FLOW CHARACTERISTICS OF BUBBLE COLUMN WITH PERFORATED DRAFT TUBE—EFFECTS OF EQUIPMENT DIMENSIONS AND GAS DISPERSION—

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The effects of equipment dimensions and gas dispersion on the flow characteristics of a bubble column with perforated draft tube were experimentally examined. Gas was dispersed into the inner section of the draft tube or into the annular section between the column and the draft tube. Under various combinations of column diameter and diameter and length of the draft tube, the flow pattern was observed and the liquid mixing time, gas holdup and specific gas-liquid interfacial area were measured.

In either gas dispersion, gas and liquid radially flowed through holes in the draft tube, and large bubbles were subdivided into small ones. Gas dispersion into the inner section was more effective in shortening the liquid mixing time. The liquid mixing time was shortened by increasing the ratio of height/column diameter, and was most shortened at a diameter ratio of draft tube/column of about 0.6. Gas dispersion into the annular section was effective in increasing the gas holdup and the interfacial area. The interfacial area was also increased by decreasing the characteristic length of the gas dispersion section.

Introduction

Bubble columns are used as gas absorbers or gas-liquid reactors, and recently they have been employed as biological reactors. When a draft tube is inserted in the column, circulation flows of gas and liquid occur and the gas holdup, bubble diameter, gas-liquid interfacial area and liquid mixing time change. There have been several studies[8,9,12] of the draft tubes contrived to improve bubble column performance.

In the previous study[2], a cylinder made of perforated plate was used as the draft tube of a bubble column and gas was dispersed into the inner section of the draft tube. The diameter and length of the draft tube and the diameter and opening fraction of the holes were changed, and the flow characteristics were measured. It was found that the liquid mixing time became shorter and the gas-liquid interfacial area became larger than those in the column with unperforated draft tube.

Koide *et al.*[5,6] used the unperforated draft tube and reported that the flow characteristics in the case of gas dispersion into the inner section of the draft tube are different from those in the case of gas dispersion into the annular section between the column and the draft tube. The flow characteristics of the column with perforated draft tube are considered to be changed by the method of gas dispersion. The effect of column diameter on the flow characteristics has not yet been examined.

In the present study the column diameter, the diameter and length of the draft tube, and the gas dispersion were changed. The flow pattern was observed, and the liquid mixing time, gas holdup and specific gas-liquid interfacial area were measured.

1. Experimental Apparatus and Procedure

A diagram of the experimental apparatus is shown in **Fig. 1**. The bubble column was made from transparent acrylic resin. The inlet of tracer for the measurement of liquid mixing time was placed near the bottom plate. The sensors for electric conductivity were fitted at three positions of the column wall: the upper end, the middle and the lower end of the draft tube. To disperse gas into the inner section of the draft tube or into the annular section between the column and the draft tube, the gas chamber was installed below the bottom plate. The gas sparger was a perforated plate. This plate had twelve holes of 2 mm diameter (six holes were drilled near the center for gas dispersion into the inner section and the others were drilled near the column wall for gas dispersion into the annular section).

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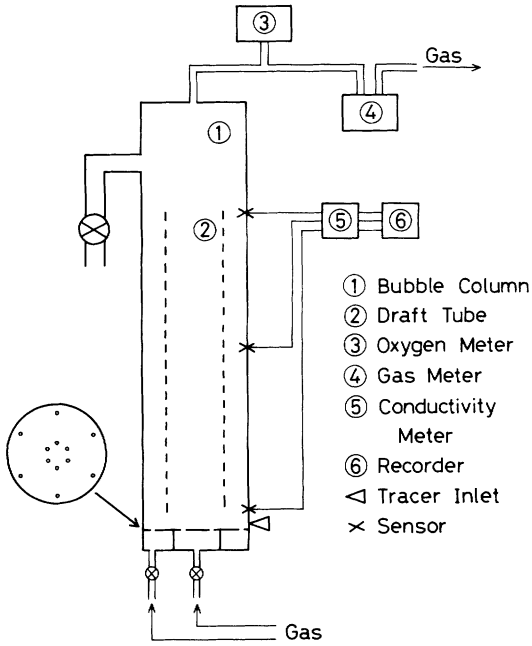

