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Effect of Geometrical Parameters of Draft Tubes and Clear Liquid Height on Gas Holdup in a Bubble Column for Gas Dispersion into Tubes

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Abstract–The effects of the geometrical parameters of draft tubes and the clear liquid height on the average gas holdup E_G in a 0.16 m I.D. bubble column for gas dispersion into the tubes were experimentally studied in an air-tap water system. The gas holdup depended on the superficial gas velocity U_G, the kinds of gas spargers, the diameter and length of the draft tubes, clearance C_b between the lower end of the draft tube and the bottom of the bubble column, and the clear liquid height H_L. E_G increased with decreasing hole diameter of the gas sparger at a small gas velocity U_G, but did not depend on the kinds of gas spargers at a large U_G. E_G decreased with increasing clear liquid height H_L. The effect of H_L on E_G was well expressed by the modified three-region model. The experimental data of E_G were correlated.

Key words: Bubble Column, Air Lift, Draft Tube, Gas Holdup, Liquid Height

INTRODUCTION

Bubble columns with a draft tube have been increasingly used in waste water treatment, fermentation and chemical processes. The gas holdup is an important parameter for the design of a bubble column with a draft tube. There have been several research studies about the gas holdup in bubble columns with a draft tube [Bello et al., 1985; Koide et al., 1983; Merchuk et al., 1994; Weiland, 1984].

Koide et al. [1983] have reported the effects of the kinds of the gas spargers, the lower clearance C_b, inner diameter of the draft tube D_i and diameter of bubble column D_T on E_G in bubble columns with a draft tube for gas dispersion into a tube. Weiland [1984] also has studied the effect of D_i on E_G for an air-water system. Bello et al. [1985] have reported the effect of the ratio of downcomer-to-riser cross sectional area on the gas holdup for concentric and external-loop bubble columns. Merchuk et al. [1994] have reported the effects of the geometrical design of draft tubes on E_G for 0.158 and 0.318 m I.D. bubble columns.

However, the effects of gas sparger type, diameter and length of the draft tube, clearance between the lower end of the draft tube and the bottom of the bubble column, and the clear liquid height on the gas holdup in the bubble column with a draft tube have not yet been fully clarified.

In this work, the effects of the kinds of gas spargers, diameter and length of the draft tube, clearance between the lower end of the draft tube and bottom of the bubble column, and height of the clear liquid on the gas holdup in the bubble column with a draft tube were experimentally studied and the results were analyzed and correlated. Also, a modified three-region model was presented to explain the effect of the clear liquid height on the gas holdup in a bubble column with a draft tube.

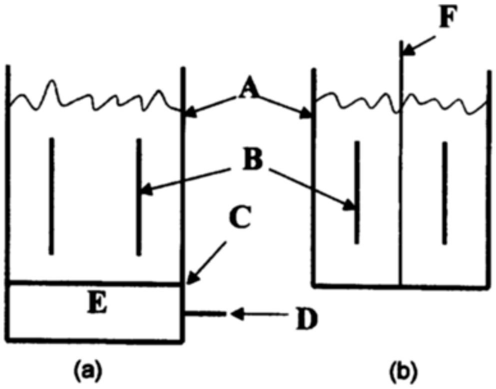

Fig. 1. Schematic diagram of experimental apparatus.
(a) bubble column with a perforated plate sparger, (b) bubble column with a vertical pipe sparger.
A=bubble column, B=draft tube, C=perforated plate, D=gas inlet, E=gas chamber, F=steel pipe gas sparger

EXPERIMENTAL

Fig. 1 shows a schematic diagram of the experimental apparatus. Fig. 1(a) and (b) show a bubble column with a perforated plate and a vertical steel pipe as a gas sparger, respectively. The bubble column used was made of transparent acrylic resin. Its diameter and height were 0.16 m and 2.4 m, respectively. The gas spargers used consisted of perforated plates and a 0.009 m I.D. steel pipe. The pipe, which had two holes on its side at 0.015 m above the bottom of the bubble column, was inserted downwards at the center of the bubble column. The end of the steel pipe was closed with a rubber stopper. Details of the gas spargers used are listed in Table 1. The draft tubes used were made of acrylic resin and polyvinyl chloride resin pipes. Their lengths were 0.50-1.40 m. Details of the draft tubes used are

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Table 1. Details of gas spargers used

No.	d [m]	n [-]	p [m]	H_N [m]	Remarks
1	0.0007	145	0.005	0	pp
2	0.001	45	0.005	0	pp
3	0.008	2	-	0.015	sp

Note : pp and sp mean a perforated plate and a steel pipe, respectively.

