

Acoustic Measurement in a Rectangular Bubble Column to Determine Bubble Size and Interfacial Area for Aqueous Solutions of Ethylene Glycol

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Abstract: Bubble sizes in bubble column affect the bubble induced mixing of phases, interfacial area and transfer processes. Acoustic technique is used to measure bubble size distribution in a rectangular bubble column of cross section 0.2m x 0.02m for air sparged into water and aqueous solutions of ethylene glycol. Five condenser mikes at intermediate distance of 0.05 m measured above the distributor plate were used to find out the variation of bubble size as the bubbles move up. Sauter-mean bubble diameter and specific interfacial area were estimated from bubble size distribution at several superficial air velocity, static bed height, distance above the distributor plate and ethylene glycol concentration. The BSD exhibited mono-modal distribution and indicated non-uniform homogeneous bubbling regime. Sauter-mean bubble diameter is independent of superficial gas velocity, static bed height and concentration of EG, although, the values were higher than that for air-water system. Sauter-mean bubble diameter decreases as the bubbles move up indicating bubble breakup to take place once the bubbles leave the sparger. The value of interfacial area increases as the static bed height decreases and distance above the distributor plate increases. For air-ethylene glycol solution the values of specific interfacial area are about 200% higher than that observed in case of air-water system. The acoustic technique may be used to measure local values of bubble sizes and specific interfacial area.

Index Terms: Acoustic measurement, bubble columns, bubble size, gas-liquid contactors, hydrodynamics, multi-phase systems.

I. INTRODUCTION

Bubble column is used as gas-liquid contactors in several chemical [1-2] and biochemical applications [3]. Gas is dispersed in forms of bubbles into liquid through a distributor. Gentle and uniform mixing in bubble columns makes it suitable as a bioreactor for shear sensitive cell processing [3]. The performance of bubble columns largely depends upon the size and number of bubbles in the column. The bubble-induced turbulence is a complex process due to bubble coalescence and bubble breakup after they are formed at the sparger. Hydrodynamic parameters such as gas holdup, bubble size and shape, bubble velocity, bubble coalescence and bubble breakup phenomena are used to specify the bubble behavior. At high gas velocity, the flow regime

change. The bubbles of different sizes are present in the column due to bubble coalescence and bubble-breakup phenomena, which may be seen in the nature of bubble size distribution (BSD). The average bubble diameter may be estimated from BSD, from which Sauter-mean bubble diameter, d_{32} , may be estimated. Specific interfacial area, a_i , required for calculation of mass transfer rate may be calculated from d_{32} and gas holdup. Photographic technique is a direct method of measurement of bubble size but is useful in transparent columns only. In opaque columns acoustic techniques has the potential to measure bubble size. This technique is based on resonance frequency of the pulsating bubbles [4]. Therefore, it is not influenced by turbulence. Vazquez et al. [5] compared photographic and acoustic techniques and found that acoustic method is as accurate as optical method. Fast processing of acoustic signal in comparison to the image processing makes it more suitable for process control purpose. Boyd and Varley [6] reviewed applications of acoustic techniques in chemical engineering processes. Strasberg [7] used the following formula developed by Minnaert to estimate bubble size from acoustic signal generated by volume pulsation of spherical bubbles. The natural frequency of sound generated by simple volume pulsation, f_0 , is inversely proportional to bubble radius, R [7].

$$f_0 = (3\gamma P_0 / \rho)^{1/2} / 2\pi R \quad (1)$$

where P_0 is the static pressure, γ is ratio of specific heats of gas in bubble and ρ is density of the liquid. Estimation of BSD from acoustic signals by different techniques was studied by Al-Masery et al. [8]. Al-Masery et al. [9] found carried out a detailed study on bubble behavior using acoustic technique. Homogeneous BSD in absence of antifoam agents and heterogeneous BSD in antifoam solutions were observed. Improvement of the acoustic technique used to get estimates of the average bubble size and its distribution was felt [9]. The present work is aimed at use of acoustic technique for measurement of bubble size locally i.e. in the sparger region, in the middle portion of the bubble column and near the top where foam layer may be present. From BSD, Sauter-mean bubble diameter, d_{32} , and specific interfacial area, a_i , were estimated.

