\[ \mu = \text{liquid viscosity} \quad \text{[Pa}\cdot\text{s}] \]
\[ n = \text{total number of moles of ions per mole of electrolyte or } 1 \text{ for non-electrolyte} \quad [-] \]
\[ \rho = \text{liquid density} \quad \text{[kg}\cdot\text{m}^{-3}] \]
\[ \sigma = \text{liquid surface tension} \quad \text{[N}\cdot\text{m}^{-1}] \]

\text{\textit{Literature Cited}}

\text{Presented in part at the 47th Annual Meeting of Society of Chemical Engineers, Japan at Tokyo, April 31, 1982.)

\text{GAS HOLDUP AND VOLUMETRIC LIQUID-PHASE MASS TRANSFER COEFFICIENT IN BUBBLE COLUMN WITH DRAUGHT TUBE AND WITH GAS DISPERSION INTO TUBE}

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The gas holdup \( \varepsilon \) and the volumetric liquid-phase mass transfer coefficient \( k_{\text{La}} \) were studied experimentally in a bubble column with a draught tube and with gas dispersion into the tube. From experimental observation \( \varepsilon \) increases with increasing gas velocity and frothing ability of liquid, while the other properties of the liquid and the column dimensions have a minor effect on \( \varepsilon \). \( k_{\text{La}} \) increases with gas velocity, column diameter, frothing ability of liquid and diffusivity of the dissolved gas, and decreases with increase in \( (D_j/D_i) \). Other dimensions of the column have a minor effect on \( k_{\text{La}} \). Based on these observations, empirical equations for \( \varepsilon \) and \( k_{\text{La}} \) are proposed which are applicable to columns with diameters of 0.1–0.3 m.

At the same gas velocity, \( k_{\text{La}} \) in this column is larger than that in the bubble column and smaller than that in the column with a draught tube and with gas dispersion into the annulus for a liquid with frothing ability.

\text{Introduction}

In the previous paper\(^8\) experimental studies of the gas holdup \( \varepsilon \) and the volumetric liquid-phase mass transfer coefficient \( k_{\text{La}} \) were described for the bubble column with draught tube, in which gas is dispersed into the annulus. On the other hand, the bubble column with draught tube into which gas is dispersed is often used in waste-water treatment, fermentation and chemical processes. In this column a stable circulating liquid flow is induced by the density difference between the aerated liquids in the draught tube and the annulus. This liquid flow enhances the heat transfer between the fluid and the column wall and makes the liquid properties homogeneous in the column. A few research works\(^3\text{–}7\text{,}11\text{) have been carried out in columns of this type. Bohner et al.\(^3\)} and Hirner et al.\(^6\) show that \( \varepsilon \), the flow rate of circulating liquid, and the specific gas-liquid interfacial area increase with increasing gas flow rate. Fukuda et al.\(^4\) have developed a column with draught tube and
multi-stage perforated plates, in which oxygen transfer performance is superior. However, the effects of the liquid properties and the column dimensions on $\varepsilon$ and $k_La$ are not clarified in these works.

The purpose of this study is to clarify experimentally the effects of gas velocity, geometrical dimensions of the column, and liquid properties on $\varepsilon$ and $k_La$ in the bubble column with draught tube into which gas is dispersed.

1. Experimental

The experimental apparatus used in this work is shown in Fig. 1. Four kinds of plexiglass columns with flat bottom were used. Their dimensions are 0.100 m, 0.140 m, 0.218 m and 0.300 m in diameter, and 2.00 m in height. Table 1 shows the dimensions of each draught tube and its height from the base plate. Single nozzles, a perforated plate and a porous glass plate were used as gas distributors. Details of the gas distributors are shown in Table 1. The gas velocity $U_g$ of air was adjusted to 0.013–0.17 m·s$^{-1}$.