Table 2. Details of draft tubes used

No.	D_i [m]	D_o [m]	No.	D_i [m]	D_o [m]
1	0.050	0.060	5	0.083	0.090
2	0.056	0.060	6	0.090	0.110
3	0.075	0.095	7	0.110	0.130
4	0.078	0.090	8	0.130	0.140

listed in Table 2.

The liquid used was tap water at room temperature. During each run, liquid was neither fed nor discharged. Air was used as the gas. The gas was dispersed into the draft tube.

The average gas holdup E_G was obtained from the following equations:

$$E_G=(H_T-H_L)/(H_T-A) \tag{1}$$

$$A=V/S \tag{2}$$

where H_T and H_L are the height of the bubbling and clear liquid layers, respectively. H_T and H_L were visually measured.

MODIFIED THREE-REGION MODEL

To express the effect of the clear liquid height, H_L, on the gas holdup in a bubble column with a draft tube, the following simple model was derived by modifying the three-region model [Yamashita, 1998]. It is assumed that the bubble column with a draft tube consists of the three regions, that is, the draft tube region, the bulk region and the foam layer as shown in Fig. 2.

From the gas balance in the bubble column with a draft tube, the following equations were derived:

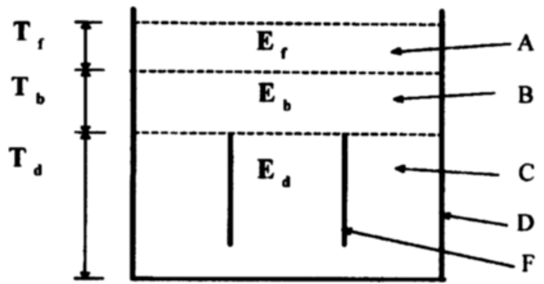

Fig. 2. Concept of three-region model.
A=foam layer, B=bulk region, C=draft tube region, D=bubble column, F=draft tube, E_i, T_i=gas holdup and thickness of i-region, respectively.

$$E_GH_{T1}=E_dT_{d1}+E_bT_b+E_fT_f \tag{3}$$

$$H_{T1}=T_{d1}+T_b+T_f \tag{4}$$

$$H_{T1}=H_{L1}/(1-E_G) \tag{5}$$

From Eqs. (3)-(5), the following equations are derived:

$$E_G=1-(1-E_b)H_{L1}/(H_{L1}+B) \tag{6}$$

$$B=E_dT_{d1}+E_fT_f-E_b(T_{d1}+T_f) \tag{7}$$

If E_b and B are independent of H_{L1} and B>0, the gas holdup E_G decreases with increasing H_{L1} and becomes equal to E_b at H_{L1}=infinity. From Eq. (6), the following equation is derived:

$$\frac{1}{1-E_G}=\frac{B}{1-E_b}\frac{1}{H_{L1}}+\frac{1}{1-E_b} \tag{8}$$

That E_b is independent of H_{L1} means that E_b does not depend on the clear liquid height H_{L1}. And that E_G decreases with increasing H_{L1} and becomes equal to E_b at H_{L1}=infinity means that the effect of the draft tube region and the foam layer on the gas holdup E_G decreases with increasing clear liquid height and can be neglected at a large H_{L1}.

EXPERIMENTAL RESULTS

1. Effect of Gas Spargers on E_G

Fig. 3 shows the effect of the gas spargers on the gas holdup in the bubble column with a draft tube of D_i=0.13 m. The average gas holdup increased with decreasing hole diameter of the gas sparger at a small U_G, but did not depend on the gas spargers at a larger U_G.

