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Study of the Particle Size Effect on Bubble Rise Velocities in a Three-Phase Bubble Column

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***Abstract*—**Experiments were performed in a three-phase bubble column to study variations of bubble rise velocities. The dynamic gas disengagement (DGD) technique and the fast response pressure transducers were utilized to investigate the bubble rise in the column. The superficial gas velocity of large bubbles and small bubbles, the rise velocities of larger and small bubble fractions were studied considering the effect of particle sizes. The results show that the superficial gas velocity associated with large bubbles linearly increase as superficial gas velocity increasing. Particle size has little effect on the both large and small bubble superficial gas velocities. The rise velocities of larger bubble fractions are larger than that of small bubble fractions, and it had different tendency at low and high superficial gas velocities when changing the particle sizes. The rise velocities of small bubble fractions increased and then had a decrease tendency when the particle size became greater.

***Keywords*—**Bubble rise velocity, gas–liquid–solid, particle size effect, three–phase bubble column.

I. Introduction

GAS–liquid–solid three–phase bubble columns have been widely used in chemical industry, petrochemical industry [1], food technology, biochemical and waste water treatment processes [2]-[4]. Bubble formation and bubble rise due to buoyancy are fundamental phenomena, and they largely affect the flow dynamics of gas–liquid reactors [5], [6]. Similarly, bubble rise velocities have serious influence on the hydrodynamics, heat transfer and mass transfer in three–phase bubble columns, and they are also related with the successful design, operation and scale–up of three-phase reactors. Bubble characteristics include the behavior of single bubble and multiple bubbles. Single bubble behaviors include bubble formation and shape, bubble rise velocity and the liquid-solid flow induced by bubbles, particle entrainment and drift effect. Multi–bubble behaviors include bubble coalescence, breakup and bubble size distribution [7]. Bubble rise velocity is one of the bubble behaviors, and it determines the contact characteristic time which affect the interface transport phenomena and the mix among gas–liquid–solid phases.

The factors affecting bubble rise velocity include, bubble size and shape, the properties of gas–liquid two–phases (surface tension, density, viscosity), the direction of liquid flow and operation conditions (temperature, pressure and gravity) [5], [8]. Chilekar et al. [9] studied bubble sizes, and two categories have been used. Bubbles with diameter larger than 8mm were large bubbles, and bubbles of 2mm–8mm diameter were small bubbles. Li et al. [10] studied the effect of solid concentrations on the rise velocities of large bubble and small bubble in a three–phase slurry bubble column. Rabha et al. [11] studied the effect of particle size and concentration on the hydrodynamics of a slurry bubble column, mainly including three-dimensional gas flow structures, gas hold-up and bubble size distributions.

Particle sizes have complex effect on the behaviors of three-phase bubble column, and the related studies are limited. The objective of the study was to investigate the effect of particle size and superficial gas velocity on the bubble rise velocities of larger and small bubbles. The dynamic gas disengagement technique and fast response pressure transducers were used. This paper is structured as follows. Experimental work is described in the second part. Subsequently, results and discussion are detailed in the third part, followed by concluding remarks.

II. Equipment and Experimental Methods

A gas–liquid–solid three–phase bubble column experimental system was built, and Fig. 1 sketched the schematic diagram of the experimental set–up. The experimental system consists of a gas-liquid-solid three-phase bubble column, an air supply system, a differential pressure signal acquisition system and a digital image acquisition system. The bubble column measured 0.8m tall, 0.1m long and 0.01m wide and was made of transparent, 6–mm–thick Plexiglas. The air supply system consists of an air blower, pipelines and flowmeters. The differential pressure signal acquisition system includes the diffused silicon pressure transmitters (GB-3000E and GB-3000HK), a data acquisition card (CDAQ-9188), power supply, positive wire, negative wire and data collection software (Labview 2010 Signal Express). The measurement range and measurement accuracy of the diffused silicon pressure transmitters are 0–2.5 kPa and 0.05%, respectively. The digital image acquisition system consists of a high resolution digital CCD camera and a computer for photo collection.