The liquids used in this work were demineralized water and aqueous solutions of glycerol, glycol, barium chloride, sodium sulfate and sodium sulfite. The value of the clear-liquid height $H_L$ is shown in Table 1. During each run, liquid was neither fed nor discharged. The operating temperature of liquid was kept at 298.2±0.5 K for the liquids except sodium sulfite aq. soln, which was kept within 298.2±1 K. Table 2 shows the properties of aqueous solutions of glycerol, glycol and sodium sulfite. Those of the other liquids used were shown in the previous paper.8)

The method of determining $\varepsilon$ is the same as that reported in the previous paper.8)

Two different methods were employed for determining $k_La$: one was the physical absorption of oxygen in the air by the liquid and the other was the chemical absorption of oxygen in the air by the aqueous solution of sodium sulfite. The former method is similar to that used in the previous work.8) In the latter the absorption rate of oxygen by 400 mol·m$^{-3}$ sodium sulfite aq. soln was found by measuring the rate of change in the concentration $c_B$ of sodium sulfite. Liquid samples were taken from the column at a certain time interval and $c_B$ was determined with iodometry. A material balance of oxygen in the solution and the stoichiometry of the reaction of sodium sulfite with oxygen give

$$k_La = \frac{1 - e}{2(c_1 - c)} \frac{dc_B}{dt}$$

where the reaction factor is assumed to be 1 as the Hatta number is about 0.1 in this work. Since the gas-film resistance is considered negligible, $c_1$ may be taken as the saturated concentration of oxygen. The concentration $c$ of the dissolved oxygen, measured by a Beckman oxygen meter, was almost constant during a run ($dc/dt \approx 0$). $k_La$ was evaluated from the slope of $c_B$ vs. $t$ line and Eq. (1).

2. Results and Discussion

When air is dispersed into the draught tube, the gas holdup in the draught tube is higher than that in the annulus. Bubble size observed in water was about 4 mm in the annulus and about 10 mm in the draught tube. The number of bubbles entrained into the annulus by the circulating liquid flow increased with increasing $U_g$.

Figure 2 shows that both $\varepsilon$ and $k_La$ increase with increasing $U_g$. No effect of the gas distributor on $\varepsilon$ is observed, but $k_La$ for the single nozzle, the perforated plate and the porous plate decrease slightly in that order.

Figure 3 shows that neither $\varepsilon$ nor $k_La$ is affected by distance $L$ between the lower end of the draught tube and the column base plate in the range of $L/D_t = 1/8–1$.

Figure 4 shows that $\varepsilon$ is slightly higher in the column having larger value of $D_h/D_o$ in the range of
Table 2. Properties of liquids at 298.2K

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$c_i$</th>
<th>$\rho$</th>
<th>$\mu \times 10^3$</th>
<th>$\sigma \times 10^3$</th>
<th>$D \times 10^6$</th>
<th>$(\sigma/\rho c_i) \times 10^6$</th>
<th>$d\ln f_g/d\ln c_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$SO$_4$ aq. soln</td>
<td>400</td>
<td>1043</td>
<td>1.102</td>
<td>73.91</td>
<td>1.97</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>35 vol.% Glycerol aq. soln</td>
<td>4910</td>
<td>1100</td>
<td>2.928</td>
<td>68.39</td>
<td>0.783</td>
<td>-0.848</td>
<td>0.148*</td>
</tr>
<tr>
<td>65 vol.% Glycerol aq. soln</td>
<td>8620</td>
<td>1172</td>
<td>12.77</td>
<td>66.21</td>
<td>0.192</td>
<td>-1.03</td>
<td>0.194*</td>
</tr>
<tr>
<td>70 vol.% Glycol aq. soln</td>
<td>12600</td>
<td>1085</td>
<td>5.339</td>
<td>51.77</td>
<td>0.456</td>
<td>-0.997</td>
<td>-**</td>
</tr>
</tbody>
</table>

* Scatchard et al. (10)
** As reliable data is not available, $d\ln f_g/d\ln c_i = 0$ is assumed.

