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GAS ABSORPTION IN A MULTI-STAGE GAS-LIQUID SPOUTED VESSEL

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Key Words: Multi-Stage Gas-Liquid Spouted Vessel, Perforated Plate, Gas Absorption Coefficient, Gas Holdup, Bubble Size Distribution, Bubbling Column, Aerated Mixing Vessel

Gas holdup, bubble size distribution and gas absorption capacity coefficient in a multi-stage gas-liquid spouted vessel are observed in this study and it is confirmed that coalescence of gas bubbles observed in the calm uniform-flow section in a single-stage spouted vessel can be avoided by introduction of perforated plates.

Experimental results show that effect of physical properties of liquid on the capacity coefficient in a spouted vessel is more similar to that observed in an aerated mixing vessel than to that of a bubbling column.

It is also observed that the gas absorption coefficient is proportional to the square root of the Sauter mean bubble diameter.

Introduction

In the gas-liquid spouted vessel, where power is supplied from a pump to the liquid and the gas is introduced at a nozzle attached to the bottom of the vessel, gas bubbles are finely broken at the nozzle outlet and dispersed into the vessel as reported by Nishikawa *et al.*[8-10] Due to the large liquid energy concentrated at the nozzle and the strong turbulence in the vessel, the liquid-phase spouted vessel is highly effective in fluidizing or dissolving solid particles[6,7] and dispersing gas bubbles because of the choking effect at the outlet of a spouting nozzle.[8,10] It was also reported by Nishikawa *et al.* that a large gas holdup and a large capacity coefficient were easily obtained in the gas-liquid or the solid-gas-liquid spouted vessel.[9] However, in the calm uniform-flow section of a large-scale gas-liquid spouted vessel some bubbles eventually coalesce, lowering local gas holdup and consequently local capacity coefficient. This effect can be excluded by proper placing of spouting nozzles or multi-stage spouted vessels. This report is about gas holdup, bubble size and gas absorption capacity coefficient in a multi-stage gas-liquid spouted vessel where the calm uniform-flow section of the vessel is divided into several sections by perforated plates, and various performances observed for the multi-stage spouted vessel are compared with those obtained for the ordinary single-stage spouted vessel or the bubbling column.

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1. Experimental Apparatus

A sketch of the experimental apparatus used in this study is shown in **Fig. 1**. The process liquid is circulated through a pump from the overflow section to the spouting nozzle attached to the bottom of the vessel. The process gas is supplied from a cylinder to the upper part of the spouting nozzle. The vessel is made of PVC resin of 5 mm thickness and the vessel diameter is 10 or 15 cm. A three-stage vessel with a 60° cone at the bottom is used as for the multi-stage

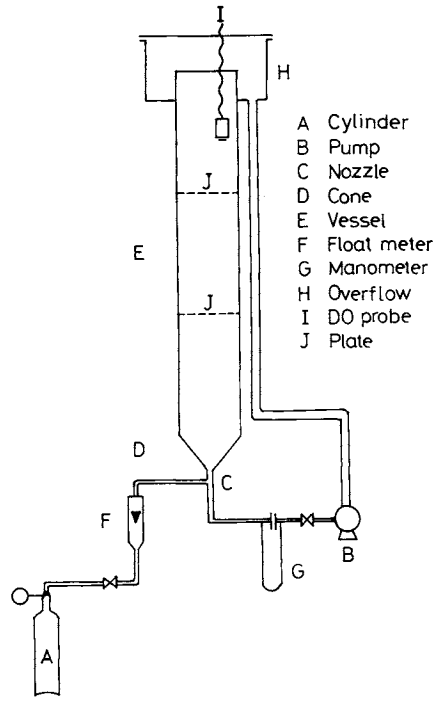

Fig. 1. Schematic diagram of experimental apparatus.

