EFFECTS OF ALCOHOLS ON GAS HOLDUP AND VOLUMETRIC LIQUID-PHASE MASS TRANSFER COEFFICIENT IN GEL-PARTICLE-SUSPENDED BUBBLE COLUMN

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The effects of alcohols, column dimensions, gas velocity, physical properties of liquids, and gel particles on the gas holdup ε_G and the volumetric liquid-phase mass transfer coefficient $k_L a$ in a gel-particle-suspended bubble column under liquid-solid batch operation were studied experimentally. It was shown that addition of alcohols to water generally increases ε_G . However, $k_L a$ values in aqueous solutions of alcohols became larger or smaller than those in water, according to the kind and concentration of the alcohol added to water. It was also shown that the presence of suspended gel-particles in the bubble column reduces values of ε_G and $k_L a$. Based on these observations, empirical equations for ε_G in the transition regime in an ethanol solution, for ε_G in the heterogeneous flow regime applicable to various alcohol solutions and for $k_L a$ in both flow regimes were proposed.

Introduction

Recently, solid-suspended bubble columns, which have been used as chemical reactors, are being used as bioreactors. In this case, cells, immobilized cells or enzymes having densities slightly higher than that of water are used as suspended particles. The liquid phase in bioreactors often includes surface-active substances as additives or as biochemical products.

To design a bubble column as a bioreactor, the gas holdup ε_G and the volumetric liquid-phase mass transfer coefficient $k_L a$ should be known. A number of research works (Gorowara and Fan, 1990; Koide *et al.*, 1984; Yasunishi *et al.*, 1986) have been done on ε_G and $k_L a$ in columns with particles having relatively high density, such as glass and bronze particles. However, only a few works (Sauer and Hempel, 1991; Sun *et al.*, 1988; Sun and Furusaki, 1988; Sun and Furusaki, 1989; Tang and Fan, 1990) have been devoted to columns with suspended solid particles of low density. These works show that both ε_G and $k_L a$ increase with increasing gas velocity and with decreasing solid concentration and liquid viscosity.

It is known from a number of works (Akita, 1987; Koide *et al.*, 1985; Oels *et al.*, 1978; Pošarac and Tekić, 1987) that the presence of surface-active substances in water decreases or increases ε_G and $k_L a$ in bubble columns. However, only a few works (Gorowara and Fan, 1990; Sauer and Hempel, 1991; Sun *et al.*, 1988; Sun and Furusaki, 1988; Sun and Furusaki, 1989) have been done on the effects of surface-active substances on ε_G and $k_L a$

in solid-suspended bubble columns.

The objective of this work is to investigate the effect of normal alcohols as surface-active substances, column dimensions, the physical properties of the liquids and the gel-particles on ε_G and $k_L a$ in a bubble column with suspended solids of low-density calcium alginate gel particles in liquid-solid batch operation.

1. Experimental

The experimental apparatus used in this work is shown in **Fig. 1**. For the study of scale-up effects, three plexiglass columns of diameters 0.14, 0.218 and 0.30 m were employed. In the case of the 0.14 m ϕ column, four different perforated-plate gas distributors were installed in turn to study the effect of hole diameter, pitch and number. Details of the columns and the gas distributors are shown in **Table 1**. Demineralized water and aqueous solutions of methanol, ethanol, butanol, hexanol and octanol were used as the liquid phase. The physical properties of these solutions are listed in **Table 2**. Before starting experiments, the slurry was maintained at $298.2 \pm 0.5\text{K}$ by circulating the liquid through the heat exchanger (8) using the pump (7). The clear slurry height H_L was 1.5 m.

As the solid phase, calcium alginate gel particles with diameters of about 3×10^{-3} m were used. These were prepared by adding 2wt.% aqueous solution of sodium alginate dropwise into 1wt.% aqueous CaCl_2 solution. Particles produced in this manner were almost spherical so that the volume mean diameter could be determined easily from photographs of the particles. In addition to sodium alginate gel particles, polystyrene particles of $d_p = 6 \times 10^{-3}$ m were

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Fig. 1 Experimental apparatus

Table 1 Bubble column configurations

Column D [m]	Perforated Plate Gas Distributor $\delta \times 10^3$ [m]	$P \times 10^2$ [m]	N [-]
0.140	0.5	1.0	151
0.140	0.7	1.0	61
0.140	1.0	1.5	55
0.140	2.5	5.0	7
0.218	2.5	5.0	18
0.300	2.5	5.0	31