$U_G > 0.06$ m·s$^{-1}$. This might be due to the fact that for the same $D_o$, the column having large value of $D_l/D_o$ has larger cross-sectional area of the draught tube, where $\varepsilon$ is larger than that in the annulus. In contrast to this, $k_{La}$ decreases slightly with increasing $D_l/D_o$. This might be due to the fact that the column having larger value of $D_l/D_o$ has smaller cross-sectional area of the annulus where the specific gas-liquid interfacial area is larger than that in the draught tube.

Figure 5 shows that when $D_l/D_o$ is constant, the inner diameter $D_o$ of the column has no effect on $\varepsilon$ but that $k_{La}$ increases with increasing in $D_o$. The circulating liquid flow seems more turbulent near the lower end of the draught tube in the larger column from a visual observation of the motion of fine bubbles, and this might enhance the gas-liquid mass transfer. Figure 5 shows that $\varepsilon$ observed by Bohner et al. (3) is slightly higher than that observed in this work in the range of $U_G > 0.04$ m·s$^{-1}$. The reason is that they determined the gas holdup by stopping gas feed and measuring the volume of liquid not overflowed but left in the column, and then measured a maximum value of gas holdup fluctuating very much in the range of $U_G > 0.04$ m·s$^{-1}$.

Figure 6 shows that $\varepsilon$ and $k_{La}$ in BaCl$_2$ aq. soln are not so much different from those in water, and those in Na$_2$SO$_4$ aq. soln are slightly higher than those in water. However, both $\varepsilon$ and $k_{La}$ in Na$_2$SO$_4$ aq. soln are much higher than those in water. The reason might be that in this solution the bubble coalescence is hindered, therefore the bubble size is smaller than that in water and a foam layer is formed on top of the aerated liquid. Figure 6 also shows that clear-liquid height $H_L$ and length of the draught tube $H$ have no effect on $\varepsilon$ and $k_{La}$.

Figure 7 shows that $\varepsilon$ and $k_{La}$ for water in the bubble column with draught tube are nearly equal to those in the column without the tube. Figure 7 also shows that $\varepsilon$ in 35 vol.% glycerol aq. soln and 70 vol.% glycol aq. soln are nearly equal to that in water, but $\varepsilon$ in 65 vol.% glycerol aq. soln is smaller than that in water. In the range of viscosity lower than 65 vol.% glycerol aq. soln, $k_{La}$ decreases with increas-
ing liquid viscosity, as the diffusivity of dissolved oxygen decreases with increasing liquid viscosity. Furthermore, in Fig. 7 ε and k_{Li} in this work are compared to those estimated by the equation of Akita et al.\textsuperscript{2)} for the bubble column without draught tube. The values of ε and k_{Li} for 35 vol.% glycerol aq. soln and those of k_{Li} for 70 vol.% glycol aq. soln are higher than those estimated by the equations of Akita et al.\textsuperscript{2)} The reason might be that these aqueous solutions have relatively high frothing ability.\textsuperscript{8)} Hence bubble coalescence is hindered in these solutions, and in the column with draught tube the small bubbles are forced to circulate with the circulating liquid flow so that the specific gas-liquid interfacial area in k_{Li} becomes large.

The above observations show that ε is affected mainly by the gas velocity and the frothing ability of liquid and slightly by the other liquid properties and (D_i/D_o). As a plot of log ε/(1 - ε)^4 vs. log U_G showed a straight line, the following empirical equation of ε was obtained by the direct search method using the data observed in this work, where the frothing ability of liquid was expressed by Marrucci's parameter\textsuperscript{9)} C_rk^2/σ, *

\begin{equation}
\varepsilon = \frac{0.124}{(1 - \varepsilon)^4} \left\{ \frac{U_G \mu}{\sigma} \left[ \frac{2\rho \sigma^3}{g \mu^2} \right]^{0.294} \left( \frac{D_i}{D_o} \right)^{0.114} \right\}
\end{equation}