Fig. 1. Experimental apparatus

Cylinders made of stainless steel perforated plate were used as the perforated draft tubes. Based on the results of the previous study[2], a hole diameter of 3 mm and an opening fraction of 37% were selected. The column diameter and the diameter and length of the draft tube are listed in **Table 1**. The distance between the lower end of the draft tube and the bottom plate was 50 mm. The pipe for liquid overflow was installed at a position 250 mm above the upper end of the draft tube. The columns with unperforated draft tube (acrylic resin cylinder) and without draft tube were also used.

Air was used as the gas, and tap water and sodium sulfite aqueous solution were used as the liquid. After the gas flow rate was controlled, the flow pattern in the column was observed. The gas holdup was estimated from the bubble-free liquid height at no aeration.

When the liquid was tap water, the tracer (10 wt% sodium chloride aqueous solution, 5 cm^3) was quickly injected and the time-change of electric conductivity was measured[9]. The liquid mixing time was defined as the time when the vibration of electric conductivity became within $\pm 5\%$ of the steady-state value. After injecting the tracer, no significant change in the flow pattern was observed. The liquid was changed after each measurement.

When the liquid was sodium sulfite solution, the oxygen concentrations in the gas flows at the inlet and the outlet were measured. Assuming that the gas was perfectly mixed in the column, from these concentrations and the gas flow rate the liquid-phase volumetric mass transfer coefficient was estimated. This volumetric coefficient was divided by the mass

Table 1. Dimensions of column and draft tube

D [m]	0.164	0.300
H [m]	1.30–3.30	1.30–3.30
H/D [—]	7.9–20.1	4.3–11
D_D [m]	0.070–0.130	0.130–0.200
D_D/D [—]	0.43–0.79	0.43–0.67
L_D [m]	1.00–3.00	1.00–3.00

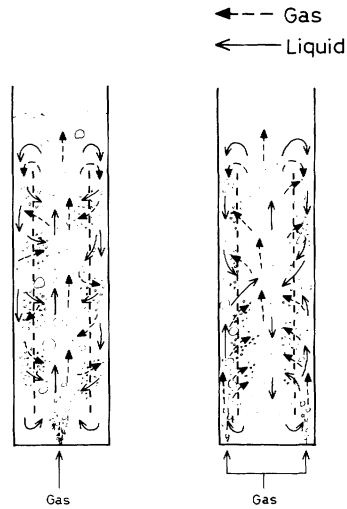

Fig. 2. Model of flow pattern

transfer coefficient and the specific gas-liquid interfacial area was obtained[1]. The concentrations of sodium sulfite and cobalt sulfate (catalyst) were 200–500 $mol \cdot m^{-3}$ and 0.1 $mol \cdot m^{-3}$, respectively. The liquid temperature was 20–22 °C and the pH was 9.4–9.6.

2. Experimental Results and Discussion

2.1 Flow pattern

Models of the flow patterns are shown in **Fig. 2**. The arrows with broken and solid lines show respectively the flows of gas and liquid. The liquid flow was observed by ink tracer.

In the case of gas dispersion into the inner section, gas and liquid flow radially through the holes in the draft tube. Part of the gas flows from the inner section to the annular section. When relatively large bubbles pass through the holes, they are subdivided into small ones. In the annular section, the bubbles were violently mixed by the downflow of a mixture of gas and liquid. The part of the liquid that flows downward in the annular section flows into the inner section.