Table 1. Vessel configuration, gas and liquid flow rates in this work

	Tower (1)	Tower (2)
Vessel diameter (D) [cm]	15	10
Nozzle diameter (d_n) [cm]	1.5	1.0
Vessel height (H) [cm]	140	115
Cone angle (θ)[°]	30	60
Hole diameter (d_h) [cm] and number of holes	$0.5^{\phi}\times 9$, $0.75^{\phi}\times 9$	$0.8^{\phi}\times 9$, $0.5^{\phi}\times 9$ $0.3^{\phi}\times 9$
Distance of plate [cm]	40	35
Gas flow rate (G) [cm^3/s]	83.3–1200	50–500
Liquid flow rate (L) [cm^3/s]	0–517	0–200

Table 2. Physical properties of liquid

	ρ [g/cm^3]	σ [g/s^2]	$D_L\times 10^5$ [cm^2/s]	μ [g/cm·s]
Water	0.995	71.0	2.63	0.008
10% Sugar solution	1.05	71.0	2.18	0.0107
20% Sugar solution	1.10	71.0	1.69	0.0160
30% Sugar solution	1.15	71.0	1.21	0.0255
40% Sugar solution	1.20	71.0	0.79	0.0475
50% Sugar solution	1.25	71.0	0.45	0.102
1% CMC solution	1.00	68.4	2.34	0.215

vessel, and each stage is divided by perforated plates with 9 holes of 3, 5 or 8 mm diameter. Details of vessel configurations are listed in **Table 1**.

2. Experimental Methods

Gas absorption capacity coefficient k_La was measured by tracing the change in dissolved oxygen concentration in the liquid using an oxygen electrode assuming perfect mixing in the vessel liquid, consulting the result reported elsewhere.[11] The time lag of the oxygen electrode in response was 5.2 seconds and it required correction when k_La was larger than $0.1\,s^{-1}$ as discussed previously.[12] Details of k_La measurement were reported in the previous paper by the present authors.[9,12,13] Photographs of gas bubbles were taken at a middle point between perforated plates through a square window to eliminate errors due to the curvature of the vessel wall. The gas holdup in the vessel was measured using the shutdown method, where the gas holdup was estimated from the liquid level under operation and that obtained after swift shutdown of liquid pumping and aeration. In estimation of the gas holdup, the foam layer was included in the gas-liquid mixture, though the void space was not.

As for process liquids, tap water, dilute CMC solutions, and 10–60% sugar solutions were used. Their physical properties are listed in **Table 2**. As for process gas, air or nitrogen from a gas cylinder was used.

The liquid temperature was controlled at 30°C using a heat transfer coil placed in the overflow section.

3. Results and Discussion

3.1 Gas holdup

Change in the state of the bubble dispersion in the vessel from the bubbling column condition to the multi-stage gas-liquid spouted vessel condition through the multi-stage bubbling column condition with increase of liquid flow rate is schematically shown in **Fig. 2**. The corresponding change in average gas holdup in the vessel is shown in **Fig. 3**. At a liquid flow rate smaller than 16.7 cm^3/s for a 10-cm vessel (0.21 cm/s in superficial gas velocity), a void space appears under each perforated plate and the gas holdup is the same as that observed for the bubbling column with a single-nozzle sparger. When the liquid flow rate is increased further, a foam layer occupies the space as shown in case (2) of Fig. 2 and the gas holdup changes with liquid flow rate as the manner shown in Fig. 3. At a liquid flow rate larger than the critical liquid flow rate for spouting, which is correlated by the present authors elsewhere,[8] the state of the bubbles in the vessel is drastically changed. Both bubbles smaller than one to two mm in diameter and bubbles larger than four to five mm disappear and the bubble sizes are equalized to a diameter of about 3 mm. The gas holdup in the vessel is also increased again at a liquid flow rate larger than the critical liquid flow rate for spouting, as shown in Fig. 3.