Table 2 Physical properties of liquids at 298 K

Liquid	C_B [mol·m ⁻³]	ρ_L [kg·m ⁻³]	$\mu_L \times 10^3$ [Pa·s]	$\sigma_L \times 10^3$ [N·m ⁻¹]	(Crk^2/σ_L) [-]
Demineralized water	0	997	0.894	72.0	0
	31.2	997	0.892	71.4	9.83×10^1
Methanol aq. soln.	156	997	0.885	70.0	3.20×10^2
	312	996	0.870	69.1	5.12×10^2
	21.7	997	0.890	71.3	2.61×10^2
Ethanol aq. soln.	109	996	0.880	69.1	9.90×10^2
	217	995	0.863	66.8	1.46×10^3
Butanol aq. soln.	13.5	996	0.891	68.5	1.16×10^4
	0.489	997	0.893	71.3	3.90×10^4
Hexanol aq. soln.	0.978	997	0.892	70.6	7.54×10^4
	9.78	997	0.884	55.6	3.35×10^5
Octanol aq. soln.	0.384	997	0.894	67.0	4.08×10^6

used as solid particles in which intraparticle diffusion of oxygen did not occur during aeration. Table 3 shows the physical properties of the gel particles and polystyrene particles used in this work.

In most experiments, the average gas holdup ε_G was calculated from Eq. (1).

$$\varepsilon_G = \frac{H_F - H_L}{H_F} \quad (1)$$

where H_L was slurry height before aeration, and H_F was visually observed height of aerated slurry bed which did

Table 3 Physical properties of particles at 298.2 K

Liquid	C_B [mol·m ⁻³]	$d_p \times 10^3$ [m]	ρ_s [kg·m ⁻³]
Gel Particles			
Demineralized water	0	3.01	1001
	31.2	3.19	1020
Methanol aq. soln.	156	3.02	1006
	312	3.01	1013
	21.7	2.76	1009
	"	2.82	1009
Ethanol aq. soln.	109	3.06	1000
	"	2.94	1001
	217	2.98	1015
Butanol aq. soln.	13.5	3.08	1012
	0.489	3.29	1014
Hexanol aq. soln.	0.978	3.29	1014
	9.78	3.29	1014
Octanol aq. soln.	0.384	3.18	1016
Polystyrene Particles			
Methanol aq. soln.	156	6.00	1087

Fig. 2 Effect of gas velocity and alcohols on ε_G and $k_L a$ in bubble column without gel-particles

not include the foam layer formed above the bed. The average gas holdup was also obtained from the pressure difference of two pressure taps (11) which were set at 0.25 m and 1.285 m above the gas distributor, respectively.

Fig. 3 Effect of gas velocity and alcohols on ϵ_G and k_La in bubble column with gel-particles

When there was excessive growth of the foam layer at high gas velocity, ϵ_G from Eq.(1) became lower than that obtained from the pressure difference. This was because part of the liquid was distributed to the foam layer, and the value of the static slurry height H_L before aeration, which was used in Eq. (1), became larger than that of the real static slurry height of the aerated slurry bed. In this case, ϵ_G value obtained by the pressure difference of two taps was used.

Physical absorption of oxygen from the air into the liquid was employed to determine k_La . Firstly, the oxygen in the slurry was purged with nitrogen gas so that the initial steady-state dissolved oxygen concentration c_0 was below 0.5 ppm. After the nitrogen feed was stopped and the gel particles had settled down, the initial concentration c_0 of dissolved oxygen in the liquid was measured with the dissolved oxygen sensor (9) shown in Fig. 1, where the liquid in the column was circulated by pump (7). Then, the solenoid valve (4) was opened to disperse air into the column for a certain period, after which the valve was closed and the concentration c of dissolved oxygen was measured. These operations of desorption and absorption of oxygen were carried out three times, changing the period t of supplying air to the column, and the relation of c vs. t was thus obtained. When polystyrene particles were used or when no particles were used, k_La was calculated by Eq. (2)

Fig. 4 Effect of solid concentration on ϵ_G and k_La
Column A: $D = 0.14$ m, $\delta = 2.5 \times 10^{-3}$ m. GP: Gel particles; PS: Polystyrene particles

$$k_La = -\frac{2.303\epsilon_L}{t} \log \frac{c_i - c}{c_i - c_0} \quad (2)$$

where c_i was the saturated concentration of dissolved oxygen. When gel particles were used, the slope of this line was used to determine k_La by the method of Sun and Furusaki (1989) where the effect of intraparticle diffusion of oxygen during gas dispersion was taken into consideration.

