MEASUREMENT OF BEHAVIOR OF GAS BUBBLES AND GAS HOLDUP IN A SLURRY BUBBLE COLUMN BY A DUAL ELECTRORESESTIVITY PROBE METHOD

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Key Words: Chemical Reactor, Slurry Bubble Column, Bubble Column, Bubble Length Distribution, Bubble Velocity Distribution, Gas Holdup

Bubble properties such as gas holdup, bubble frequency, bubble length and bubble rising velocity in a slurry bubble column were measured by using a dual electroresistivity probe method.

The radial distribution of local gas holdup, εg, was parabolic in the range, where mean solid holdup, εs, was less than 0.2. In the range of εs ≥ 0.2, however, εg in the region of dimensionless radius, r/Rc, from 0.4 to 0.8 decreased considerably owing to the concentration of bubbles in the central region of the column. The value of cross-sectionally averaged gas holdup, εg, agreed fairly well with that predicted by Koide’s equation for heterogeneous flow in a slurry bubble column.

The cumulative bubble length distribution, Fd, followed a log-normal distribution. On the other hand, the cumulative bubble rising velocity distribution, Fv, followed a normal distribution. The superficial gas velocity, Ug, had little effect on Fd and Fv in the slurry bubble column with high solid content.

When Ug was larger than about 4 cm/s, the median of Fd and that of Fv in the slurry bubble column were larger than the corresponding values in the bubble column. On the other hand, the variance of Fd in the slurry bubble column was almost the same as that in the bubble column and the variance of Fv in the slurry bubble column was smaller than that in the bubble column.

Introduction

Slurry bubble columns are widely used as chemical reactors for various processes in industrial practice. Many research works have been conducted on hydrodynamic characteristics including axial distribution of suspended solids,2,8,12,17,18 gas holdup8,11,12 and liquid mixing6,8 and gas-liquid mass transfer7,9,11 in slurry bubble columns. Recently, the authors23) have investigated the effect of solid concentration on the volumetric liquid-phase mass transfer coefficient, kLa, and on the axial distribution of solid holdup in the slurry bubble column with a gas-liquid concurrent upflow system.

Bubble properties such as bubble size, bubble rising velocity and gas holdup are very important in analyzing hydrodynamics and gas-liquid mass transfer in the slurry bubble column. A limited amount of data, however, has been presented concerning the bubble diameter9,12 in the slurry bubble column.

The purpose of this work is to investigate the fundamental properties of gas bubbles such as gas holdup, bubble frequency, bubble size distribution and bubble rising velocity distribution in the slurry bubble column. The bubble properties were measured by using a dual electroresistivity probe method.4,5,10,13,14,15,16,19,21,22)

1. Experimental

1.1 Experimental apparatus

Figure 1 is a schematic diagram of the experimental apparatus. The main experimental column, made of transparent acrylic resin, was 0.15 m in inner diameter and 1.2, 1.7 or 3.2 m in height. Its bottom section was equipped with a bed support made of two sheets of stainless steel wire nets (200 over 12mesh), a gas distributor and a conical calming section filled with 4-mm Raschig rings. The gas distributor consisted of eight stainless steel tubes of 3 mm O.D. and 2.6 mm I.D. Each of the tubes was equidistantly arranged and horizontally inserted through the column wall toward the axis, protruding 25 mm from the inside wall surface. At the top of the column a cylindrical screen with a diameter of 0.2 m and a height of 0.25 m, made of 200 mesh stainless steel wire net, was installed to prevent particle carryover and to maintain a constant bed height.

Several pairs of stainless steel sheets (25 × 100 mm) were attached to the inside wall surface as electroconductivity probes in the axial direction. The distance between adjacent probes was 0.1 to 0.3 m. Pressure taps were installed along the wall and con-
Nected to pressure manometers. The distance between adjacent taps was 0.1 to 0.2 m.

A dual electroresistivity probe designed to be movable in the radial direction was installed at a position 0.56 m above the bed support screen. As shown in Fig. 1, the probe was made of 0.25 mm-diameter platinum wire coated with epoxy resin and encased in an 0.8 mm-diameter stainless steel tube except for the sharply finished tip. The front part of the supporting tube was bent by 0.25 \( \pi \) rad downward. The vertical distance between the two needle points was 3 mm. A reference electrode, made of stainless steel sheet (25 \( \times \) 100 mm), was attached to the inside wall surface facing the probe points.