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II. EXPERIMENTAL SETUP

Experimental setup made of Perspex sheet consisted of a rectangular column (0.37m x 0.2m x 0.02m) (Fig 1). Two glass walls were used to avoid erosion of the wall and for visual observation. Air was sparged through a distributor, which consisted of a perforated plate having 200 holes of 0.0015 m diameter. Over it 0.005 m glass beads were filled up to a height of 0.05 m. A 200 mesh of SS was placed over the beads acting as calming section. The bubble column consisted of a conical bottom below the perforated plate. The gas was supplied using a compressor followed by a rotameter. On one side of the bubble column five inexpensive condenser mikes were fixed at 0.0 m, 0.05m, 0.1m, 0.15m and 0.2 m distance measured above SS mesh. Acoustic signals were measured by one of these mikes at a time.

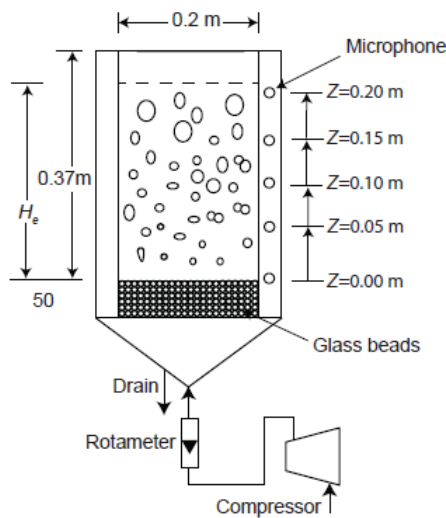


Fig. 1: Schematic diagram of experimental setup

A. Experimental Procedure

Air was bubbled through liquid, filled up to a height so that all mikes are submerged. The properties of these solutions estimated from data available in literature [10,11] are presented in Table 1. Flow rate of air was measured using a rotameter. Acoustic signals were measured at 44100 Hz using ‘voice recorder’ of Microsoft Windows. Such recordings were made at several superficial gas velocities, U_g , and static bed height, $H_s = 0.10, 0.15$ and 0.20 m and height above the sparger, $Z = 0.00, 0.05$ and 0.15 m for air-water system and air-aq. soln. of Ethylene glycol. The value of U_g was varied in the range of $0.00417 - 0.167$ m s⁻¹ for air-water system and in the range of $0.0556 - 0.222$ m s⁻¹ air-aq. soln. of Ethylene glycol. Any data, for which a mike was not submerged throughout the duration of acoustic signal measurement, was discarded.

B. Acoustic Signal Analysis

Acoustic signal was analysed in the following manner.

(i) The acoustic signal measured at 44100 Hz as ‘wma’ files were converted to ‘wav’ file and stored as ‘wav’ file. The signal was cropped as non-overlapping sequential sets of 2048 data points. It corresponds to 0.0464 s, during which not more than 4 to 5 bubbles were present.

(ii) Matlab’s ‘fft’ function was used for each such acoustic segment. The peaks in signal were determined using Matlab’s ‘findpeak’ function with peaks separated by 100 data points.

(iii) The signal has low (<200 Hz) and high frequency components which were not considered due to unrealistic bubble size not confirmed visually. High frequencies may be due to turbulence etc. Bubbles of 0.5 mm were discarded. Low frequency signal may be due to hydrodynamics process such as fluctuation of the liquid height and hence discarded.

(iv) The bubble diameter, d_b , corresponding to each frequency was determined. Since, while obtaining value of d_b , low frequencies were discarded, bubble size smaller than 0.0005 m were not considered. Bubble-size distribution were obtained using MATLAB’s ‘histogram’ command with 25 equally spaced bins. The bubble size distribution (BSD) is plotted between numbers of bubble, N_b , as a function of bubble diameter, d_b , thus obtained. This procedure gave the values of minimum and maximum values of d_b .