2. Results and Discussion

2.1 Experimental results of ϵ_G and k_La

Figures 2 and 3 show the effect of the superficial gas velocity U_G and the kind of alcohols on ϵ_G and k_La in aqueous solutions of normal alcohols in bubble columns without and with gel particles respectively. Data for demineralized water are also shown for comparison. It is seen that both ϵ_G and k_La increase with increasing U_G . It can be seen that for the same U_G , ϵ_G values obtained in aqueous solutions of alcohols, except octanol, are greater than those obtained in water. Moreover, it is seen that for the same U_G , k_La increases with carbon number n of the alcohol up to 4. However, further increase in n decreases the values of k_La . A comparison of Figs. 2 and 3 shows that addition of gel-particles to the bubble column decreases both ϵ_G and k_La values.

Figure 4 shows that as ϕ_s increases at constant U_G , both ϵ_G and k_La decrease in an aqueous solution of methanol. Figure 4 also shows that the effect of ϕ_s of polystyrene particles on ϵ_G and k_La is similar to that of gel particles.

Figure 5 shows that ϵ_G decreases with increasing δ , while k_La decreases with increasing δ in the range of $\delta \leq 0.001$ m.

Figure 6 shows that while ϵ_G is enhanced by

Fig. 5 Effect of gas distributor on ϵ_G and $k_L a$ in bubble column with and without gel-particles

increasing column diameter, $k_L a$ remains practically constant. The increase in ϵ_G is probably due to the fact that increased downward liquid flow particularly near the wall entrains a sufficient number of fine bubbles so as to cause ϵ_G to increase. However, it might also be possible that the concentration of oxygen in these fine bubbles probably reaches equilibrium with that in the liquid very rapidly, or that their surfaces become immobile because of adhering alcohol molecules. Consequently, they might not contribute to mass transfer in the column, and $k_L a$ remains constant for increasing column diameter, while ϵ_G increases. It should be noted that the above observations for liquids of relatively high frothing ability are in sharp contrast to the results obtained in pure liquids and liquids of very low frothing ability by other authors (Akita and Yoshida, 1973). In the latter case, the gas holdup was found to be independent of the column diameter when the column diameter was 0.15 m or greater, and $k_L a$ was found to increase slightly with increasing column diameter.

2.2 Flow regime

Three flow regimes were recognized in bubble flow for $\phi_s = 0$: the homogeneous flow, transition and hetero-

Fig. 6 Effect of column diameter on ϵ_G and $k_L a$

Fig. 7 Flow regimes and gas holdup in bubble column with and without gel particles. Shaded area shows transition regime for air-ethanol aq. soln system without gel particles

geneous flow regimes. Attempts have been made to determine the flow regime in bubble columns by using the U_G vs ϵ_G curve (Koide *et al.*, 1984). Figure 7 shows Eq. (3) of Koide *et al.* (1966) for ϵ_G in homogeneous flow and Eq. (4) of Koide *et al.* (1984) for ϵ_G in the heterogeneous flow of the air-water two-phase system.

Fig. 8 Effect of (Crk^2/σ_L) on $\epsilon_G/(\epsilon_{GH})_0$

$$\frac{U_s}{U_T} = \left\{ 1 + 0.0167 \left(\frac{d_{BS}^2 g \rho_L}{\sigma_L} \right)^{2.16} \right\} \times \left\{ 0.27 + 0.73 (1 - \epsilon_G)^{2.80} \right\} \quad (3)$$

where $U_s = U_G/\epsilon_G - U_L/(1 - \epsilon_G)$

$$\left[\frac{\epsilon_{GH}}{(1 - \epsilon_{GH})^4} \right]_0 = 0.277 \left(\frac{U_G \mu_L}{\sigma_L} \right)^{0.918} Mo^{-0.252} \quad (4)$$