The gas holdup observed in the multi-stage spouted vessel is compared with that observed in the ordinary

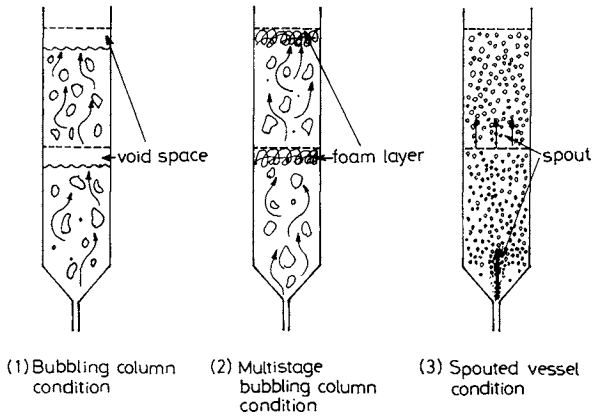

Fig. 2. State of bubble dispersion in a multi-stage gas-liquid contactor.

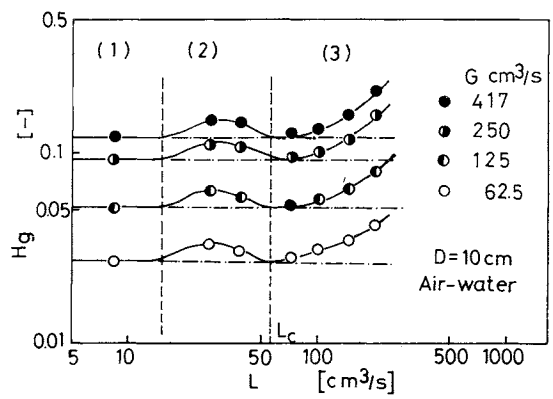

Fig. 3. Gas holdup and liquid flow rate (tower (2), d_h= 0.5 cm).

single-stage vessel in **Fig. 4**. The estimated gas holdup for the single-stage spouted vessel using the correlative equation by the present authors[8] shows good agreement with observed values for the multi-stage spouted vessel, as shown in this figure, though a large difference is observed in the multi-stage bubbling column condition before spouting occurs because of the appearance of the foam layer under the perforated plates. It was also observed in this study that the local gas holdup in each section divided by the perforated plates gives almost the same value, though 10 to 25% smaller gas holdup than the average value is obtained in the upper part of the calm uniform-flow section of the ordinary single-stage spouted vessel.[8]

For the perforated plates with 9 holes of 3 mm diameter, a gas holdup about 5% larger than that obtained for perforated plates with 5-mm holes was obtained in the multi-stage spouted vessel condition. However, the load on the pump to circulate liquid in this case becomes larger and some intermittent spouting motion is superimposed on the steady spouting motion when the liquid flow rate is increased beyond a certain value. As similar phenomena were observed for an ordinary spouted vessel with a narrow nozzle, too small an opening cannot be recommended. When

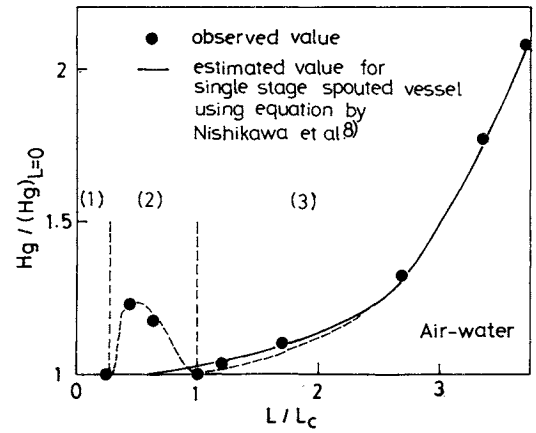

Fig. 4. Gas holdup in a multi-stage gas-liquid spouted vessel (tower (2), d_h=0.5 cm).

perforated plates with 8-mm holes are used, the local gas holdup in the section becomes smaller because of the ineffective readispersion of gas bubbles from the perforated plates, though a larger gas holdup is still obtained than that obtained in the upper part of the calm uniform-flow section of the ordinary spouted vessel.