Water and aqueous solutions of glycerol were used as the liquids. The liquid temperature was maintained at 293.2 K in the liquid reservoir. Air was used as the gas. Glass beads with a density of 2500 kg \( \cdot \) m\(^{-3} \) were used as the solids. The physical properties of the liquids are presented in Table 1. In this case, KCl was added to the liquid, and its concentration was maintained in the range from 5 to 10 mol \( \cdot \) m\(^{-3} \). The particles properties and the corresponding experimental conditions are presented in Table 2.

The axial distribution of solid holdup, \( \varepsilon_s \), and the corresponding mean solid holdup, \( \bar{\varepsilon}_s \), in the column were preliminarily measured by combining the electroconductivity probe method and the static pressure method.\(^{23} \) When two slurry layers, i.e., the dense region and the lean region, were formed, the gas holdup and the bubble properties in the dense region were measured by the dual-probe method.

### 1.2 Method of measuring bubble properties

The electric circuits for the signal processing system are shown in Fig. 2. AC voltage at a frequency of 95 kHz was applied to the probe. The difference in conductivities of gas phase and slurry phase was detected by the probe. The output signal from the probe was transformed into a square wave in the wave-reforming section, and finally the reformed signals were processed with a microcomputer (AIM 65, Rockwell International). In the Schmitt trigger circuit, the threshold level of the leading edge of the signal and that of the trailing edge were set at 20% and 15%, respectively, of the highest level of the bubble signal.\(^{4,13,16} \)

The local gas holdup, \( \varepsilon_g \), was determined from the lower probe signal passage as the ratio of the sum of the duration time for the bubble to the measuring period. The local bubble frequency, \( n_b \), was determined from the number of leading edges of the bubble signals. For 89 s, the microcomputer took the data of the signal at 85 \( \mu \)s intervals. After several data processings, the mean values of \( \varepsilon_g \) and \( n_b \) were obtained as

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Liquid} & \rho_l \text{ [kg/m}^3\text{]} & \mu_l \text{ [mPa} \cdot \text{s]} & \gamma_l \text{ [mN/m]} \\
\hline
\text{Water} & 998 & 1.00 & 72.8 \\
5GL & 1012 & 1.20 & 72.4 \\
16GL & 1040 & 1.70 & 71.5 \\
20GL & 1051 & 1.95 & 71.2 \\
50GL & 1127 & 6.60 & 68.8 \\
\text{5GL, 16GL, 20GL and 50GL: 5, 16, 20 and 50 vol% glycerol aqueous solution.} \\
\end{array}
\]

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
d_r \text{ [mm]} & \text{Mesh size} & \text{Liquid} & V_r \text{ [cm/s]} & H \text{ [m]} & \varepsilon_r \text{ [-]} \\
\hline
0.056 & 200–400 & Water & 0.26 & 1.2 & \leq 0.4 \\
0.16 & 80–100 & Water & 1.63 & 1.2 & 1.7 & \leq 0.4 \\
5GL & 1.42 & 1.2 & 1.7 & \leq 0.4 & \leq 0.13 \\
16GL & 1.07 & 1.2 & 1.7 & \leq 0.4 & 0.94 \\
20GL & 0.94 & 1.2 & 1.7 & \leq 0.4 & 0.29 \\
50GL & 0.29 & 1.2 & 1.7 & \leq 0.4 & 0.23 \\
0.23 & 60–65 & Water & 2.8 & 1.7 & \leq 0.4 \\
0.46 & 32–35 & Water & 6.7 & 3.2 & \leq 0.5 \\
\end{array}
\]
local values in the column. The measurements were
carried out at radial positions of 0, 34, 47, 58 and
67 mm from the column axis, which divided the
column into 5 annular sections of equal area. The
cross-sectionally averaged value of gas holdup, $\bar{\varepsilon}_g$, was
obtained from Eq. (1):

$$\bar{\varepsilon}_g = \frac{2}{R_w^2} \int_0^{R_w} \varepsilon_g r dr$$

(1)

The cross-sectionally averaged value of bubble
frequency, $\bar{n}_b$, was obtained in the same way as that
for $\bar{\varepsilon}_g$.