The region between the curves of these equations in Fig. 7 is defined as the transition regime for the air-water system with $\phi_s = 0$. Koide *et al.* (1984) recommended that for estimations of ϵ_G , the empirical equation of ϵ_G in the heterogeneous flow and that in the transition regime, respectively, be used for columns of $D\delta \geq 2 \times 10^{-4} \text{ m}^2$ and $D\delta < 2 \times 10^{-4} \text{ m}^2$. If this criterion is assumed applicable to the flow in the air-ethanol aq. soln system, the ϵ_G vs U_G curve obtained for $\phi_s = 0$ and $\delta = 2.5 \times 10^{-3} \text{ m}$ is the one for heterogeneous flow regime for this system. As the ϵ_G values calculated by Eq. (3) for the air-water system with $\delta = 0.5 \times 10^{-3} \text{ m}$ almost agree with those for the air-ethanol aq. soln system in Fig. 7, the shaded area in Fig. 7 shows the region of the transition regime for the air-ethanol aq. soln. system. Then, the observed values of ϵ_G in Fig. 7 indicate that most experiments with $\phi_s = 0$ were carried out in the heterogeneous flow and transition regimes. It is also noted that in columns with $\delta = 0.7 \times 10^{-3} \text{ m}$ and 10^{-3} m , the presence of gel particles causes the flow regime to approach heterogeneous flow.

Based on the above observation, it is necessary to differentiate different flow conditions when the correlation equations for the gas holdup are derived.

2.3 Correlations of ϵ_G and $k_L a$

2.3.1. Correlation of ϵ_G

(1) Heterogeneous flow in aqueous solutions of alcohol with $\phi_s = 0$. The fact that at the same gas velocity, ϵ_G in

aqueous solutions of alcohols, except octanol, is larger than that in water, as shown in Fig. 2, indicates that bubble coalescence is hindered in these solutions. Coalescence of two bubbles occurs when the thin film between them ruptures. Marrucci (1969) has introduced a parameter, Crk^2/σ_L , which governs the coalescence of bubbles, and has shown that coalescence is more hindered in liquids with higher values of the parameter. Crk^2/σ_L values* at given molar concentrations C_B of alcohol are shown in Table 2. This table shows that the value of Crk^2/σ_L increases with the carbon number n of alcohol. Figure 8 shows that the $\epsilon_G/(\epsilon_{GH})_0$ value increases with increasing value of Crk^2/σ_L in the range of $Crk^2/\sigma_L < 2 \times 10^4$, and vice versa in the range $Crk^2/\sigma_L \geq 2 \times 10^4$, where $(\epsilon_{GH})_0$ has been calculated from Eq. (4). This figure also shows that $\epsilon_G/(\epsilon_{GH})_0$ increases with n up to 4, and further increase in n reduces the value of $\epsilon_G/(\epsilon_{GH})_0$. As an alcohol becomes more lipophilic and its solubility in water decreases with increasing n value, there is a possibility that a spot of alcohol agglomerate appears in the thin liquid film between touching bubbles, the film becomes thinner by the surface tension differences between the spot and the surrounding surface adjacent to the spot and finally the film ruptures. Therefore, the degree of hindering bubble coalescence depends not only on Crk^2/σ_L but also on the solubility of alcohol and its lipophilic-hydrophilic property. Also, Fig. 6 shows that ϵ_G increases with increasing column diameter. Considering these facts, but not introducing the effects of the solubility and the lipophilic-hydrophilic property of alcohol on ϵ_G for simplicity of the correlation of ϵ_G , the following equation for ϵ_G was obtained for data with $\delta = 2.5 \text{ mm}$ and $\phi_s = 0$,

$$\frac{\epsilon_{GH}/(1 - \epsilon_{GH})^4}{[\epsilon_{GH}/(1 - \epsilon_{GH})^4]_0} = 1 + 0.00468 Bo^{0.465} f(Crk^2/\sigma_L) \quad (5)$$

where

$$f(Crk^2/\sigma_L) = \left(\frac{Crk^2}{\sigma_L} \right)^{0.223} \left[1 + 0.0143 \left(\frac{Crk^2}{\sigma_L} \right)^{0.466} \right]^{-1} \quad (6)$$

and $[\epsilon_{GH}/(1 - \epsilon_{GH})^4]_0$ was given by Eq. (4). The average error of estimating ϵ_G by Eq. (5) was within 10.9% for 59 data.