and the range of experimental conditions was 1.93 \times 10^{-4} \leq (U_G/\sigma) \leq 2.85 \times 10^{-2}, \quad 1.31 \times 10^{6} \leq (\rho \sigma^3/g \mu^2) \leq 6.04 \times 10^{10}, \quad 0.471 \leq (D_i/D_o) \leq 0.743, \quad 0 \leq (C_rk^2)/\sigma \leq 67.3. The average error in estimating ε by Eq. (2) was 6.2% for 116 data, and Fig. 8 shows that values of ε estimated by Eq. (2) agree well with those observed experimentally. In determining Eq. (2) data observed in sodium sulfite aq. soln were not used, as the sulfite concentration changed during runs. The exponents of ρ, μ, σ and U_G in Eq. (2) are similar to those in the equation of Akita et al.\textsuperscript{2)} for ε in the column without draught tube.

* Details of determining this parameter are shown in the previous paper.\textsuperscript{9)} The functional form of the denominator including this parameter in Eq. (2) is similar to that used in the previous paper\textsuperscript{8)} for ε in the bubble column with draught tube, in which gas is dispersed into the annulus.
The observation above shows that $k_L a$ is affected by $U_g$, the liquid properties, $D_l$ and $D_o$. As Akita et al.\textsuperscript{2)} have shown that a better empirical correlation of $k_L a$ is obtained by using $\varepsilon$ instead of $U_g$ for the bubble column, log $k_L a$ is plotted against log $\varepsilon$ in Fig. 9, which shows straight lines having a slope of 1.36. Therefore, the following empirical equation of $k_L a$ was obtained by dimensional analysis and the least square method, where the exponent of the Schmidt number ($\mu/\rho D$) was assumed to be 0.5 as was done by Akita et al.\textsuperscript{2)}:

$$
\frac{k_L a D_o^2}{D} = 0.477 \left( \frac{\mu}{\rho D} \right)^{0.500} \left( \frac{g D_o^2 \rho}{\sigma} \right)^{0.873} \left( \frac{g D_o^3 \rho^2}{\mu^2} \right)^{0.257} \left( \frac{D_l}{D_o} \right)^{-0.542} \varepsilon^{1.36} \tag{3}
$$

and the range of experimental conditions was $3.69 \times 10^2 \leq (\mu/\rho D) \leq 5.68 \times 10^4$, $1.36 \times 10^4 \leq (g D_o^3 \rho/\sigma) \leq 1.22 \times 10^4$, $2.27 \times 10^8 \leq (g D_o^3 \rho^2/\mu^2) \leq 3.32 \times 10^{11}$, $0.471 \leq (D_l/D_o) \leq 0.743$, $0.037 \leq \varepsilon \leq 0.21$, $0 \leq (Cr / \sigma) \leq 0.003$. The average error in estimating $k_L a$ by Eq. (3) was 13% for 116 data. Figure 10 shows that the estimated values of $k_L a$ by Eq. (3) agree relatively well with those observed experimentally.

Figure 11 shows that for Na$_2$SO$_3$ aq. soln $k_L a$ values observed in this work are larger than those observed by Akita et al.\textsuperscript{1)} in the bubble column with a single nozzle, and slightly smaller than those observed by Fukuda et al.\textsuperscript{4)} in the column with draught tube in which a perforated plate is used. Wang et al.\textsuperscript{11)} measured the oxygen transfer rate in Bacillus subtilis fermentation using glucose as carbon source in the bubble column with draught tube ($D_o = 0.300$ m, $D_l = 0.206$ m). The oxygen transfer rate is about 50% larger than that observed in water in this work with the column of $D_o = 0.300$ m. This difference might be due to the difference in liquid properties.
Fig. 12. Comparison of $\varepsilon$ and $k_{La}$ observed in this work with values observed in bubble column with draught tube and with gas dispersion into the annulus. $D_0 = 0.140 \text{m}$; $D_t = 0.082 \text{m}$; $L/D_t = 1/2$; $H = 1.40 \text{m}$; $H_L = 1.50 \text{m}$.

dispersion into the annulus$^8$ than in the column used in this work, and $k_{La}$ is also larger in the former column than in the latter one for most liquids. The reason is considered to be that bubble coalescence in the section into which gas is dispersed is less frequent for gas dispersion into the annulus than for gas dispersion into the draught tube.