At a small U_G, smaller bubbles are generated from the gas sparger with small diameter holes and rise with little change in their sizes. At a large U_G, bubble sizes depend mainly upon the

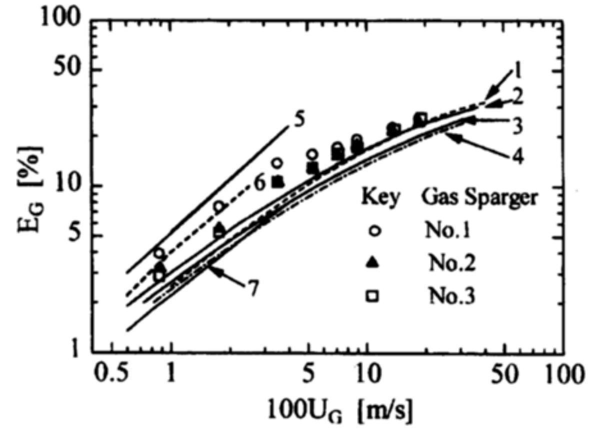

Fig. 3. Effect of kinds of gas spargers on gas holdup and comparison between E_G and the correlations of gas holdups by previous investigators for air-water system at 293 K.
The experimental conditions are D_i=0.13 m, L_d=1.40 m, C_b=0.03 m and H_L=1.50 m. 1. Yamashita and Inoue [1975], 2. Akita and Yoshida [1973], 3. Koide et al. [1983] for F_{ai}=0.8125, 4. Koide et al. [1983] for F_{ai}=0.3125, 5. Merchuk et al. [1994], 6. Data of Merchuk et al. [1994] at D_T=0.318 m, D_i=0.216 m, L_d=3.27 m, C_b=0.010-0.080 m and C_t=0.040 and 0.240 m, 7. Merchuk et al. [1994] at D_T=0.158 m, D_i=0.11 m, L_d=1.395 m, C_b=0.012 and C_t= 0.178 m

turbulence in the bubble column. Therefore, the gas holdup increases with decreasing hole diameter of the gas sparger at a small U_G, but did not depend on the kinds of the gas spargers at a large U_G.

Fig. 3 also shows the comparison between this work and the previous studies for the gas holdup. It is clear that the experimental data for Nos. 2 and 3 gas spargers are nearly equal to the correlations of the gas holdup in the bubble column without draft tubes by Akita and Yoshida [1973], and Yamashita and Inoue [1975]. The gas holdup calculated by the correlation of Koide et al. [1983] for the bubble column with a draft tube and with gas dispersion into the draft tube is slightly smaller than the experimental data in this work.

The data of Merchuk et al. [1994] for a 0.318 m I.D. bubble column with a 0.216 m I.D. draft tube is nearly equal to the data for the No. 1 gas sparger. Their data for a 0.158 m I.D. bubble column with a 0.110 m I.D. draft tube are slightly smaller than the experimental data in this work, because they used a wide separator of 0.213 m inner diameter on the top of the bubble column. The gas sparger used by Merchuk et al. [1994] was a ring sparger of d=0.001 m and n=40. The correlation of Merchuk et al. [1994] is slightly larger than the experimental data in this work.

Koide et al. [1983] have reported for a 0.14 m I.D. bubble column with a draft tube that the gas holdup does not depend on the kinds of gas spargers, but that the volumetric mass transfer coefficient depends on the kinds of gas spargers. The reason why the gas holdup by Koide et al. [1983] does not depend on the kinds of the gas spargers is not clear.

2. Effect of Inner Diameter D_i of the Draft Tube on E_G

Figs. 4 and 5 show the effect of the inner diameter D_i of the draft tube on gas holdup E_G in the bubble column with a draft tube at L_d/H_L=0.833 and 0.333 for L_d=0.50 m, respectively. E_G at D_i=0.16 m means the gas holdup in the bubble column without a draft tube. Fig. 4 shows that the gas holdup E_G increased with decreasing D_i and was maximum at D_i=0.078 m-0.09 m at a large U_G. However, Fig. 5 shows that the gas holdup E_G was nearly constant in the range of D_i>0.078 m and decreased slightly with decreasing D_i in the range of D_i<0.078 m. It is clear from these figures that the maximum of the gas holdup increases with increasing ratio of (L_d/H_L). This means that the effect of D_i on E_G increases with increasing ratio of (L_d/H_L). At U_G=.0.0088 m/s, E_G did not depend upon D_i and was nearly constant.

