 1.0 mm/s studied are shown as frequency histograms in **Fig. 2**. Various analytical distribution functions were tested for their adequacy in representing the observed bubble size distributions. It was found that the logarithmic-normal distribution function provides the most reasonable approximation for all the spargers. This is verified by the near straight lines obtained on plotting the cumulative bubble size distribution data on log-normal probability coordinates (**Fig. 3**). The observation agrees with the findings of various investigators, including Miyahara and Hayashino (1995), who used much larger orifices for bubble generation.

It may be noticed from Table 2 and Fig. 3 that the differences in the average bubble size and bubble

Table 2 Minimum, maximum and arithmetic average bubble size values obtained for the spargers used, $U_g = 1.0$ mm/s

Sparger	d_{min} , [mm]	d_{max} , [mm]	d_{avg} , [mm]	Standard Deviation, [mm]
0	0.87	3.59	1.66	0.48
1	0.34	1.49	0.70	0.23
2	0.27	1.23	0.48	0.14
3	0.14	1.00	0.39	0.11
4	0.20	1.06	0.44	0.15

Fig. 2 Frequency histogram for bubbles generated by the Sparger 1, at $U_g = 1.0$ mm/s

size distribution for Spargers 3 and 4 are negligible, which may indicate that there is a limiting pore size, beyond which neighbouring pores begin to have an influence on each other, forcing coalescence of bubbles from adjacent pores. The limiting average pore size seems to be around 50 μm in diameter. In all cases, within the range used, the superficial gas velocity is found to have little effect on the bubble size distribution. As an illustration, cumulative size distribution data for different U_g obtained for Sparger 0 are shown in **Fig. 4**. Comparable observations were made for the average, minimum and maximum bubble sizes also.

2.2 Sauter mean bubble diameter

Sauter mean bubble diameter (d_{32}) is a popular representation of the mean bubble size for a distribution in the chemical engineering context. Using d_{32} , the gas-liquid interfacial area may be estimated directly from gas holdup measurements. The experimental d_{32} values obtained for all the spargers are shown in **Table 3**. It may be noticed that for the range of superficial gas velocities used, there is little variations in the d_{32} values.

The representation of all the bubble size distributions obtained in the present work by log-normal distribution is fortuitous, as it provides the opportunity of obtaining an analytical expression for

Fig. 3 Cumulative distribution of bubbles generated by the spargers plotted on log-normal probability coordinates, $U_g = 1.0$ mm/s

Fig. 4 Effect of U_g on size distribution of bubbles generated by Sparger 0

d_{32} . The analytical probability function for log-normal distribution is given by the expression (Orr, 1966)

$$f(d_b) = \frac{1}{\log \sigma_g \sqrt{2\pi}} \exp\left(\frac{-(\log d_b - \log d_g)^2}{2 \log^2 \sigma_g}\right) \quad (1)$$

where d_b is the bubble size, $\log d_g$ is the log-geometric mean given by the expression

$$\log d_g = \frac{\sum_{i=1}^{i=j} (n_i \log d_{bi})}{\sum_{i=1}^{i=j} n_i} \quad (2)$$

where n_i is the number of bubbles in a group "i" whose average bubble diameter is d_{bi} and "j" is the number of class intervals. $\log \sigma_g$, the log-geometric mean standard deviation, is given by

Table 3 Experimental and estimated sauter mean bubble diameter d_{32} values [μm]

U_g , mm/s	Sparger 0		Sparger 1		Sparger 2		Sparger 3		Sparger 4	
	Expt.	Esti.	Expt.	Esti.	Expt.	Esti.	Expt.	Esti.	Expt.	Esti.
0.25	1711	1763	654	691	528	556	343	335	376	386
0.5	1808	1851	697	712	530	548	421	409	422	445
0.75	1947	1940	707	729	507	519	447	430	496	494
1.0	1911	1913	792	863	540	574	465	452	534	543
1.25	2064	1987	816	820	546	565	523	550	572	587

$$\log \sigma_g = \sqrt{\frac{\sum_{i=1}^j n_i (\log d_{bi} - \log d_g)^2}{\sum_{i=1}^j n_i}} \quad (3)$$

Sauter mean bubble diameter values for the log-normal distribution function can be estimated from the ratio of the third and second moments of the distribution, which follows from the definition of d_{32} , given as

$$d_{32} = \frac{\sum_{i=1}^{i=n} n_i d_{bi}^3}{\sum_{i=1}^{i=n} n_i d_{bi}^2} \quad (4)$$

The final expression for Sauter mean bubble diameter from log-normal distribution may be derived as (Orr, 1966)

$$\log d_{32} = \log d_g + 5.7565 \log^2 \sigma_g \quad (5)$$

The d_g and σ_g values determined from the experimental data were used to estimate the Sauter mean bubble diameter values applying Eq. (5), and are shown in Table 3. The good agreement between the experimental and estimated d_{32} values confirms the suitability of log-normal distribution for fitting the size distribution of bubbles generated by porous spargers used in the present work.