Conclusions

1) The gas holdup $\varepsilon$ in the bubble column with a draught tube into which gas is dispersed increases with increasing gas velocity and frothing ability of the liquid. The other liquid properties and the dimensions of the column have a minor effect on $\varepsilon$. Based on these observations an empirical equation for $\varepsilon$ is proposed which is applicable to columns with diameters of $0.1-0.3 \text{m}$.

2) The volumetric liquid-phase mass transfer coefficient $k_{La}$ in this column increases with increasing gas velocity, column diameter, frothing ability of the liquid and diffusivity of the dissolved gas, and decreases with increasing values of $(D_t/D_0)$. Based on these observations an empirical equation for $k_{La}$ is proposed which is applicable to columns with diameters of $0.1-0.3 \text{m}$.

3) The performance of this column in gas-liquid mass transfer is better than that of the bubble column without draught tube but worse than that of the column with draught tube and with gas dispersion into the annulus, when a liquid with frothing ability is used. However, performance is similar among these three columns for pure liquid such as water which has no frothing ability ($Crk^2/\sigma = 0$).

Acknowledgment

The authors are highly grateful to Asahi Garasu Kogyogijyutsu Shoreikai for generous financial support of this research work. Also, the authors would like to thank Mr. Yoshihiko Kubo and Mr. Shunichi Mase for their assistance during the experimental work.

Nomenclature

- $a$ = specific gas-liquid interfacial area based on aerated liquid volume \([\text{m}^{-1}]\)
- $A$ = Hamaker constant \([\text{J}]\)
- $C$ = \(2c_1 \left( \frac{d e^*}{d e} \right)^2 \frac{1}{\nu R T} \frac{1}{d c_1} \left[ 1 + (d \ln f_j/d \ln c_j) \left[ 1 + (x_1 v_1/x_2 v_2) \right] \right] \left[ \text{J} \right] \)
- $Crk^2/\sigma$ = parameter of bubble coalescence proposed by Murrucci$^9$ \([-\text{]}\)
- $c$ = concentration of oxygen \([\text{mol} \cdot \text{m}^{-3}]\)
- $c_B$ = concentration of sodium sulfite \([\text{mol} \cdot \text{m}^{-3}]\)
- $c_i$ = saturated concentration of oxygen \([\text{mol} \cdot \text{m}^{-3}]\)
- $c_1$ = concentration of component 1 \([\text{mol} \cdot \text{m}^{-3}]\)
- $D$ = diffusivity of dissolved gas \([\text{m}^2 \cdot \text{s}^{-1}]\)
- $D_t$ = inner diameter of draught tube \([\text{m}]\)
- $D_e$ = inner diameter of column \([\text{m}]\)
- $f_i$ = activity coefficient of component 1 \([-\text{]}\)
- $g$ = gravitational acceleration \([\text{m} \cdot \text{s}^{-2}]\)
- $H$ = length of draught tube \([\text{m}]\)
- $H_F$ = level of aerated liquid during operation \([\text{m}]\)
- $H_L$ = clear-liquid height \([\text{m}]\)
- $k$ = \((12\pi \eta/Ar)^{1/3}\) \([\text{m}^{-1}]\)
- $k_L$ = liquid-phase mass transfer coefficient \([\text{m} \cdot \text{s}^{-1}]\)
- $k_{La}$ = volumetric liquid-phase mass transfer coefficient based on aerated liquid volume \([\text{s}^{-1}]\)
- $L$ = distance between lower end of draught tube and base plate of column \([\text{m}]\)
- $N$ = number of pores \([-\text{]}\)
- $R$ = gas constant \([\text{J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}]\)
- $r$ = radius of bubble \([\text{m}]\)
- $T$ = liquid temperature \([\text{K}]\)
- $t$ = time \([\text{s}]\)
- $t_w$ = wall thickness of draught tube \([\text{m}]\)
- $U_0$ = gas velocity based on cross section of column and based on average static pressure in column \([\text{m} \cdot \text{s}^{-1}]\)
- $V_i$ = volume of draught tube \([\text{m}^3]\)
- $V_1, V_2$ = molar volume of components 1 and 2 in liquid \([\text{m}^3 \cdot \text{mol}^{-1}]\)
- $x_1, x_2$ = mole fraction of components 1 and 2 in liquid \([-\text{]}\)
- $\delta$ = pore diameter \([\text{m}]\)
- $\varepsilon$ = average gas holdup \([-\text{]}\)
- $\mu$ = liquid viscosity \([\text{Pa} \cdot \text{s}]\)
- $\nu$ = total number of moles of ions per mole of electrolyte or 1 for non-electrolyte \([-\text{]}\)
- $\rho$ = liquid density \([\text{kg} \cdot \text{m}^{-3}]\)
- $\sigma$ = liquid surface tension \([\text{N} \cdot \text{m}^{-1}]\)