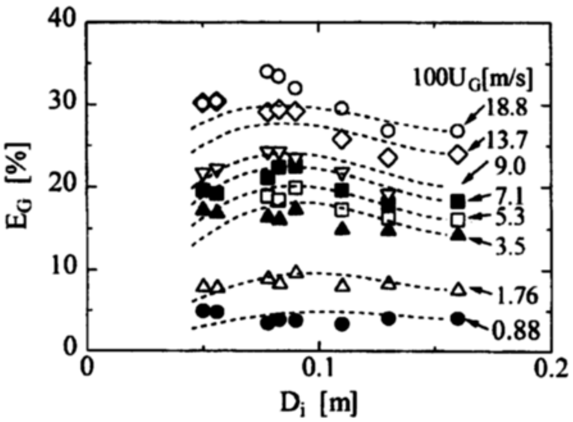

Fig. 4. Effect of D_i on E_G at H_L=0.60 m, L_d=0.50 m, C_b=0.03 m and L_d/H_L=0.833.

Dotted lines mean calculated values by Eqs. (9)-(13) with experimental data of E_S.

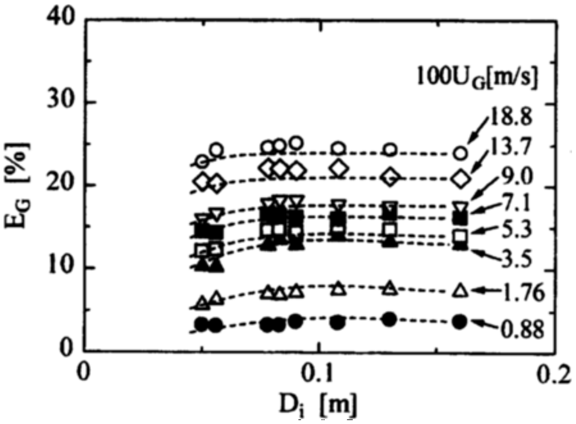

Fig. 5. Effect of inner diameter D_i of draft tube on E_G at H_L=1.50 m, L_d=0.50 m, C_b=0.03 m, L_d/H_L=0.333 and No. 1 gas sparger.

Dotted lines mean calculated value of E_G by Eqs. (9)-(13) with experimental values of E_S.

Fig. 6 shows the effect of D_i on E_G at (L_d/H_L)=0.933 and L_d=1.40 m. Though the ratio of (L_d/H_L)=0.933, E_G increased only slightly with decreasing D_i and was maximum at about D_i=0.080 m in the range of U_G>0.035 m/s. In the range of U_G <0.035 m/s, E_G was nearly constant in the range of D_i>0.056 m, but decreased slightly at D_i=0.050 m. These results are explained as follows.

When gas is spouted into a shallow liquid layer at a high speed, the liquid layer becomes a froth layer or a foam layer, and the gas holdup in the layer increases substantially with increasing U_G and decreasing H_L. However, the gas holdup becomes nearly constant in the range of H_L>H_{LC} [Kawagoe et al., 1974; Takahashi et al., 1974; Yamashita, 1985, 1997]. H_{LC} is the critical clear liquid height above which the gas holdup becomes

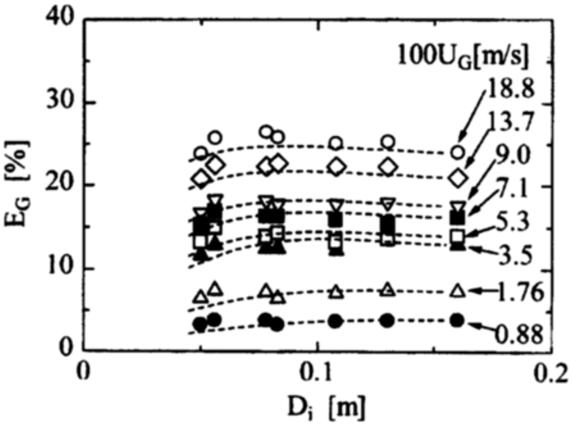

Fig. 6. Effect of inner diameter D_i of draft tube on E_G at H_L=1.50 m, L_d=1.40 m, C_b=0.03 m, L_d/H_L=0.933 and No. 1 gas sparger.