As shown in Fig. 4, ϵ_G decreases as ϕ_s increases. Based on data observed on using gel particles, Eq. (7) was obtained:

$$\frac{\epsilon_{GH}/(1 - \epsilon_{GH})^4}{[\epsilon_{GH}/(1 - \epsilon_{GH})^4]_0} = \frac{1 + 0.00468 Bo^{0.465} f(Crk^2/\sigma_L)}{1 + 2.34 \phi_s^{0.799} Bo^{-0.0464}} \quad (7)$$

*Details of determining this parameter were described in the previous paper (Koide *et al.*, 1985) and $(d \ln f_B / d \ln C_B)$ was assumed, equal to zero.

Fig. 9 Comparison of ε_G values estimated by Eqs. (7) and (11) with those observed in heterogeneous flow and transition regimes PS: Polystyrene particles

The average error of estimating ε_G by Eq. (7) was within 9.65% for 135 data with $\phi_s \neq 0$. **Figure 9** shows that ε_G estimated by Eq. (7) agree well with those observed.

(2) Transition regime. In an aqueous solution of ethanol with $\phi_s = 0$, the transition regime was observed when $\delta < 2.5 \times 10^{-3}$ m. In this case, the gas holdup data were correlated by modifying Eq. (8) proposed by Koide *et al.* (1984) for air-nonfrothing liquid systems.

$$\varepsilon_{GT} = \varepsilon_{GH} \left[1 + M \exp \left\{ - \left(\ln \frac{U_G}{U_{GC}} \right)^2 \right\} \right] \quad (8)$$

where

$$M = 0.0045 \left(\delta / PN \right)^{-0.682} Bo^{-0.398} Mo^{-0.139} \quad (9)$$

$$\frac{U_{GC} \mu_L}{\sigma_L} = 24.2 \left(\delta / PN \right)^{-0.468} Bo^{-0.521} Mo^{0.384} \quad (10)$$

and ε_{GH} was calculated from Eq. (5). The coefficients of the right-hand sides of Eqs. (9) and (10) are modified ones of the original equations proposed by Koide *et al.* (1984) to fit data for aqueous solutions of ethanol. Eqs. (8)-(10) predict ε_G in the transition regime with an average error of 12.8% for 26 data.

For $\phi_s \neq 0$, Eq. (8) was modified to account for the effect of solid concentration.

Fig. 10 Preliminary correlation of $k_L a$ with parameter of retardation of surface flow of bubble

$$\varepsilon_{GT} = \frac{\varepsilon_{GH} \left[1 + M \exp \left\{ - \left(\ln \frac{U_G}{U_{GC}} \right)^2 \right\} \right]}{1 + 2.18 \phi_s^{1.56}} \quad (11)$$

The error of estimating ε_G using Eq. (11) was within 12.9% for 53 data. Figure 9 shows that ε_G estimated by Eq. (11) agree well with those observed. However, Eq. (11) may apply only to an aqueous solution of ethanol with $C_B = 109$ mol·m⁻³. Further study of the aqueous solutions of other alcohols is necessary to obtain a more generally applicable correlation for the transition regime.

2.3.2. Correlation of $k_L a$.

Figure 2 shows that the addition of alcohols to water increases ε_G but increases or decreases $k_L a$. As ε_G increases, the gas-liquid interfacial area a increases. Hence, the decrease in $k_L a$ might be induced by the reduction of k_L as a result of the retardation of surface flow on bubbles by surface-active substances adsorbed on the gas-liquid interface. Koide *et al.* (1985) and Yamazoe (1986) correlated the degree of this retardation with the parameter $(\Pi k_L / U_s \mu_L) / \sqrt{Re_B^*}$. This degree of retardation was used to explain the reduction in the value of k_L by surfactants such as alcohols. To show how the $k_L a$ is related to the parameter, the ratio $(k_L a \sigma_L / \rho_L D_L g) / (k_L a \sigma_L / \rho_L D_L g)_0$ was plotted against $(\Pi k_L / U_s \mu_L) / \sqrt{Re_B^*}$ in **Fig. 10**. The quantity $(k_L a \sigma_L / \rho_L D_L g)_0$ was calculated from Eq. (12) proposed by Koide *et al.* (1983) and observed values of ε_G .

