

# 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].

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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,  $\gamma$  is ratio of specific heats of gas in bubble and  $\rho$  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.



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

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,  $a_b$ , were estimated.

## 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.

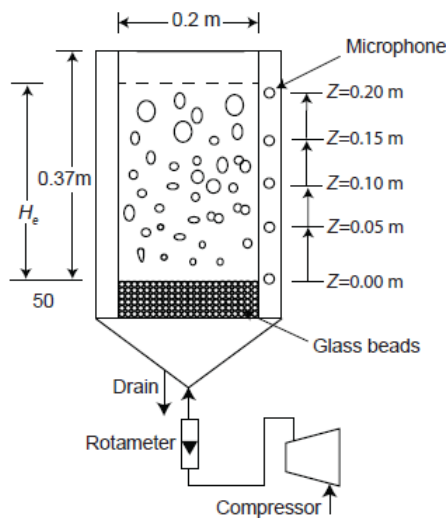


Fig. 1: Schematic diagram of experimental setup

### 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<sup>-1</sup> for air-water system and in the range of  $0.0556 - 0.222$  m s<sup>-1</sup> 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	$\rho$ (kg m <sup>-3</sup> )	$\mu$ (kg m <sup>-1</sup> s <sup>-1</sup> )	$\sigma$ (N m <sup>-1</sup> )
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

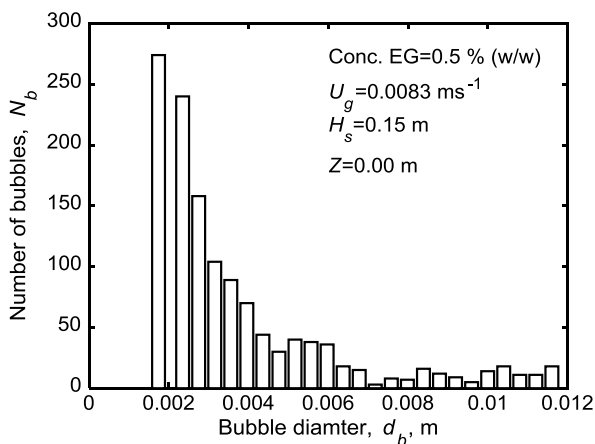
## III. RESULTS AND DISCUSSION

### A. Bubble-Size Distribution

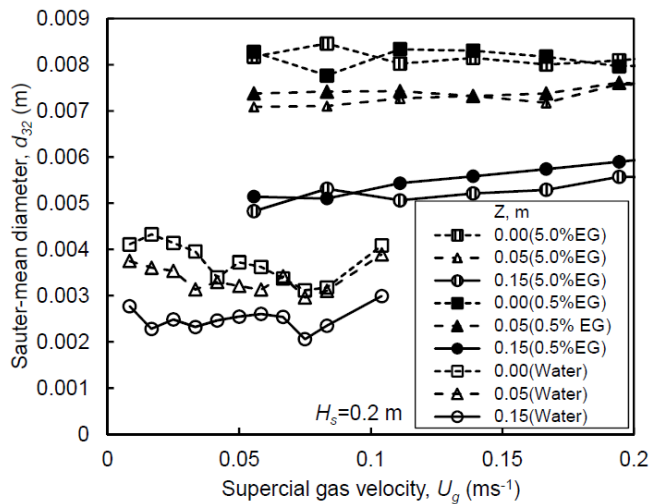
BSD for 0.5% (w/w) EG solution superficial air velocity,  $U_g = 0.083$  m s<sup>-1</sup>, and static bed height,  $H_s = 0.15$  m for distance of mike above distributor plate,  $Z = 0.00$  m is presented in Fig 2. The maximum bubble diameter is 0.0116 m. Most of the bubbles are of the size about 0.002 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 0.15 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 vales 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 ( $Z=0.00$  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  $d_{32} \times 10^3$ , m at  $H_s=0.2$  m as a function of  $U_g$  and  $Z$**

$U_g \times 10^2$ $\text{ms}^{-1}$	Z, m (5% EG)			Z, m (0.5% EG)		
	0.0	0.0	0.1	0.0	0.0	0.1
	0	5	5	0	5	5
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  $d_{32} \times 10^3$ , m for 5% EG at  $H_s=0.2$  as a function of  $U_g$  and  $Z$**

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

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

$U_g \times 10^2$ $\text{ms}^{-1}$	Z, m		
	0.0	0.0	0.1
	0	5	5
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