(v) Sauter-mean bubble diameter, d_{32} , was estimated using individual values of bubble diameter, d_b in the following formula.

$$d_{32} = \frac{\sum_i d_i^3}{\sum_i d_i^2} \quad (2)$$

Table 1: Properties of liquids (at average temperatures). Values of viscosity were estimated from data of Jerome et al. [11]. Surface tension were estimated from data of Nakanishi et al. [10]

Liquid	ρ (kg m ⁻³)	μ (kg m ⁻¹ s ⁻¹)	σ (N m ⁻¹)
Water	996	0.000894	72
Ethylene Glycol (0.5% w/w)	997.5	0.000906	71.9
Ethylene Glycol (5.0% w/w)	1002	0.001029	71.2

III. RESULTS AND DISCUSSION

A. Bubble-Size Distribution

BSD for 0.5% (w/w) EG solution superficial air velocity, $U_g = 0.083$ m s⁻¹, and static bed height, $H_s = 0.15$ m for distance of mike above distributor plate, $Z = 0.00$ m is presented in Fig 2. The maximum bubble diameter is 0.0116 m. Most of the bubbles are of the size about 0.002 m. Since few large bubbles are also present. The flow regime may be called as non-uniform homogeneous flow regime. The BSD was a mono model distribution in all cases studied.

B. Sauter-Mean Bubble Diameter

The entire experimental data of d_{32} for EG solution are presented in Table 2 and 3. The data for water is presented in Table 4. The effect of U_g , H_s , and Z on d_{32} for air-distilled water and air-aq. soln. of EG was studied and is presented in the following. Variation of d_{32} as a function of U_g for $H_s = 0.20$ m and conc. (w/w) of EG= 0.5% and 5.0 %, and $Z = 0.00$ m, 0.05 m and 0.015 m is presented in Fig. 3. For comparison purpose the values of air-distilled water, hereafter referred as water, are also shown. The values of d_{32} seem



to be independent of U_g indicating no change in the flow regime. Though the values of d_{32} are higher than that for air-water system, the concentration of EG shows no significant effect on d_{32} . As the values of Z increases, the values of d_{32} decreases i.e. the bubble size decreases after the bubbles leave the sparger.

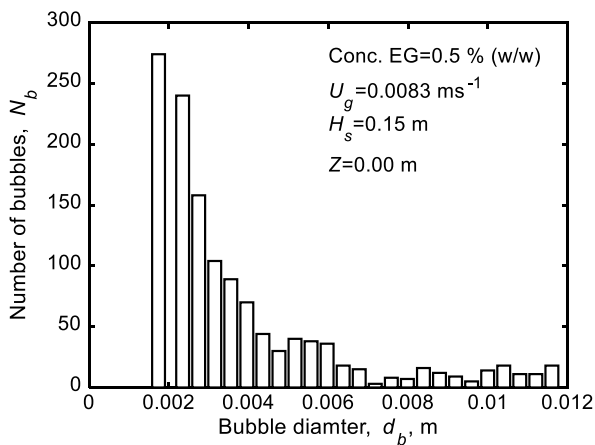


Fig. 2: Bubble size distribution for 0.5%(w/w) ethylene glycol solution at $U_g=0.0083 \text{ ms}^{-1}$, $H_s=0.15 \text{ m}$ and $Z=0.00 \text{ m}$

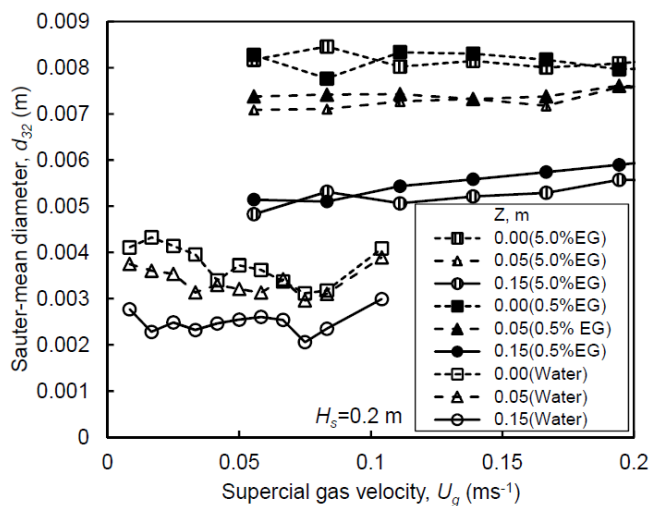


Fig. 3: Sauter-mean diameter as a function of U_g and Z for air-water and air-ethylene glycol solutions

The observation is in accordance to the finding of BSD, which also showed only one peak for air-distilled water system.