$$\left(\frac{k_L a \sigma_L}{\rho_L D_L g} \right)_0 = 2.11 Sc^{0.5} Mo^{-0.159} \varepsilon_G^{1.18} \quad (12)$$

Eq. (12) applies to bubble columns with liquids of very low frothing ability and no frothing ability. In the calculation of the ratios plotted in Fig. 10, the physical properties of the alcohol solutions were used. It can be seen in Fig. 10

*The d_B values were calculated from the equation $d_B = (6\delta\sigma_L / \rho_L g)^{1/3}$ and U_B was assumed equal to U_s .

Fig. 11 ε_G vs. $k_L a$

that the ratio tends to unity in the range $(\Pi_{\infty} k_1 / U_s \mu_L) / \sqrt{\text{Re}_B} \leq 10^{-3}$ and decreases in the range $(\Pi_{\infty} k_1 / U_s \mu_L) / \sqrt{\text{Re}_B} > 10^{-3}$.

Figure 11 indicates a strong dependence of $k_L a$ value on ε_G . As can be seen in this figure, slopes of the $k_L a$ versus ε_G lines are about 1.3 for aqueous solutions of alcohols. This does not agree with the value of 1.18 in Eq. (12). Hence, this equation has to be modified to suit the relation between ε_G and $k_L a$ in this work.

Finally, it is noted that $k_L a$ decreases as ϕ_s increases and remains constant with increasing column diameter, while ε_G increases. With these considerations, the correlation equation for $k_L a$ based on data observed with and without using gel particles was obtained as follows:

$$\frac{k_L a \sigma_L}{\rho_L D_L g} = 12.9 Sc^{0.5} Mo^{-0.159} Bo^{-0.184} \varepsilon_G^{1.30} \times \left[0.47 + 0.53 \exp \left(-41.4 \frac{\Pi_{\infty} k_1}{\mu_L U_s} Re_B^{-1/2} \right) \right] \times [1 + 0.62 \phi_s]^{-1} \quad (13)$$

Estimates of $k_L a$ values by Eq. (13) are plotted against experimental values in Fig. 12. The average error of estimating $k_L a$ values by Eq. (13) was within 14.7% for 214 data observed in the heterogeneous flow and transition regimes. As ε_G instead of U_G was used in Eq. (13) $k_L a$ data observed in both flow regimes could be correlated by a single equation, Eq. (13).

2.3.3 Application of correlations of ε_G and $k_L a$ to the slurry of solid particles.

The above correlations of ε_G and $k_L a$ are based on

Fig. 12 Comparison of $k_L a$ values estimated by Eq. (13) with those observed in heterogeneous flow and transition regimes PS.: Polystyrene particles

data obtained by using gel particles as a solid phase. Figures 9 and 12, respectively, show that Eq. (7) predicts well the ε_G values and Eq. (13) the $k_L a$ values for the polystyrene particles-methanol aq. soln. system.

2.4 Comparison of this work with previous ones

Sun *et al.* (1988) and Sun and Furusaki (1989) have given empirical equations for ε_G and $k_L a$ based on data observed in a 0.07 m ϕ bubble column with suspended calcium alginate gels. The values for ε_G and $k_L a$ estimated from their empirical equations are much larger than those observed in this work. The reason for this might be due to the fact that a dimensionless term including the column diameter has been used in their equations, though their experiments were done using only a 0.07 m ϕ column.

Sauer and Hempel (1991) have proposed empirical equations for ε_G and $k_L a$ in a 0.14 m ϕ bubble column with suspended solid particles of various plastics and sand ($\rho_s = 1020-2780 \text{ kg} \cdot \text{m}^{-3}$). The values for ε_G and $k_L a$ estimated from their equation roughly agree with those observed for water and aqueous solutions of hexanol and octanol but are much lower than those observed in aqueous solutions of methanol, ethanol and butanol.

Kelkar *et al.* (1983) have proposed empirical equations of ε_G for $\phi_s = 0$ based on data obtained in columns of diameter 0.14 and 0.3 m. The equation for ε_G predicts relatively well the gas holdups in hexanol and octanol solutions in this work.