Dotted lines mean calculated value of E_G by Eqs. (9)-(13) with experimental values of E_S.

constant. Takahashi et al. [1974] have reported that H_{LC} is 0.50 m. The gas velocity at the top of the draft tube and the effect of the spouting of the gas from the draft tube increase with decreasing D_i. Therefore, the gas holdup increases with decreasing D_i, and the maximum of the gas holdup increases with increasing ratio of (L_d/H_L). However, when the length L_d of the draft tube is long, the effect of D_i becomes very small, because the top section above the draft tube becomes a small portion of the entire bubbling layer. Therefore, for L_d=1.40 m the gas holdup increased only very slightly with decreasing D_i even at (L_d/H_L)=0.933.

The reason why the gas holdup for the draft tube of D_i= 0.05-0.056 m decreased slightly is because the circulation of the gas and liquid is weak and most of the annular section is almost bubble-free, though the effect of the spouting of gas and liquid is large.

Weiland [1984] has studied the effect of D_i on E_G under the condition of U_G<0.035 m/s, D_T=0.20 m, F_{ai}=0.59-1.0, L_d=1.50 m, H_L=1.70 m and L_d/H_L=0.77 for an air-water system and reported that the gas holdup is almost equal to E_S in the range of F_{ai}>0.74 and that the gas holdup is rather small at F_{ai}=0.59. It is clear from Fig. 5 in the range of U_G<0.035 m/s that E_G is nearly equal to E_S in the range of F_{ai}>0.35 and that E_G is rather small at F_{ai}=0.313. The experimental results in this work resemble those of Weiland [1984].

Koide et al. [1983] have reported that E_G is proportional to $F_{ai}^{0.114}$ in the range of F_{ai}=0.471-0.743, L_d=1.40 m and D_T=0.10-0.300 m. The results of Koide et al. [1983] are nearly equal to those at large L_d in this work.

3. Effect of Clearance C_b between Lower End of Draft Tube and Bottom of Bubble Column

Fig. 7 shows an example of the effect of C_b on E_G. The experimental conditions are D_i=0.056 m, L_d=1.40 m, H_L=1.55 m and the No. 2 gas sparger. E_G was nearly constant at a small U_G. However, at a large U_G, E_G increased with increasing C_b and became maximum at $C_b=C_{b,m}$. E_G became nearly constant in the range of $C_b>C_{b,cr}$. This result is explained as follows.

At a large U_G, the circulation of liquid increases with increasing C_b and bubbles begin to descend into the annulus. Therefore, E_G increases with increasing C_b in the range of $C_b<C_{b,m}$. In the range of $C_b>C_{b,m}$, the circulation of liquid becomes so strong that bubbles rise faster in the draft tube. Therefore, E_G begins to decrease with increasing C_b. However, in the range of $C_b>C_{b,cr}$, the clearance is so large that the circulation of liquid and gas does not depend on C_b. Therefore, E_G becomes nearly constant.

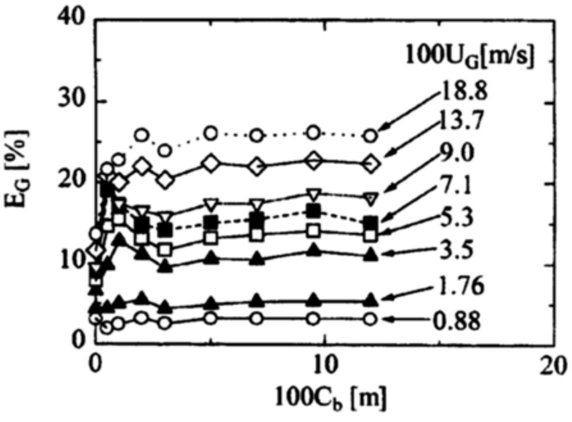

Fig. 7. Effect of C_b on E_G in No. 2 gas sparger at D_i=0.056 m, L_d=1.40 m and H_L=1.55 m.