Pohorecki et al. [12] obtained following equation for d_{32} .

$$d_{32} = 0.289\rho^{-0.552} \mu^{-0.048} \sigma^{0.442} U_g^{-0.124} \quad (3)$$

Eqn. 3 shows that d_{32} to decrease with increasing U_g . It is in accordance with earlier findings of Pohorecki et al. [13]. The experimental values of d_{32} are independent of U_g . Since EG solution has density and viscosity higher than that of water and has surface tension lower than that of water, the values of d_{32} estimated using Eqn. 3 for EG solution must be lower than that of water. However, the present experimental values of d_{32} are higher than that of water. Examining the values of d_{32} at the sparger ($Z=0.00 \text{ m}$) it can be observed that bubbles formed at the sparger in the case of EG solutions are larger than that formed in case of water.

Table 2: Values of $d_{32} \times 10^3, \text{ m}$ at $H_s=0.2 \text{ m}$ as a function of U_g and Z

$U_g \times 10^2 \text{ ms}^{-1}$	$Z, \text{ m (5\% EG)}$			$Z, \text{ m (0.5\% EG)}$		
	0.00	0.05	0.15	0.00	0.05	0.15
5.56	8.2	7.1	4.8	8.3	7.4	5.1
8.33	8.5	7.1	5.3	7.8	7.4	5.1
11.11	8.0	7.3	5.1	8.3	7.4	5.4
13.89	8.1	7.3	5.2	8.3	7.3	5.6
16.67	8.0	7.2	5.3	8.2	7.4	5.7
19.44	8.1	7.6	5.6	8.0	7.6	5.9
22.22	8.2	7.5	5.6	8.0	7.5	6.1

Table 3: Values of $d_{32} \times 10^3, \text{ m}$ for 5% EG at $H_s=0.2 \text{ m}$ as a function of U_g and Z

$U_g \times 10^2 \text{ ms}^{-1}$	$Z=0.00 \text{ m}$		$Z=0.05 \text{ m}$		$Z=0.15 \text{ m}$	
	$H_s, \text{ m}$	$H_s, \text{ m}$	$H_s, \text{ m}$	$H_s, \text{ m}$	$H_s, \text{ m}$	$H_s, \text{ m}$
5.6	0.1	0.15	0.1	0.15	-	0.15
8.3	5.9	6.9	4.6	6.0	-	3.0
11.1	5.7	7.0	4.6	6.0	-	3.7
13.9	5.7	7.0	4.7	6.2	-	3.9
16.7	5.6	7.1	4.7	6.2	1.4	4.2
19.4	5.7	7.0	4.8	6.3	1.9	4.4
22.2	5.7	7.1	4.8	6.4	2.4	4.5
	5.8	7.0	5.0	6.5	2.8	4.6

Table 4: Values of $d_{32} \times 10^3, \text{ m}$ for water at as a function of U_g, H_s and Z

$U_g \times 10^2 \text{ ms}^{-1}$	$Z, \text{ m}$		
	0.00	0.05	0.15
0.83	4.1	3.8	2.8
1.67	4.3	3.6	2.3
2.50	4.1	3.5	2.5
3.33	4.0	3.1	2.3
4.17	3.4	3.3	2.5
5.00	3.7	3.2	2.5
5.83	3.6	3.1	2.6
6.67	3.4	3.4	2.5
7.50	3.1	3.0	2.1
8.33	3.2	3.1	2.3
10.42	4.1	3.9	3.0

Effect of Z on d_{32} : As the value of Z , increases from 0.00 m to 0.15 m, the values of d_{32} decreases by 40% in case of water as well as in case of EG solution. It may be possible only when either bubble breakup is more prominent than bubble coalescence or small bubbles in the column are carried away towards the top along strong induced current by large bubbles resulting in accumulation of small bubbles in the upper portion of the column. Bubble breakup is less probable as it was not observed visually. Present trend is in contradiction to the findings of Schäfer et al. [14] who observed that the value of d_{32} increased as the bubbles moved up away from the distributor plate possibly due to bubble coalescence being dominant in their studies.