These observations imply that attachment of perforated plates with proper holes can solve the problem of coalescence of gas bubbles in the calm uniform-flow section of the spouted vessel to maintain a larger gas holdup or gas absorption capacity coefficient in a gas-liquid or a solid-gas-liquid spouted vessel.

3.2 Bubble diameter and specific surface area

It was previously reported by the present authors[10] that the bubble size distribution in the gas-liquid spouted vessel is shown by the normal distribution as

$$f(X)=\exp[-(X-d_m)^2/2\sigma^2]/\sigma\sqrt{2\pi} \qquad (1)$$

where d_m and σ are arithmetic mean bubble diameter and standard deviation in the bubble size distribution, respectively.

It is observed in this study that d_m for the multi-stage spouted vessel is 10–20% smaller than that for the ordinary spouted vessel and that the dimensionless variance $(\sigma/d_m)^2$ is only about 0.01 at most in the multi-stage spouted vessel. Eguchi *et al.*[4] stated that a drop population can be treated as one of uniform size in considering the mass transfer from droplets in an extraction column if the dimensionless variance of gas bubbles is less than about 0.03. Accordingly, a bubble population in the multi-stage spouted vessel can be treated as one of uniform size and the same value for the arithmetic mean bubble diameter can be used also for the Sauter mean bubble diameter.

Change of the Sauter mean bubble diameter in the multi-stage spouted vessel with the superficial gas velocity is shown in **Fig. 5** and compared with that observed in the bubbling column.

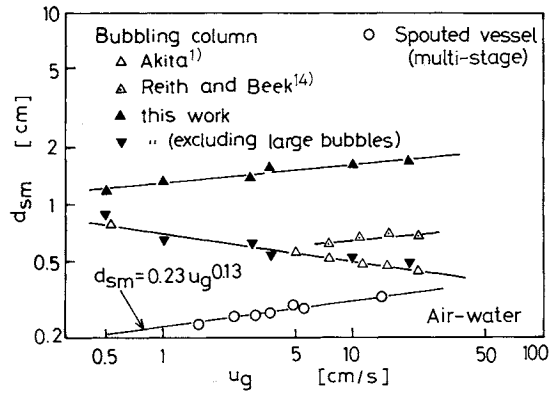

Fig. 5. Sauter mean bubble diameter and superficial gas velocity.

The following equation is obtained for the air-water system multi-stage spouted vessel with perforated plates having 5-mm holes in this work.

$$d_{sm}(=d_m)=0.23u_g^{0.13} \tag{2}$$

It is also seen from Fig. 5 that the exponent of 0.13 is also applied for the bubbling column with a single-nozzle sparger when all gas bubbles are counted in estimation of the Sauter mean bubble diameter. The Sauter mean bubble diameter in a bubbling column with a single-nozzle sparger, however, decreases with increasing superficial gas velocity when large gas bubbles of which frequency of appearance is about 0.1–0.5% in number are excluded in counting.

The specific surface area obtained for the multi-stage spouted vessel from photographic pictures of the bubble swarm and the gas holdup observed using Eq. (3) is compared with that obtained in the single-stage spouted vessel or the bubbling column with a single-nozzle sparger in **Fig. 6**.

$$a=6H_g/d_{sm} \tag{3}$$

It can be seen from this figure that the specific surface area of gas bubbles in the multi-stage spouted vessel is about 20% larger than that in the ordinary single-stage spouted vessel of the same superficial liquid and gas velocities, and that values of one-tenth to one-third for the multi-stage spouted vessel are observed for the bubbling columns by Akita,[1)] Reith and Beek[14)] and Nishikawa *et al.* in this work.