As shown in Fig. 3, the velocity of a bubble, $U_b$, and
the vertical length (chord length) of the bubble, $L_b$,
were calculated from the lag time between the two
signals, $\Delta t$, and the duration time for the bubble, $\tau$,
respectively:

$$U_b = \frac{2l}{(\Delta t_1 + \Delta t_2)}$$ \hspace{1cm} (2)

$$L_b = \frac{U_b(\tau_1 + \tau_2)}{2}$$ \hspace{1cm} (3)

where $l$ was the distance between two probes and $t$
was the real time.

For the measurements of $U_b$ and $L_b$, signal acqui-
sition was made by using the microcomputer. For
about 3 s, the microcomputer stored the data for the
two points simultaneously at 86 $\mu$s intervals. The
values of $\Delta t_1$, $\Delta t_2$, $\tau_1$ and $\tau_2$ were then printed out
successively, or the stored data were converted to
analog signals which were drawn out on a strip chart.
From these records, several sets of bubble signals
which satisfied all the constraints described below
were obtained. The constraints to avoid accounting of
unreasonable signal pairs were:

(i) $\Delta t_1$ and $\Delta t_2$ have the same sign.
(ii) $0.75 \leq 2\tau_1/(\tau_1 + \tau_2) \leq 1.25$
(iii) The value of $U_b$ calculated from Eq. (2) lies in
the range from $-0.8$ to $+2.5$ m/s.

Note that about 50% of the signal pairs detected by
the probe were excluded.

Radial positions for measuring $L_b$ and $U_b$ were 0,
47 and 67 mm from the column axis. All the effective
data obtained at these three measuring positions were
summed up to get the cross-sectionally averaged
bubble properties. Although the bubble frequency
decreased appreciably with radial distance from the
axis, the signal processing time at each measuring
position was almost equal. The total number of
effective bubbles was 50 to 120 for each run.

2. Results and Discussion

2.1 Gas holdup and bubble frequency

Figure 4 shows typical radial distributions of local
gas holdup, $\varepsilon_g$, and those of bubble frequency, $n_b$, for
various superficial gas velocities, $U_g$, in the slurry
bubble column. The value of $\varepsilon_g$ takes on a maximum
at the axis and decreases with increasing radial dis-
tance, approaching zero at the wall. The radial distri-
bution of $\varepsilon_g$ can be expressed well by the parabolic
profile from the recirculation flow model20) for the
range of $\varepsilon_g < 0.2$. In the range of $\varepsilon_g > 0.2$, the value of $\varepsilon_g$
in the region of $r/R_w$ from 0.4 to 0.8 decreases
considerably. The shape of radial distribution of $n_b$
resembles that of $\varepsilon_g$ for the corresponding condition.

Figure 5 shows the relationships between the
cross-sectionally averaged gas holdup, $\bar{\varepsilon}_g$, and $U_g$
in the slurry bubble column for various particle diam-
eters and $\varepsilon_g$. The value of $\bar{\varepsilon}_g$ increases with increasing
$U_g$ and decreases with increasing $\varepsilon_g$. The estimated
values of $\bar{\varepsilon}_g$ from the correlation equation of
Akita and Yoshida1) for the bubble column and
those from Koido's equation11) for heterogeneous
flow in a slurry bubble column are shown in the fig-
ure. The values of $\bar{\varepsilon}_g$ observed agree with those esti-
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mated by these correlations for the corresponding
operational conditions.

The values of $\bar{\varepsilon}_g$ in the glass beads-water slurry
observed by Kojima and Asano12) and those in the
glass beads-sodium sulfite aqueous solution slurry
observed by Kato et al.29) are also shown in the figure.
The value of $\bar{\varepsilon}_g$ of Kojima and Asano is larger than
that in this work at high $U_g$. This deviation may be
due to the difference in type of gas distributor. The value of $\bar{d}_g$ of Kato et al. is much larger than that in this work. However, the effect of $\bar{d}_g$ on $\bar{d}_g$ is similar to that observed in this work.