Effect of H_s on d_{32} : Variation of d_{32} for 5.0% (w/w) aq. soln. of EG as a function of U_g for $H_s = 0.10, 0.15$ and 0.20 m and



Acoustic Measurement in a Rectangular Bubble Column to Determine Bubble Size and Interfacial Area for Aqueous Solutions of Ethylene Glycol

$Z = 0.05$ m is presented in Fig. 4. The value of d_{32} increases with increasing value of H_s , which could be due to more residence time available for bubbles to coalescence. This trend is surprising as for the same value of H_s the value of d_{32} decreases with increasing value of Z .

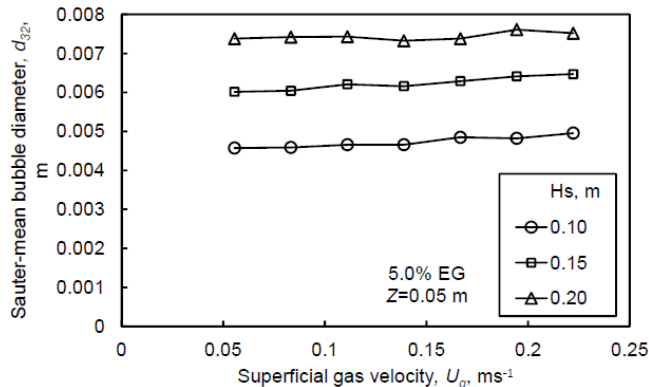


Fig. 4: Effect of H_s and U_g on d_{32} for 5% (w/w) ethylene glycol solution at $Z=0.05$ m

C. Specific Interfacial Area

Specific interfacial area, a_i , an important parameter for estimation of mass-transfer rate in bubble columns may be estimated from the values of d_{32} and gas holdup, ε .

$$a_i = 6\varepsilon/d_{32} \quad (4)$$

It may be noted that the value of a_i is proportional to ε .

Gas holdup: Gas holdup is experimentally determined from the values of expanded bed height, H_e .

$$\varepsilon = (H_e - H_s) / H_e \quad (6)$$

Values of ε at $H_s = 0.10$ m, 0.15 m and 0.20 m for air-aq. EG soln. and $H_s = 0.20$ m for air-water are presented in Fig. 5. Gas holdup increases with increasing U_g . Its values for aq. soln. of EG are lower than that for water. Due to higher gas holdup, the data could not be obtained for high value of U_g to avoid overflow. No specific trend on effect of conc. of EG and H_s on gas holdup were observed. It was essential keep the mikes always submerged in the solution.

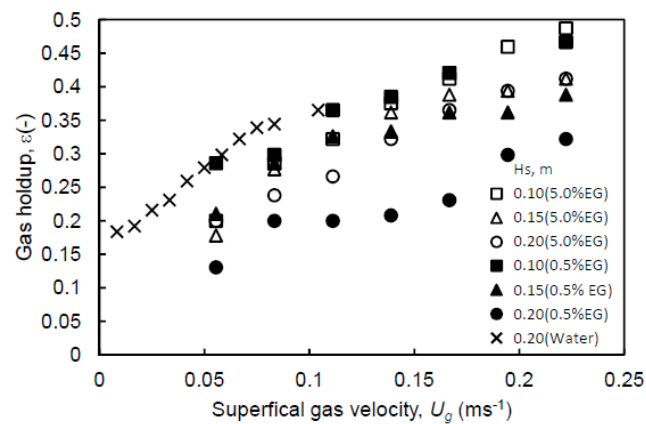


Fig. 5: Gas holdup as a function of U_g and H_s for air-water and air-ethylene glycol solutions

Variation of a_i as a function of U_g for $H_s = 0.20$ m and conc. (w/w) of EG = 0.5% and 5.0%, and $Z = 0.00$ m, 0.05 m and 0.015 m is presented in Fig. 6.