3.3 Gas absorption capacity coefficient

Figures 7 and **8** show change of the gas absorption capacity coefficient k_La with liquid or gas flow rate in the multi-stage spouted vessel. As in the case of the gas holdup, k_La gives slightly larger values in the multi-stage bubbling column condition than in the bubbling column condition and k_La decreases with increasing liquid flow rate to the critical liquid flow rate for spouting in the same manner observed for the gas holdup. Above the critical liquid flow rate for

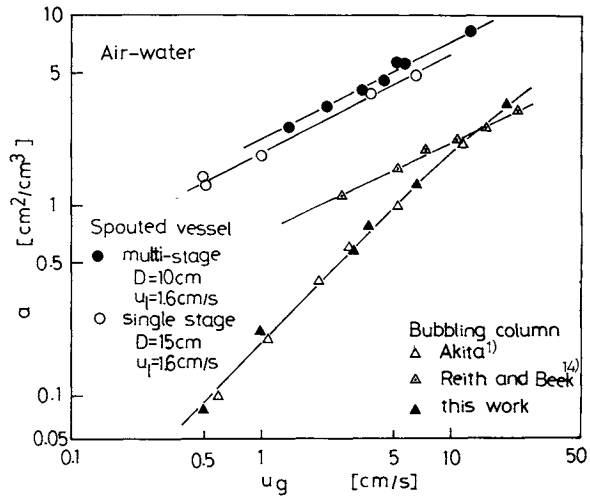

Fig. 6. Specific surface area and superficial gas velocity.

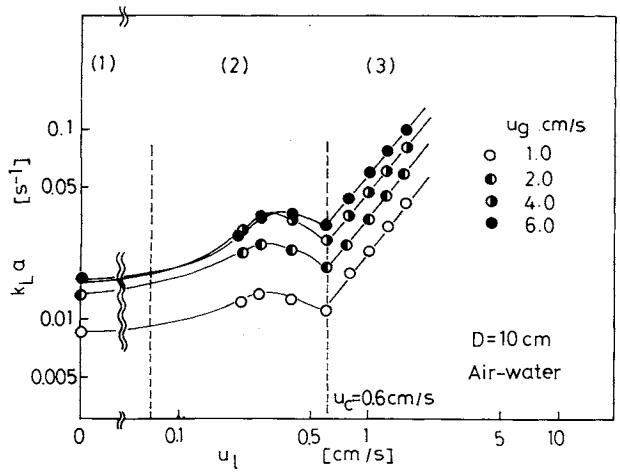

Fig. 7. Gas absorption capacity coefficient and superficial liquid velocity (tower (2), $d_h=0.5$ cm).

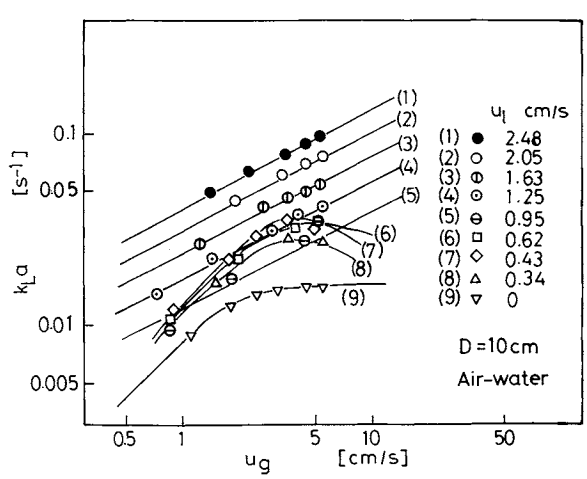

Fig. 8. Gas absorption capacity coefficient and superficial gas velocity (tower (2), $d_h=0.5$ cm).

spouting, k_La increases in proportion to $u_l^{1.2}$ and $u_g^{1/2}$ in the range of this work.

k_La for the multi-stage spouted vessel is compared with values obtained for the ordinary single-stage

spouted vessel or the bubbling column in **Fig. 9**. This figure shows that k_La in bubbling columns are about 1/3–1/5 of those obtained for the multi-stage spouted vessel in the range of liquid flow rate shown in Fig. 9. It can be also seen from this figure that k_La for the multi-stage spouted vessel is 25% larger than k_La obtained in the ordinary spouted vessel, though the specific surface area in the multi-stage spouted vessel is 20% larger.

k_La values obtained when the concentration of sugar solution is changed are shown in **Fig. 10**, and the effect of physical properties on k_La for the multi-stage gas-liquid spouted vessel is shown as follows.

$$k_La=14.7\mu^{-1/2}D_L^{1/2}\sigma^{-1/2}\rho u_g^{1/2}u_l^{1.2} \qquad (4)$$

where μ, D_L, σ and ρ are liquid viscosity, liquid-phase diffusivity, surface tension and specific weight of liquid, respectively.