Conclusions

Addition of alcohols to water generally increases the gas holdup ε_G . However, values of the volumetric liquid-phase mass transfer coefficient $k_L a$ in aqueous solutions of alcohols become larger or smaller than those in water according to the kind and concentration of the alcohol added to water. It is also shown that the presence of suspended gel-particles in the bubble column reduces values of ε_G and $k_L a$. Based on these observations, empirical equations for ε_G in the transition regime in an ethanol solution, for ε_G in the heterogeneous flow regime applicable to various alcohol solutions and for $k_L a$ in both flow regimes are proposed.

Nomenclature

A	= Hamaker constant	[J]
a	= gas-liquid interfacial area	[m ²]
Bo	= $D^2 g \rho_L / \sigma_L$, Bond number	[-]
Crk^2 / σ_L	= Marrucci parameter	[-]
C	= $\frac{2 C_B}{v R T} \left(\frac{d\sigma_L}{dc_B} \right)^2 \frac{1}{1 + (d \ln f_B / d \ln C_B)} \times \frac{1}{1 + (x_B v_B / x_w v_w)}$	[N]
C_B	= concentration of alcohol	[mol·m ⁻³]
c	= concentration of dissolved oxygen	[mol·m ⁻³]
c_i	= saturated concentration of dissolved oxygen	[mol·m ⁻³]
c_0	= initial concentration of dissolved oxygen	[mol·m ⁻³]
D	= internal column diameter	[m]
D_B	= diffusivity of alcohol in liquid	[m ² ·s ⁻¹]
D_L	= diffusivity of oxygen in liquid	[m ² ·s ⁻¹]
d_B	= bubble diameter	[m]
d_p	= particle diameter	[m]
f_B	= activity coefficient of alcohol	[-]
g	= gravitational acceleration	[m·s ⁻²]
H_F	= aerated slurry height	[m]
H_L	= static slurry height	[m]
k	= $(12\pi\sigma_L/Ar)^{1/3}$	[m]
$k_L a$	= volumetric liquid-phase mass transfer coefficient	[s ⁻¹]
k_1	= $-(d\sigma_L/dc_B)(3U_S r/2D_B)^{1/2}/rRT$	[-]
Mo	= $g\mu_L^4/\rho_L\sigma_L^3$, Morton number	[-]
N	= number of holes in gas distributor	[-]
n	= carbon number of normal alcohol	[-]
P	= pitch of gas distributor hole	[m]
Re_B	= $d_B v_B \rho_L / \mu_L$, Reynolds number	[-]
r	= $d_B/2$, bubble radius	[m]
Sc	= $\mu_L/\rho_L D_L$, Schmidt number	[-]
T	= absolute temperature	[K]
t	= time	[s]
U_B	= bubble rise velocity	[m·s ⁻¹]
U_G	= superficial gas velocity	[m·s ⁻¹]
U_{GC}	= gas velocity when $\varepsilon_{GT}/\varepsilon_{GH}$ is maximum	[m·s ⁻¹]
U_L	= liquid velocity	[m·s ⁻¹]
U_S	= slip velocity	[m·s ⁻¹]
U_T	= terminal velocity of a single bubble	[m·s ⁻¹]
v_B, v_w	= molar volumes of alcohol and water	[m ³ ·mol ⁻¹]
x_B, x_w	= mole fractions of alcohol and water	[-]
δ	= diameter of holes in gas distributor	[m]
ε_G	= gas holdup	[-]
ε_L	= liquid holdup	[-]
ε_S	= solid holdup	[-]
ϕ_S	= $\varepsilon_S/(\varepsilon_S + \varepsilon_L)$, volume fraction of particles in unaerated slurry	[-]
μ_L	= liquid viscosity	[Pa·s]
v	= total number of moles of ions per mole of electrolyte or 1 for non-electrolyte	[-]

Π_∞	= $-C_B (d\sigma_L/dc_B)$, surface pressure	[N·m ⁻¹]
ρ_L	= liquid density	[kg·m ⁻³]
ρ_S	= density of particles	[kg·m ⁻³]
σ_L	= liquid surface tension	[N·m ⁻¹]

<Subscripts>

<i>est.</i>	= estimated value
<i>H</i>	= heterogeneous flow regime
<i>obs.</i>	= observed value
<i>T</i>	= transition regime
0	= without solid particles, and for liquids of no frothing ability or low frothing ability

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