In the range of U_G<0.018 m/s for C_b=0.095 m, gas leakage from the lower end of the draft tube into the annulus occurred due to the fluctuation of bubble flow just above the gas sparger, but did not occur in the range of U_G>0.035 m/s because of the strong circulation of the liquid. For C_b=0.12 m, the gas leakage from the lower end of the draft tube into the annulus occurred at all U_G, because of too large a C_b value.

$C_{b,m}$ and $C_{b,cr}$ depended on D_i and U_G, and most data for $C_{b,m}$ and $C_{b,cr}$ were less than 0.01 m and 0.03 m, respectively. Koide et al. [1983] have reported that E_G is not affected by C_b in the range of C_b=0.010 m-0.082 m for a 0.082 m I.D. draft tube in a 0.14 m I.D. bubble column. Their data are nearly equal to C_b for D_i=0.078 m in this work.

Merchuk et al. [1994] have reported for 0.158 and 0.318 m I.D. bubble columns with a draft tube that E_G increases with $C_b^{0.1}$. The reason why their data increased with $C_b^{0.1}$ is not clear, but the difference from this work may be small.

Fig. 8 shows the effect of F_{ai} on the gas holdup E_G at C_b=0. E_G at C_b=0 decreased remarkably with decreasing F_{ai}, because the bubble-free annulus increased with decreasing F_{ai}.

4. Effect of Length L_d of Draft Tube on E_G

For a large D_i, the gas holdup increased slightly with increasing L_d at a large U_G and was nearly constant at a small U_G. However, for D_i=0.05 m, E_G decreased with increasing L_d and became minimum at L_d=1.03 m as shown in Fig. 9. Fig. 9 shows the effect of L_d on E_G/E_s for D_i=0.05 m. E_G at L_d=0 means E_s. E_s means the average gas holdup in the bubble column without a draft tube. This result is explained as follows.

The upper clearance C_t above the draft tube decreases and the spouting effect of the gas and liquid from the draft tube into the upper section increases with increasing L_d at a given H_L. However, for the draft tube of small D_i, the circulation of liquid is weak and most bubbles, except very fine ones, do not descend; most of the annular region is almost bubble –free. Therefore, the

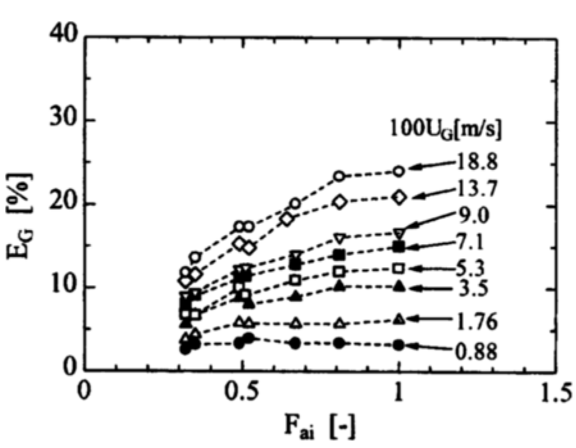

Fig. 8. Effect of F_{ai} on gas holdup at C_b=0.
The experimental conditions are L_d=1.40 m, H_L=1.40 m and No. 2 gas sparger

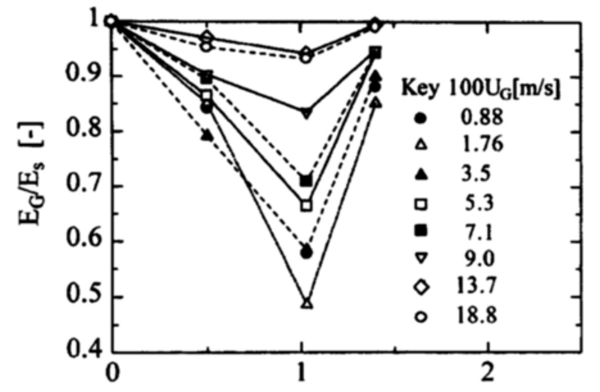

Fig. 9. Effect of L_d on E_G at D_i=0.050 m, C_b=0.03 m, H_L=1.50 m and No. 1 gas sparger.