In the case of gas dispersion into the annular section, the downflow of a mixture of gas and liquid frequently occurs and large coalesced bubbles flow upward locally in the annular section. Mostly gas from the gas sparger flows into the inner section at the lower part of the draft tube. The liquid flow was observed as follows. In the zone below about half the

column height, liquid flows from the annular section into the inner section. In the zone above about half the column height, on the other hand, liquid flows upward in the inner section and flows downward in the annular section.

These flow patterns were the same for the columns of different dimensions.

2.2 Liquid mixing time

The liquid mixing times for the gas dispersions into the inner and annular sections are shown in **Fig. 3**. The abscissa, w_G, is the superficial gas velocity based on the cross-sectional area of the column. The liquid mixing times in the columns with unperforated draft tube and without draft tube are also plotted.

In all cases the liquid mixing time is proportional to about -0.5 power of gas velocity. This is similar to the results of Weiland *et al.*[10] where it is proportional to -0.41 power. When the gas velocity is the same, the liquid mixing time in the column with perforated draft tube is much shorter than in the columns with unperforated draft tube or without draft tube. This is because of the radial flows of gas and liquid, which promote liquid mixing in the column with perforated draft tube. For the perforated draft tube the liquid mixing time is shorter in gas dispersion into the inner section than in gas dispersion into the annular section, because the zone of the radial flows of gas and liquid is wider in the former than in the latter.

The decrement of liquid mixing time in the column with perforated draft tube to that in the column without draft tube ($=1-t_m/t_{mO}$) was examined. Under the present experimental conditions, the liquid mixing time in the column without draft tube, t_{mO}, was expressed by the following equation.

$$t_{mO}=0.40D^{0.8}(H/D)^2 w_G^{-0.5} \qquad (1)$$

$$0.164 \leqq D \leqq 0.300\,\text{m}, \quad 4.3 \leqq H/D \leqq 20$$

As in the previous study[2], the decrement of liquid mixing time was hardly affected by the gas velocity.

The effect of the ratio of height/column diameter, H/D, on the decrement of liquid mixing time is shown in **Fig. 4**. The decrement hardly depends on the gas dispersion and becomes larger as H/D becomes higher. This is because of the higher frequency of radial flows of gas and liquid. No significant effect of column diameter is found.

The effect of the draft tube/column diameter ratio, D_D/D, on the decrement is shown in **Fig. 5**. For both gas dispersions the decrement reaches maximum when D_D/D is about 0.6. For the unperforated draft tube the liquid circulation flow rate is the largest when D_D/D is about 0.6[3,7], and then the liquid mixing time reaches minmum. From this, it is considered for the perforated draft tube that the liquid circulation flow rate was highest when D_D/D was about 0.6 and that the liquid mixing time was governed by the liquid circulation flow rate.

Weiland[11] has reported that the optimum value of D_D/D is 0.9 for the liquid mixing time when gas is dispersed into the inner section of the unperforated draft tube. From the correlation of Kawase *et al.*[4],

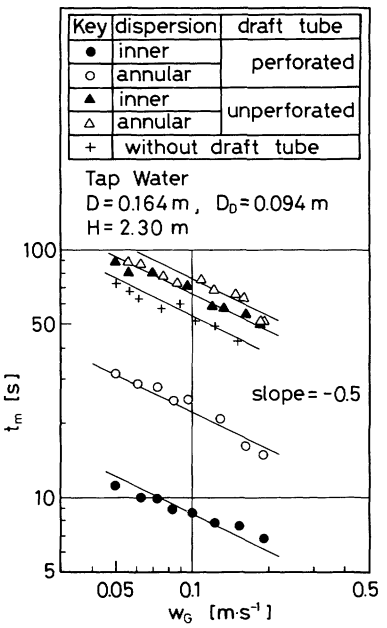

Fig. 3. Effect of gas dispersion on liquid mixing time

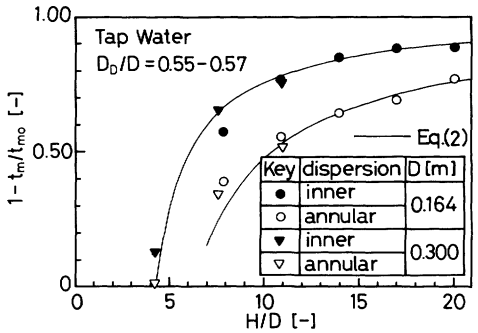

Fig. 4. Plots of decrement of liquid mixing time against ratio of height/diameter of column