The effect of various physical properties on k_La for the gas-liquid spouted vessel is more similar to that of the aerated mixing vessel than to that of the bubbling column as compared in **Table 3**.

The gas absorption coefficient k_L is plotted against the Sauter mean bubble diameter in **Fig. 11**, and k_L in the multi-stage and ordinary spouted vessels is given by the following equation.

$$k_L=0.091d_{sm}^{1/2} \qquad (5)$$

It is also seen from this figure that k_L values for the spouted vessel is much larger than those obtained for a single gas bubble by several authors,[2,3,5] although bubbles in the spouted vessel rise in the vessel liquid independently. This effect may be due to the turbulence in the liquid, considering that the almost tendency is observed in effects of physical properties on k_La in the spouted vessel and the aerated mixing vessel as compared in Table 3. A slope of 1/2 was also observed in the aerated vessel with a vibrating disc by Tojo[15] in which strong turbulence in the liquid was expected.

The relation of k_L to the Sauter mean bubble diameter in the bubbling column in this work becomes almost the same as that reported by Akita when the Sauter mean bubble diameter is estimated (excluding the large gas bubbles) as

$$k_L=0.05d_{sm}^{1/2} \quad \text{for bubbling column (excluding large gas bubbles)} \qquad (6)$$

The slope, however, becomes 2 when all bubbles are counted in estimation of d_{sm} as follows.

$$k_L=0.045d_{sm}^{2} \quad \text{for bubbling column (including all gas bubbles)} \qquad (7)$$

Almost the same relation is obtained by Reith and Beek,[14] as shown in Fig. 11.

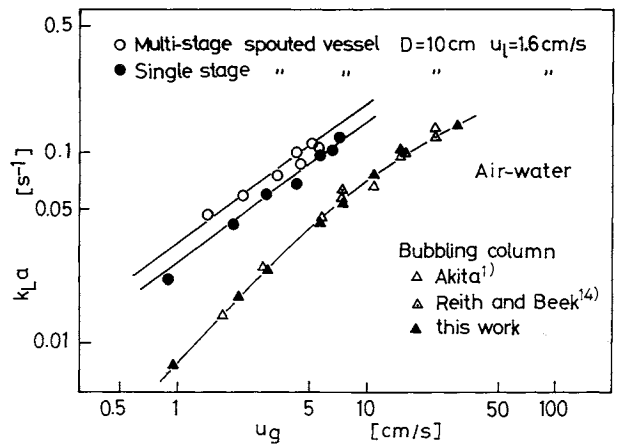

Fig. 9. Comparison of capacity coefficient for various gas-liquid contactors.

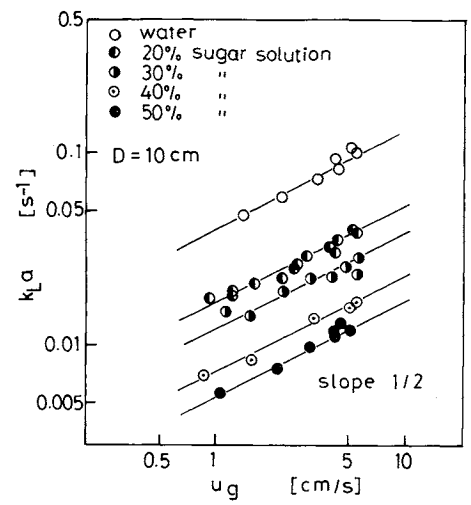

Fig. 10. Capacity coefficient in a multi-stages spouted vessel with various process liquids (tower (2), d_h=0.5 cm).