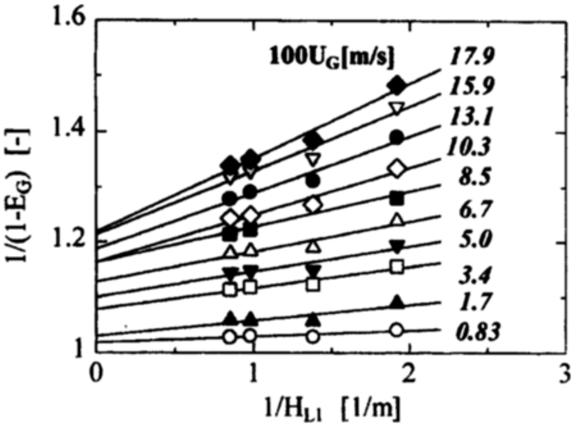

Fig. 10. Plot of $1/(1-E_G)$ vs. $1/H_{L1}$ at D_i=0.09 m, L_d=0.50 m, C_b=0.03 m and No. 2 gas sparger.

gas holdup decreases with increasing L_d. However, at L_d=1.40 m the gas holdup again increases due to the spouting effect of gas and liquid into the shallow liquid layer above the top of the draft tube. So the gas holdup became minimum at L_d=1.03 m.

5. Effect of Clear Liquid Height H_L on E_G

E_G decreased with increasing H_L. Fig. 10 shows the plot of $1/(1-E_G)$ vs. $(1/H_{L1})$. It is clear that the experimental data are well expressed by Eq. (8) and that the effect of the clear liquid height on the gas holdup can be well expressed by the modified three-region model. Table 3 shows the values of E_b and B obtained from Fig. 10.

Merchuk et al. [1994] have also reported that E_G is proportional to $C_t^{-0.07}$. C_t is the top clearance above the draft tube and is equal to $(H_L-L_d-C_b)$. Therefore, this means that E_G decreases slightly with increasing H_L.

6. Correlation of Experimental Data

E_G was correlated in the range of C_b>0.03 m using the following equations:

$$E_G/E_S=Z_1Z_2 \tag{9}$$

$$Z_1=1-(1-F_{ai})^M \tag{10}$$

$$Z_2=1+70\left(\frac{L_d}{D_T}\right)^{-2}\left(\frac{L_d}{H_L}\right)^q[F_{ai}(1-F_{ai})]^2 \tag{11}$$

$$M=18(Fr)^{0.41} \tag{12}$$

$$q=35.3(Fr)^{0.83} \tag{13}$$

These equations are applicable for D_i=0.05-0.13 m, L_d=0.50-1.40 m, H_L=0.60-1.55 m and C_b=0.03-0.182 m.

Fig. 11 shows the comparison between the experimental data for E_G and values calculated by Eqs. (9)-(13) with the experimental data for E_s. The average error with Eqs. (9)-(13) was 7.67% for 1,056 data for E_G. Dotted lines in Figs. 4-6 mean values for E_G calculated by Eqs. (9)-(13) with the experimental data for E_s. It is clear from these figures that Eqs. (9)-(13) show fairly good agreement with the experimental data.