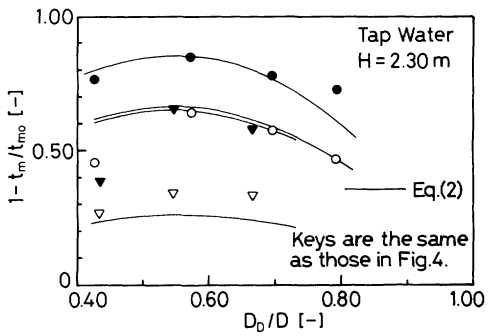

Fig. 5. Plots of decrement of liquid mixing time against diameter ratio of draft tube/column

the optimum value of D_D/D is about 0.8 in the case of gas dispersion into the inner section and about 0.6 in the case of gas dispersion into the annular section. The effect of D_D/D in the column with perforated draft tube coincides with that in gas dispersion into the annular section by Kawase *et al.*

The decrement of liquid mixing time was expressed by the following equation.

$$1-t_m/t_{mO}=4.8[1-c_1(H/D-3)^{-0.8}] \times(D_D/D)^{1.2}(1-D_D/D) \qquad (2)$$

for gas dispersion into inner section:

$$c_1=1.3$$

for gas dispersion into annular section:

$$c_1=2.6$$

$$0.164\leqq D\leqq 0.300\,\mathrm{m}, \qquad 4.3\leqq H/D\leqq 20,$$

$$0.43\leqq D_D/D\leqq 0.79$$

The value of 3 in $(H/D-3)$ might show that the effect of shortening the liquid mixing time by the perforated draft tube does not appear when H/D is too small. The curves calculated by Eq. (2) are shown in Figs. 4 and 5. The calculated results from Eqs. (1) and (2) agreed with the experimental data within an error of $\pm 25\%$.

2.3 Gas holdup and specific gas-liquid interfacial area

The gas holdup and the specific gas-liquid interfacial area are shown in **Fig. 6**. The liquid is sodium sulfite aqueous solution. Whether the perforated or unperforated draft tube is used, the gas holdup is higher when gas is dispersed into the annular section rather than into the inner section. This agrees with the results for the column with unperforated draft tube of Koide *et al.*[5,6]. When gas is dispersed into the inner section, the gas holdup in the column with perforated draft tube is lower than that in the column with unperforated draft tube. In the column with perforated draft tube, part of the gas flows from the inner section to the annular section and the gas velocity in the inner section becomes lower. The gas holdup is considered to fall because of lower gas velocity in the inner section. When gas is dispersed into the annular section the tendency is the opposite. This reason is considered to be that the gas upflow is restrained by the downflow in the annular section and the complex liquid flow in the column. These trends were the same when the combination of equipment dimensions was changed or when tap water was used.

The specific gas-liquid interfacial areas in the columns with perforated or unperforated draft tubes are larger in the case of gas dispersion into the annular section than in the case of gas dispersion into the inner section. For both gas dispersions,

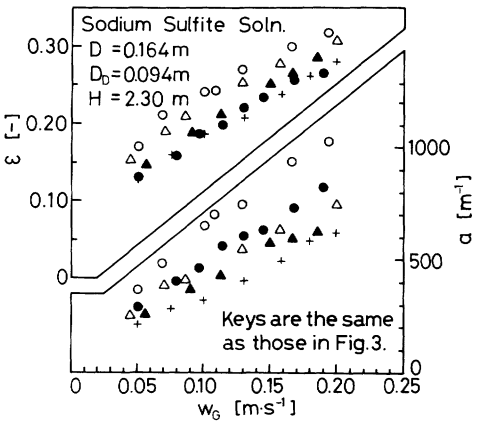

Fig. 6. Effect of gas dispersion on gas holdup and specific gas-liquid interfacial area