Table 3. Exponents observed for physical properties, superficial gas velocity and liquid velocity on correlation of k_La

	μ	D_L	σ	ρ	u_g	u_l
Gas-liquid spouted vessel	−0.5	0.5	−0.5	1.0	0.5	1.2
Bubbling column	−0.3	0.5	−0.7	1.0	1.0	0
Aerated mixing vessel	−0.5	0.5	−0.5	1.0	0.33	0

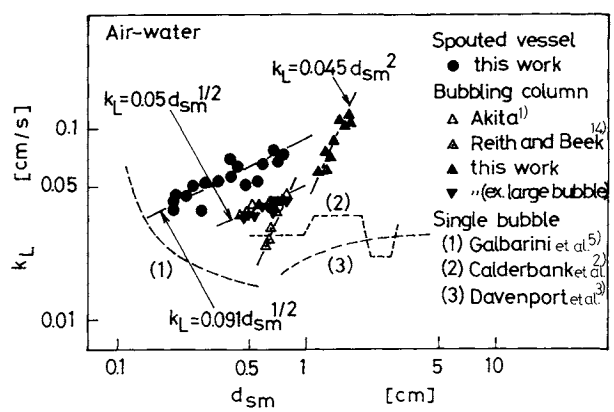

Fig. 11. Gas absorption coefficient and Sauter mean bubble diameter.

In any case, k_L for the spouted vessel is at least as large as twice of k_L in the bubbling column at the same d_{sm} value.

It can be said from above observations that the difference in k_La for the multi-stage spouted vessel and the ordinary spouted vessel is mainly due to the larger specific surface area of gas bubbles in the multi-stage spouted vessel. However, the effect of renewal of the mass transfer surface at redispersion from the perforated plates may cause a small increase in k_La, about 5%, in the multi-stage spouted vessel because k_La for the multi-stage spouted vessel is about 25% larger, though the specific surface area is 20% larger, as stated above. Considering experimental errors, however, it is difficult to distinguish the difference in the plot in Fig. 11.

The manner of change in bubble dispersion state in the vessel from the bubbling column condition to the multi-stage spouted vessel condition through the multi-stage bubbling column condition as observed in this study can be varied with configurations of vessel and plate, gas and liquid velocities, and liquid properties. Accordingly, further studies are needed to understand the phenomena in the multi-stage spouted vessel or the multi-stage bubbling column.

Conclusions

By introduction of perforated plates in the calm uniform-flow section of the gas-liquid spouted vessel, coalescence of gas bubbles in the large-scale gas-liquid spouted vessel is excluded. The gas absorption capacity coefficient for the multi-stage spouted vessel is about 25% larger than that obtained for the ordinary single-stage spouted vessel, though the values of gas holdup show almost no difference.

The relationship between the gas absorption coefficient and the Sauter mean bubble diameter was also obtained.

Nomenclature

a	=	specific surface area	[cm]
d_h	=	hole diameter in perforated plate	[cm]
d_m	=	arithmetic mean bubble diameter	[cm]
d_n	=	nozzle diameter	[cm]
d_{sm}	=	Sauter mean bubble diameter	[cm]
D	=	vessel diameter	[cm]
D_L	=	diffusion coefficient	[cm^2/s]
G	=	gas flow rate	[cm^3/s]
H	=	vessel height	[cm]
H_g	=	gas holdup	[—]
k_L	=	gas absorption coefficient	[cm/s]
k_La	=	gas absorption capacity coefficient	[s^{-1}]
L	=	liquid flow rate	[cm^3/s]
L_c	=	critical liquid flow rate for spouting	[cm^3/s]
u_c	=	critical liquid velocity for spouting	[cm/s]
u_g	=	superficial gas velocity	[cm/s]
u_l	=	superficial liquid velocity	[cm/s]
μ	=	liquid viscosity	[g/cm·s]
σ	=	surface tension [g/s^2] or standard deviation	[cm]
ρ	=	liquid density	[g/cm^3]

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