2.3 The ratio between d_{32} and d_{max}

Another property of a bubble size distribution which is of interest is the ratio between Sauter mean (d_{32}) and maximum bubble (d_{max}) diameter values. The d_{32}/d_{max} values are commonly used in theoretical determination of bubble sizes in gas-liquid processing vessels. An analytical expression for the d_{32}/d_{max} value for the distributions represented by log-normal distribution function may be obtained by defining d_{99} , the diameter that is larger than 99% of all the diameters in the cumulative number distribution of bubbles, as the maximum bubble diameter, d_{max} (Hesketh, *et al.*, 1987). In the following discussions,

therefore, the terms d_{99} and d_{max} are used synonymously. The cumulative number fraction of bubbles less than size d_b for a population represented by a log-normal distribution is given by the relationship (Randolph and Larson, 1971)

$$F(z) = 0.5 (1 + \text{erf}(z)) \quad (6)$$

where $z = \ln(d_b/d_g)/\sqrt{2} \ln \sigma_g$

Substituting $F(z) = 0.99$ for d_{99} in Eq. (6), we find

$$F(z) = 0.99 = 0.5 (1 + \text{erf}(z)) \quad (7)$$

which can be rearranged as

$$\text{erf}(z) = 0.98 \quad (8)$$

From cumulative normal distribution tables, the value of $\ln(d_{99}/d_g)/\ln \sigma_g$ which leads to an area of 0.98 under the cumulative normal curve is found to be (Herdan, 1960)

$$\frac{\ln(d_{99}/d_g)}{\ln \sigma_g} = 2.33 \quad (9)$$

from which we get

$$d_{99} = d_g \exp(2.33 \ln \sigma_g) \quad (10)$$

Now dividing the expression for d_{32} given by Eq. (5) by Eq. (10), we get

$$d_{32}/d_{99} \cong d_{32}/d_{max} = \exp(2.5 \ln^2 \sigma_g - 2.33 \ln \sigma_g) \quad (11)$$

It can be seen from Eq. (11) that d_{32}/d_{max} value for a bubble size distribution represented by log-normal distribution may be estimated if the geometric mean standard deviation σ_g value is known. This exercise was carried out for the experimental bubble size distribution data obtained in this study. The d_{32}/d_{max} ratios for all the spargers was found to be nearly the same. The average d_{32}/d_{max} value obtained by combining all the experimental results was found to have a value of 0.63.

It is interesting to note that the above determined d_{32}/d_{max} value of 0.63 is comparable to values obtained by other investigators, under various operating conditions. Hesketh *et al.* (1987) determined the d_{32}/d_{max} value to be 0.62 for the equilibrium size distribution of bubbles formed during gas-liquid flows in a pipeline. Similarly, Evans (1990) found the ratio to be 0.61 for bubbles produced as the result of gas entrainment by a confined liquid jet, in a non-coalescing medium. Furthermore, Calabrese *et al.* (1986) and Zhang *et al.* (1985) report d_{32}/d_{max} values of 0.6 and 0.62, respectively, for droplets formed in agitated liquid-liquid dispersions. In all the instances cited, the measured size distributions are reached under various degrees of turbulence, and both in the presence and absence of coalescence effects. In the present situation, there is no coalescence or breakup after bubble generation at the sparger surface. Also, the gas flow was well under bubbly flow conditions and was not found to induce any significant liquid circulation in the vessel. The comparable d_{32}/d_{max} values observed for the very diverse conditions in the above studies is remarkable, and requires further considerations.