Figure 6 shows that the effect of $\mu_1$ on $\bar{d}_g$ is small in the slurry bubble column in the range of $\bar{e}_g \leq 0.13$. However, at $\bar{e}_g = 0.20$, $\bar{d}_g$ decreases gradually with increasing $\mu_1$. The values of $\bar{d}_g$ estimated by Koide's equation agree with those observed in this work.

Kara et al. reported that $\bar{d}_g$ in a coal-water slurry decreased with increasing $\bar{e}_g$. The values of $\bar{d}_g$ in the column with 0.07 mm coal particles observed by Kara et al. agree fairly well with those for small particles in this work.

Figure 7 shows that the observed values of $\bar{d}_g$ at a small $\bar{e}_g$ in the slurry bubble column and those in the bubble column are slightly larger than those predicted by Koide's equation. However, the observed values in this work agree fairly well with those predicted with a coefficient of variation of 28%. From the above results, it may be remarked that Koide's equation is applicable to the slurry bubble column with high solid content up to $\bar{e}_g = 0.4$.

2.2 Distributions of bubble properties

Figure 8 shows the cumulative bubble length distributions, $F_l$, in the bubble column and those in the slurry bubble column. The values of $\bar{n}_b$ are also noted in the figure. The bubble length distribution for both the bubble column and the slurry bubble column follows a log-normal distribution. This trend is similar to that observed by Akita and Yoshida in the bubble column. The values of median, $L_m$, and logarithmic standard deviation, $\sigma_l$, for $F_l$ are also noted in the figure.

In the bubble column, most of the values of $L_b$ are less than 5 mm and the value of $\sigma_l$ is small in the range of $U_g \leq 2.2$ cm/s, where the flow mode is termed homogeneous flow (Deckwer et al.). In the range of $U_g \geq 3.9$ cm/s, where the flow mode is termed heterogeneous flow (Deckwer et al.), large bubbles of $L_b \geq 10$ mm are produced and the values of $L_m$ and $\sigma_l$ increase with $U_g$.

In the slurry bubble column at $\bar{e}_g = 0.13$, large bubbles appear even at small $U_g$. $U_g$ has little effect on $F_l$ except in the region of $U_g$ less than about 1 cm/s. The value of $\sigma_l$ for the slurry bubble column is similar in magnitude to that for heterogeneous flow in the bubble column, while the value of $L_m$ for the former is two or three times as large as that for the latter. The value of $\bar{n}_b$ for the slurry bubble column is much
smaller than that for the bubble column at the same $U_g$.

**Figure 9** shows the cumulative bubble velocity distributions, $F_v$, in the bubble column and those in the slurry bubble column. The experimental conditions in this figure are consistent with those in Fig. 8. The bubble velocity distribution in both the bubble column and the slurry bubble column follows a normal distribution. The values of median, $U_m$, and the standard deviation, $\sigma_v$, for $F_v$ are also noted in the figure.

In the range of $U_g \leq 2.2 \text{ cm/s}$ for the bubble column, the value of $\sigma_v$ is small and the values of $U_b$ mostly lie in the range from $-0.4$ to $0.6 \text{ m/s}$. On the other hand, in the range of $U_g \geq 3.9 \text{ cm/s}$ the distribution extends to both directions of the $U_b$ coordinate. The value of $\sigma_v$ increases with $U_g$, but that of $U_m$ remains almost constant.

No appreciable effect of $U_g$ on the bubble velocity distribution is resulted from changing $U_g$ from 0.8 to $8 \text{ cm/s}$ in the slurry bubble column. The values of $U_b$ mostly lie in the range from 0 to $1.4 \text{ m/s}$. The ratio of the numbers of descending bubbles to the total for the slurry bubble column is much smaller than that for heterogeneous flow in the bubble column. The value of $U_m$ for the slurry bubble column is about three times as large as that for heterogeneous flow in the bubble column, while the value of $\sigma_v$ for the former is smaller than that for the latter.

From Figs. 8 and 9, it may be considered that the growth of a bubble in a slurry bubble column may be enhanced by the increased interaction between bubble surface and slurry particles. Thus, in the slurry bubble column with high solid content the bubbles grow rapidly just above the gas distributor even at small $U_g$. The small bubbles in the slurry bubble column rise with relatively high speed following the large bubbles.