The value of a_i increases with increasing U_g in all the cases. Since d_{32} is independent of U_g , the increase is due to increase in ε . It is due to the fact that high number of bubbles generated at the gas distributor at large gas velocity. The values of a_i in case of aq. soln. of EG are about 200% lower than that in case of water. No specific dependence on Z could be observed. It might be due to a combined effect of ε and Z . Correlation of Pohorecki et al. [13] given below considers only U_g to affect a_i .

$$a_i = 1120U_g^{0.63} \quad (7)$$

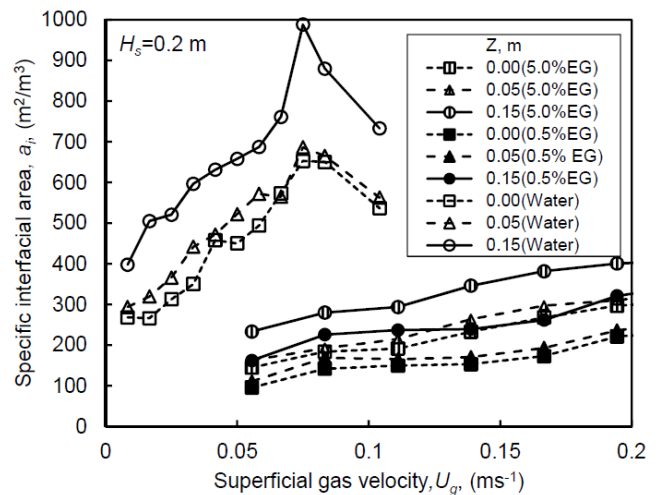


Fig. 6: Specific interfacial area as a function of U_g and Z for air-water and air-ethylene glycol solutions

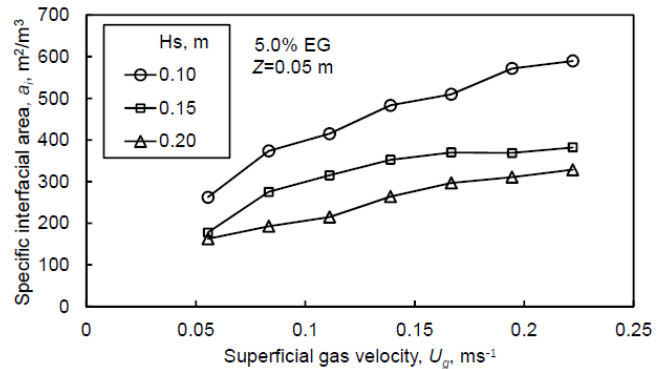


Fig. 7: Effect of H_s and U_g on a_i for 5% (w/w) ethylene glycol solution at $Z=0.05$ m

Effect of H_s on a_i : Variation of a_i with U_g for static bed height for 5% (w/w) EG soln. at $H_s = 0.10$ m, 0.15 m and 0.20 m and $Z = 0.05$ m is presented in Fig. 7. The value of a_i increases with increasing value of U_g . Since the value of d_{32} is independent of U_g , the trend is due to increasing ε with increasing U_g . The value of a_i increases with decreasing H_s . Though, the value of d_{32} decreases with increasing value of H_s , the effect of H_s on a_i may be attributed to a combined effect of ε and d_{32} .

IV. CONCLUSIONS

Local values of BSD were measured as a function of distance above distributor plate in a rectangular column for air-water and air-ethylene glycol solution systems. The BSD exhibited mono-modal distribution indicating non-uniform homogeneous bubbling regime. Values of d_{32} were estimated from BSD and experimental values of gas holdup. The value of d_{32} is independent of U_g , H_s , and concentration of EG, although, it is higher than that for air-water system. As the values of Z increases, the values of d_{32} decreases. Variation of d_{32} along Z may be used to study bubble coalescence and bubble breakup as the bubble moves up in a column. The value of a_i increases with decreasing H_s and increasing Z . For air-EG solution the values of a_i are about 200% higher than that observed in air-water system. Thus EG may be used as an additive to increase mass-transfer rate.

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