Table 3. Values of E_b and B obtained from Fig. 10

100 U_G [m/s]	E_b [-]	100 B [m]	100 U_G [m/s]	E_b [-]	100 B [m]
0.83	0.0182	0.0104	8.5	0.139	0.0505
1.70	0.0295	0.0269	10.3	0.128	0.0833
3.4	0.0705	0.0351	13.1	0.156	0.0872
5.0	0.0924	0.0408	15.9	0.176	0.0956
6.7	0.113	0.0487	17.9	0.178	0.111

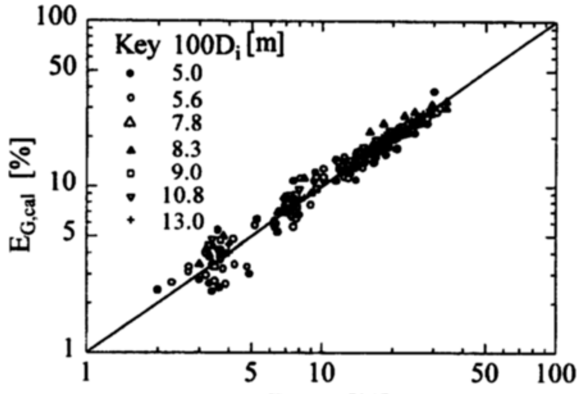

Fig. 11. $E_{G,cal}$ vs. $E_{G,exp}$ for No. 1 gas sparger.

CONCLUSION

The effects of the geometrical parameters of draft tubes and the clear liquid height on the average gas holdup E_G in a 0.16 m I.D. bubble column for the gas dispersion into a draft tube were experimentally studied in an air-tap water system. E_G depended on the kinds of the gas spargers, U_G, D_i, L_d, C_b, and H_L.

E_G increased with decreasing hole diameter of the gas sparger at a small gas velocity U_G, but did not depend on the kinds of gas spargers at a large U_G. At a large L_d, E_G did not depend on D_i and was nearly equal to E_s, but at a small L_d, E_G increased with increasing ratio of (L_d/H_L) and was maximum at D_i=0.078-0.09 m.

In the range of U_G>0.035 m/s, E_G increased with increasing C_b in the range of $C_b<C_{b,m}$, and was maximum at $C_{b,m}$. But in the range of U_G<0.035 m/s, E_G was nearly constant. In the range of $C_b>C_{b,cr}$, E_G did not depend on C_b and was nearly constant.

E_G at C_b=0 increased with increasing F_{ai}. E_G decreased with increasing clear liquid height H_L. The effect of H_L on E_G was well expressed by the modified three-region model. The experimental data of E_G in the range of $C_b > C_{b,cr}$ were correlated by Eqs. (9)-(13).

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NOMENCLATURE

A : parameter defined by Eq. (2) [m]

B : parameter defined by Eq. (7) [m]

C_b : clearance between lower end of draft tube and bottom of bubble column [m]

$C_{b,m}$: C_b at which E_G becomes minimum or maximum [m]

$C_{b,cr}$: critical value of C_b above which E_G becomes constant [m]

C_t : clearance between upper end of draft tube and top of clear liquid [m]

d : diameter of hole [m]

D_i : inner diameter of draft tube [m]

D_o : outer diameter of draft tube [m]

D_T : inner diameter of bubble column [m]

E_b : average gas holdup in bulk region [-]

E_d : average gas holdup in draft tube region [-]

E_f : average gas holdup in foam layer [-]

E_G : average gas holdup [-]

$E_{G,cal}$: calculated value of average gas holdup [-]

$E_{G,exp}$: experimental value of average gas holdup [-]

E_s : average gas holdup in the bubble column without a draft tube [-]

F_{ai} : D_i/D_T [-]

F_r : Froude number=($U_G/\sqrt{gD_T}$) [-]

g : gravitational acceleration [m /s^2]

H_L : clear liquid height [m]

H_{L1} : H_L-A [m]

H_N : height of gas inlet [m]

H_T : height of bubbling layer [m]

H_{T1} : H_T-A [m]

L_d : length of draft tube [m]

M : parameter defined by Eq. (12) [-]

n : number of holes [-]

p : pitch [m]

q : parameter defined by Eq. (13) [-]

S : cross-sectional area of bubble column [m^2]

T_b : thickness of bulk region [m]

T_d : thickness of draft tube region [m]

T_{d1} : T_d-A [m]

T_f : thickness of foam layer [m]

U_G : superficial gas velocity [m/s]

V : volume of draft tube and steel pipe [m^3]

Z_1 : parameter defined by Eq. (10) [-]

Z_2 : parameter defined by Eq. (11) [-]

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