**Conclusions**

The following results are obtained for the bubble properties in a slurry bubble column.

1) The shape of the radial distributions of local gas holdup and bubble frequency is parabolic in the range of mean solid holdup, $\bar{\varepsilon}_s$, less than 0.2. In the range of $\bar{\varepsilon}_s \geq 0.2$ the gas holdup and the bubble frequency decrease considerably in the region of $r/R_w$ from 0.4 to 0.8.

2) The cross-sectionally averaged gas holdup, $\bar{\varepsilon}_g$, decreases with increasing $\bar{\varepsilon}_s$, but the effect of liquid viscosity on $\bar{\varepsilon}_g$ is not appreciable. In the range of $\bar{\varepsilon}_s \leq 0.4$, $\bar{\varepsilon}_g$ can be predicted fairly well by Koide’s equation for heterogeneous flow.

3) The cumulative bubble length distribution, $F_l$, follows a log-normal distribution. $F_l$ in the slurry bubble column with high solid content lies in a larger bubble size region than that for heterogeneous flow in the bubble column, and is little affected by the gas velocity.

4) The cumulative bubble velocity distribution, $F_v$, follows a normal distribution. $F_v$ in the slurry bubble column with high solid content lies in a larger velocity region than that in the bubble column, and is little affected by the gas velocity.

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**Nomenclature**

- $d_p$: particle diameter [mm]
- $F_l$: cumulative bubble length distribution [%]
- $F_v$: cumulative bubble velocity distribution [%]
- $H$: column height [m]
- $k_{la}$: volumetric liquid-phase mass transfer coefficient [s⁻¹]
- $L_b$: vertical bubble length (chord length) [m]
- $L_c$: arithmetic mean of $L_b$ in column [m]
- $L_m$: median of bubble length distribution [m]
- $l$: distance between two probes [m]
- $n_b$: bubble frequency [s⁻¹]
- $n_b$: cross-sectionally averaged bubble frequency [s⁻¹]
- $r$: radial distance from axis [m]
- $R_w$: column radius [m]
- $t$: real time [s]
- $U_b$: bubble rising velocity [m/s]
- $U_c$: arithmetic mean of $U_b$ in column [m/s]
- $U_g$: superficial gas velocity [m/s]
- $U_l$: superficial liquid velocity [m/s]
- $U_m$: median of bubble velocity distribution [m/s]
- $V_t$: terminal settling velocity of a single particle [m/s]
- $\gamma_l$: surface tension of liquid [N/m]
- $\delta_t$: lag time between two probes [s]
- $\varepsilon_h$: gas holdup
- $\varepsilon_g$: cross-sectionally averaged gas holdup
- $\varepsilon_s$: solid holdup
FLOW STRUCTURE AND MASS TRANSFER FOR A WAVY CHANNEL IN TRANSITIONAL FLOW REGIME

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Key Words: Fluid Flow, Vortex Structure, Transitional Flow, Wavy Channel, Mass Transfer, Flow Visualization, Electrochemical Method

The relationship between flow structure and mass transfer in a wavy channel was investigated in the range from laminar to turbulent flow. Laminar flow has a steady two-dimensional structure, but turbulent flow has an unsteady three-dimensional vortical structure. In particular, the flow field in a large recirculation vortex within the furrow of a wavy wall shows an intermittent reversed flow and a nonuniformity of flow in the spanwise direction for turbulent flow. The flow intermittency is closely related to the mass transfer, and a remarkable increment of mass transfer rate is induced near the flow reattachment point in the large recirculation vortex, which suggests a renewal of the concentration boundary layer because of the flow intermittency.

Introduction

The channel with wavy walls is one of several devices employed for enhancing the heat and mass transfer efficiency of processes having high Peclet numbers, such as in plate heat exchangers, electrodialyzers and membrane blood oxygenators.

In previous reports, heat and mass transfer for laminar flow has been analyzed by calculation, while studies of fully turbulent flow have been carried out by experiment. However, investigations in the transitional flow regime have been quite limited. Recently the authors experimentally found that the increment of