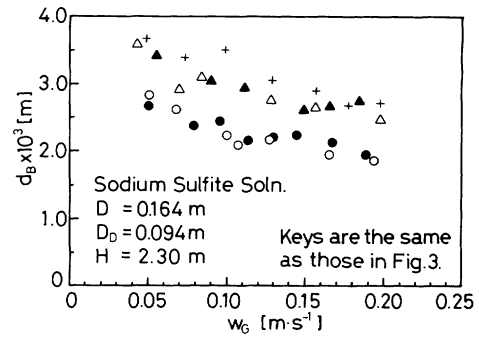

Fig. 7. Bubble diameter estimated from gas holdup and specific gas-liquid interfacial area

the gas-liquid interfacial area in the column with perforated draft tube is larger than that in the column with unperforated draft tube, though the gas holdup in the former is lower than that in the latter in the case of gas dispersion into the inner section. These trends are considered to be due to the difference in bubble diameter. The bubble diameter was estimated from the following equation.

$$d_B=6\varepsilon/a \qquad (3)$$

The estimated value of bubble diameter is shown in **Fig. 7**. In all cases, it decreases with increasing gas velocity. When the gas velocity is the same, the bubble diameter in the column with perforated draft tube is smaller than that in the column with unperforated draft tube. This is because of bubble subdivision through the holes. For the perforated draft tube, no significant effect of the gas dispersion on the bubble diameter is found. From this, it is considered that the difference in gas-liquid interfacial area between the two gas dispersions depends on the difference of gas holdup.

The increment of specific gas-liquid interfacial area in the column with perforated draft tube to that in the column without draft tube $(=a/a_O-1)$ was examined. It was hardly affected by gas velocity.

Under the present experimental conditions the gas-liquid interfacial area in the column without draft tube, a_O, was independent of the diameter and height of the column, and was expressed by the following equation.

$$a_O = 1900 w_G^{0.74} \qquad (4)$$
$$0.164 \leqq D \leqq 0.300\,\text{m}, \quad 4.3 \leqq H/D \leqq 20$$

The effect of H/D on the increment of specific gas-liquid interfacial area is shown in **Fig. 8**. The increment increases with increasing H/D because the frequency of bubble subdivision becomes higher. When H/D is the same, as the column diameter becomes larger the bubbles become harder to be subdivided and the increment becomes slightly lower.

The effect of D_D/D on the increment is shown in **Fig. 9**. From the data of the 0.164-m column, the following facts are found. When gas is dispersed into the inner section, the increment decreases with increasing D_D/D. When gas is dispersed into the annular section, the increment increases with increasing D_D/D. But it decreases sharply when D_D/D exceeds about 0.7. For the data of the 0.300-m column, a similar trend is imaginable. From these facts, it is considered that the frequency of bubble subdivision depends on the characteristic length of the gas dispersion section. Here, the characteristic length was regarded as the draft-tube diameter for gas dispersion into the inner section, and the length of the clearance between column and draft tube for gas dispersion into the annular section.

As shown in **Fig. 10**, the increment is plotted against the characteristic length of the gas dispersion section. For the 0.164-m column, the increment becomes maximum when the characteristic length is 0.02–0.03 m, and decreases with increasing characteristic length when the characteristic length exceeds these values. No significant effect of gas dispersion on the increment is found. The data of the 0.300-m column shows the same trend.