(Subscription)

- est. = estimated value
- obs. = observed value

Literature Cited

GAS-LIQUID MASS TRANSFER IN THE JET REACTOR WITH LIQUID JET EJECTOR

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Liquid-side volumetric mass transfer coefficients and effective gas-liquid specific interfacial areas were measured from the longitudinal distribution of oxygen concentration in gas phase by catalytic sulfite oxidation with air in the spouting and the calm sections, which were the lower and upper regions respectively in the jet reactor with liquid jet ejector.

Both liquid-side volumetric coefficients and effective gas-liquid specific interfacial areas increased with the kinetic energy of the liquid jet, and their values in the spouting section were larger than those in the calm section. Further, effective gas-liquid specific interfacial area showed greater values than in other types of reactors, at a similar power supply per unit reactor volume.

Introduction

In gas-liquid jet reactors with two-phase nozzles such as an ejector, both gas and liquid phases are concentrically introduced and the kinetic energy of the liquid jet is utilized to disperse gas into fine bubbles. Therefore, larger gas-liquid interfacial areas and higher mass transfer rates can be obtained than in other types of reactors. Recently, jet reactors are increasingly used in various industries, such as absorbers of sparingly soluble gases, in waste water treatment, and as fermentors in the production of single-cell protein from biomass.

Up to now, several workers have studied the mass transfer characteristics of jet reactors, i.e., liquid-side volumetric mass transfer coefficients and interfacial areas. All of these studies produced overall values for the entire reactor column. It has been pointed out, however, that the flow regime in the jet reactor varies with liquid flow rate and is divided into different two sections, i.e., the spouting section and the calm section, the border of which is the critical height determined by column diameter. According to our previous works, the characteristics with respect to hydrodynamics and liquid-phase mixing are quite different between these two sections. From these differences it can be presumed that the mass transfer characteristics should be different between the two sections. To design a jet reactor effectively, the difference in mass transfer between the two sections should be clarified, but no works have referred to such a difference.

Analysis of the component in gas or liquid phase at reactor inlet and outlet gives only the overall value for the entire reactor, as in other works. In this work, for the jet reactor with liquid jet ejector, liquid-side volumetric mass transfer coefficients and specific gas-liquid interfacial areas in each flow section were independently determined by measuring the concentration distribution of dissolving gas in gas phase along the jet reactor column. Then the effects of operating variables on such mass transfer characteristics in each flow section were studied and compared with those in other types of gas-liquid reactors.

1. Basic Mass Balances

1.1 Absorption rate

The catalytic oxidation of sodium sulfite solutions