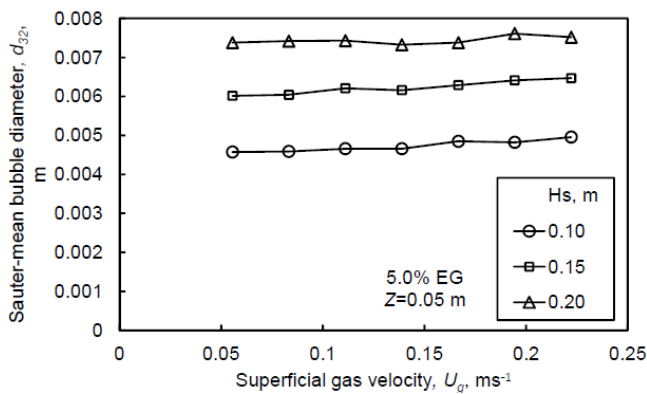
**Effect of  $Z$  on  $d_{32}$ :** As the value of  $Z$ , increases from 0.00 m to 0.15 m, the values of  $d_{32}$  decreases by 40% in case of water as well as in case of EG solution.



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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  $Z = 0.05$  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 coalesce. 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,  $\varepsilon$ .

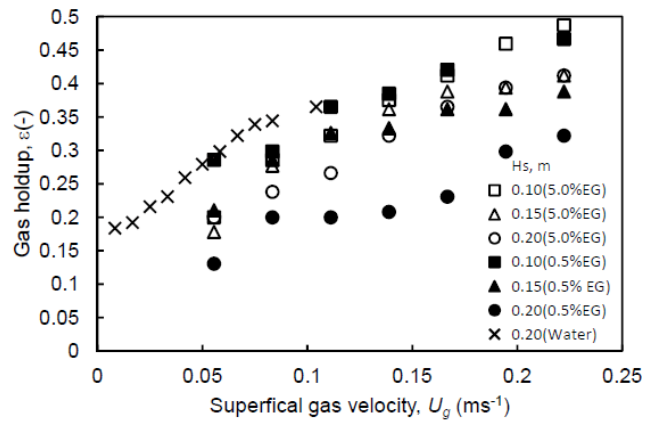
$$a_i = 6\varepsilon/d_{32} \quad (4)$$

It may be noted that the value of  $a_i$  is proportional to  $\varepsilon$ .

**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  $\varepsilon$  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.

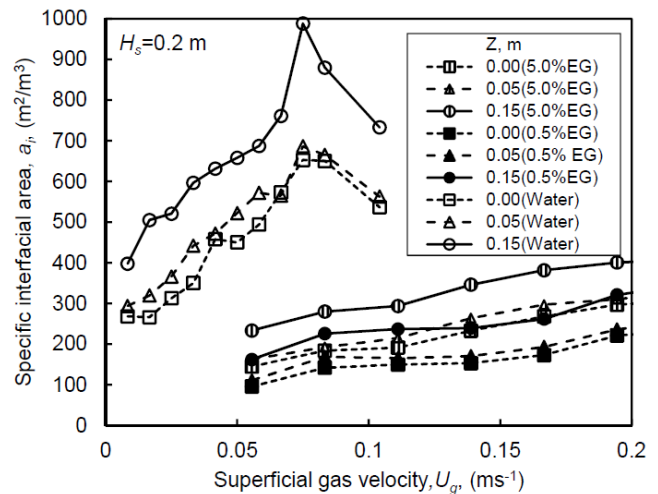


**Fig. 5: Gas holdup as a function of  $U_g$  and  $H_s$  for air-water and air-ethylene glycol solutions**

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  $0.15$  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  $\varepsilon$ . 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  $\varepsilon$  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**

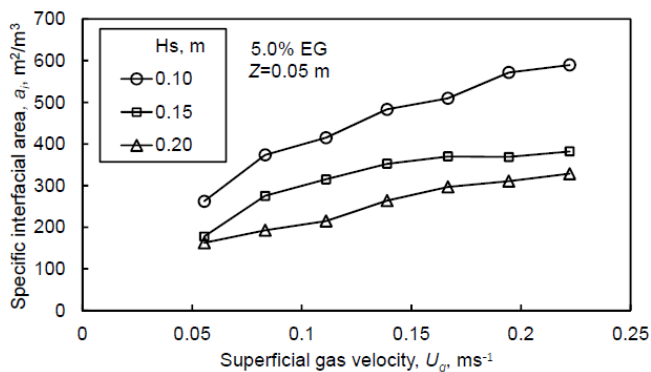


Fig. 7: Effect of  $H_s$  and  $U_g$  on  $a_i$  for 5% (w/w) ethylene glycol solution at  $Z=0.05$  m

**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  $\varepsilon$  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  $\varepsilon$  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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