The increment of gas-liquid interfacial area was expressed by the following equation. The data were excluded for characteristic lengths below 0.02 m.

for 0.164-m column:

$$a/a_O - 1 = 0.090(H/D - 4)^{0.4}(L_C/D)^{-0.8} \qquad (5)$$

for 0.300-m column:

$$a/a_O - 1 = 0.096(H/D - 4)^{0.4}(L_C/D)^{-0.6}$$
$$4.3 \leqq H/D \leqq 20, \qquad 0.20 \leqq L_C/D \leqq 0.80$$

The curves calculated by Eq. (5) are shown in Figs. 8 and 10. The calculated results from Eqs. (4) and (5) agreed with the experimental data within an error of $\pm 20\%$.

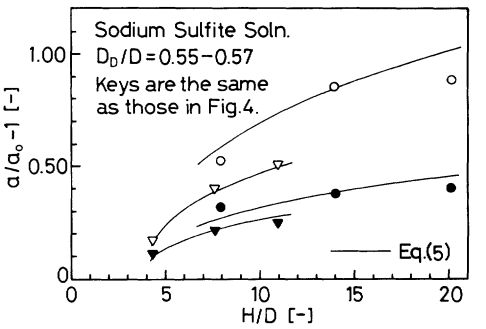

Fig. 8. Plots of increment of specific gas-liquid interfacial area against ratio of height/diameter of column

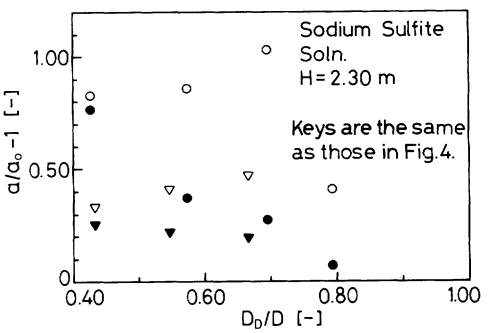

Fig. 9. Plots of increment of specific gas-liquid interfacial area against diameter ratio of draft tube/column

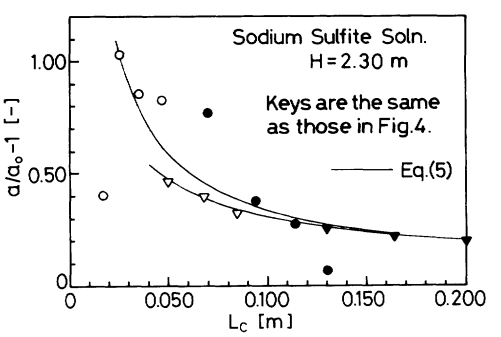

Fig. 10. Plots of increment of specific gas-liquid interfacial area against characteristic length

Conclusion

Flow characteristics of the bubble column with perforated draft tube were experimentally examined. The following facts were clarified.

(1) For gas dispersions into both the inner and annular sections, radial flows of gas and liquid occur and large bubbles are subdivided into small ones when they pass through the holes in the draft tube.

(2) Gas dispersion into the inner section is effective in shortening the liquid mixing time. The decrement of liquid mixing time increases with increasing H/D and reaches maximum when D_D/D is about 0.6.

(3) Gas dispersion into the annular section is effective in increasing the gas holdup and the specific gas-liquid interfacial area. The increment of gas-

liquid interfacial area is strongly dependent on the characteristic length of the gas dispersion section.

Nomenclature

a	=	specific gas-liquid interfacial area	[m^{-1}]
D	=	inner diameter of column	[m]
D_D	=	inner diameter of draft tube	[m]
d_B	=	bubble diameter ($=6\varepsilon/a$)	[m]
H	=	column height	[m]
L_C	=	characteristic length	[m]
L_D	=	draft tube length	[m]
t_m	=	liquid mixing time	[s]
w_G	=	superficial gas velocity based on cross-sectional area of column	[$m \cdot s^{-1}$]
ε	=	gas holdup	[—]

〈Subscript〉

O	=	without draft tube

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