Conclusion

It has been observed that the size distribution of bubbles generated by introducing gas through fine pores (10 μm to 200 μm in diameter) is unimodal in nature and is defined adequately by a log-normal distribution function. It is believed that the reported bubble sizes accurately represent the actual distribution as produced on the sparger surface, and the information may be useful in testing proposed models for bubble formation at pores. The work should be extended to cover larger diameter pores and higher gas rates. It would appear there is little change in bubble size below a sparger pore diameter of around 50 μm . This would indicate that there is a limiting pore size, beyond which coalescence between bubbles being formed in adjoining pores cannot be avoided, even in non-coalescing media. If true, there is a practical limit in attempting to produce fine bubble by porous spargers, a point which requires theoretical scrutiny. Another remarkable feature which requires further deliberations is that the ratio between the Sauter mean and maximum bubble diameters. It maintains a constant value for all the conditions studied, and compares well with values obtained previously in diverse systems, including turbulent fluid flow.

The observations made in this study would be applicable to many chemical and bio-chemical operations, where the presence of various salts or organic agents (sometimes as impurities), render the system non-coalescing.

Nomenclature

d_{32}	= Sauter mean bubble diameter	[μm]
d_{99}	= bubble diameter larger than 99% of the diameters in the cumulative distribution	[μm]
d_{avg}	= arithmetic mean bubble diameter	[μm]
d_b	= bubble diameter	[μm]
d_{bi}	= average diameter of bubbles in group "i"	[μm]
d_g	= log-geometric mean	[μm]
d_{max}	= maximum bubble diameter	[μm]
Δp	= pressure drop across the sparger	[mm of mercury]
U_g	= gas superficial velocity	[m/s or mm/s]
σ_g	= log-geometric mean standard deviation	

Literature Cited

- Akita, K. and F. Yoshida; "Bubble Size, Interfacial Area, and Liquid-Phase Mass Transfer Coefficient in Bubble Columns," *Ind. Eng. Chem., Process Des. Develop.*, **13**, 84-91 (1974)
- Buchholz, H., R. Buchholz, J. Lucke and K. Schugerl; "Bubble Swarm Behaviour and Gas Absorption in Non-Newtonian Fluids in Sparged Columns," *Chem. Eng. Sci.*, **33**, 1061-1070 (1978)
- Calabrese, R. V., T. P. K. Chang and P. T. Dang; "Drop Breakup in Turbulent Stirred-Tank Contactors. Part I: Effect of Dispersed-Phase Viscosity," *AIChEJ*, **32**, 657-666 (1986)
- Deckwer, W.; "Absorption and Reaction of Isobutane in Sulfuric Acid-III, Considerations on the Scale up of Bubble Columns," *Chem. Eng. Sci.*, **32**, 51-57 (1977)
- De Vivo, D. G. and B. L. Karger; "Studies in the Flotation of Colloidal Particulates: Effects of Aggregation in the Flotation Process," *Sep. Sci.*, **5**, 145-167 (1970)
- Evans, G. M.; A Study of a Plunging Jet Bubble Column, Ph. D thesis, Univ. of Newcastle, Australia (1990)
- Heijnen, J. J. and van't Riet, K.; "Mass Transfer, Mixing and Heat Transfer Phenomena in Low Viscosity Bubble Column Reactors," *Chem. Eng. J.*, **28**, B21-B42 (1984)
- Herdan, G.; *Small particle statistics*, Butterworths & Co. (Publishers) Limited, London, England (1960)
- Hesketh, R. P., T.W. Fraser Russell, and A.W. Etchells; "Bubble Size in Horizontal Pipelines," *AIChEJ*, **33**, 663-667 (1987)
- Koide, K., S. Kato, Y. Tanaka and H. Kubota; "Bubbles Generated from Porous Plate," *J. Chem. Eng. Japan*, **1**, 51-56 (1968)
- Miyahara, T. and T. Hayashino; "Size of Bubbles Generated from Perforated Plates in Non-Newtonian Liquids," *J. Chem. Eng. Japan*, **1**, 51-56 (1968)
- Orr, C.; *Particulate technology*, The Macmillan company, New York, USA (1966)
- Randolph, A. D. and M. A. Larson; *Theory of particulate processes: analysis and techniques of continuous crystallization*, Academic Press, New York, USA (1971)
- Solanki, M. K. S., A. K. Mukherjee and T. R. Das; "Bubble Formation at Closely Spaced Orifices in Aqueous Solutions," *Chem. Eng. J.*, **49**, 65-71 (1992)
- Zhang, S. H., S. C. Yu, Y. C. Zhou and Y. F. Su; "A Model for Liquid-Liquid Extraction Column Performance-The Influence of Drop Size Distribution on Extraction Efficiency," *Can. J. Chem. Eng.*, **63**, 212-226 (1985)