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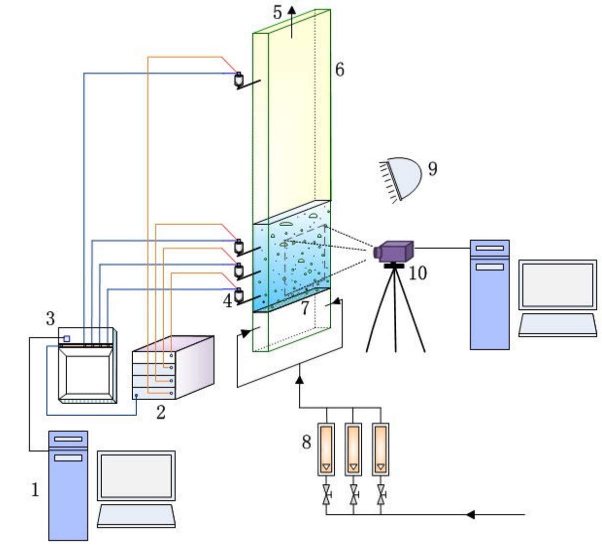


Fig. 1 A schematic diagram of the experimental set-up 1. Computer; 2. Power supply; 3. Data collector; 4. Differential pressure sensor; 5. Gas outlet; 6. A three-phase bubble column; 7. Metal sintered plate distributor; 8. Flowmeters; 9. Light; 10. CCD camera

The gas phase was air measured by three rotameters. Air was sparged upward through the gas distributor and into the bubble column. Tap water was used as the liquid phase, which was operated in batch mode. Spherical glass powders constituted the solid phase, and the particle properties were shown in Table I. There were four pressure taps (40, 90, 140and 490mm) above the gas distributor, which were located on the side wall of the three-phase bubble column. From the bottom to the top, the taps were numbered one through number four. The differential pressures were measured with a frequency of 500 Hz for 100 s and then converted into voltage signals, which were transferred through an A/D converter to a computer. A 1000–W floodlight was used for lighting.

TABLE I
PARTICLE PROPERTIES

Particles	ρ_s (kg/m^3)	d_s (μm)	C_s (V/V)
Glass bead 1	2500	75	9%
Glass bead 2	2500	150	9%
Glass bead 3	2500	200	9%

The dynamic gas disengagement technique was used to study bubble rise velocities, and the principle was that different bubble classes had distinguished rise velocities. The variation data of dynamic pressure in the bubble column based on quick stoppage of gas supply was collected and analyzed and then figure out the bubble rise velocities and the superficial gas velocity of bubbles. The whole process of the dynamic gas disengagement technique consisted of four stages: steady operation, the first period (large bubble disengagement) and the second period (small bubble disengagement) of gas disengagement, and gas free suspension. The pressure time series between two pressure points (number one and number two taps) were used to be analyzed. Based on mass balance during the second period of gas disengagement, the amount of gas due to small bubbles in the region between two taps should be equal to that of liquid flowing back in, and the equation was:

$$U_{g,sm} = \frac{-\Delta H d\left[\varepsilon_g\left(t\right)\right]}{dt} \qquad (1)$$

$U_{g,sm}$ is the superficial gas velocity associated with small bubbles, ΔH is the height between two pressure taps, which can be calculated from the slope of the second period of gas disengagement [10]. The superficial gas velocity associated with large bubbles, $U_{g,L}$; single bubble rise velocity of larger bubble, $V_{b,L}$, and single bubble rise velocity of small bubble, $V_{b,sm}$ were defined by function (2)–(4) [10]:

$$U_{g,L} = U_g - U_{g,sm} \qquad (2)$$

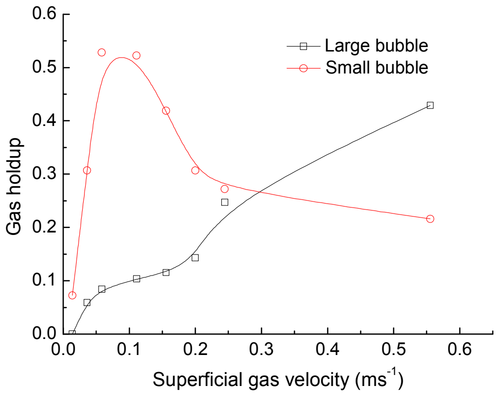
$$V_{b,L} = U_{g,L} / \varepsilon_{b,L} \qquad (3)$$

$$V_{b,sm} = U_{g,sm} / \varepsilon_{b,sm} \qquad (4)$$

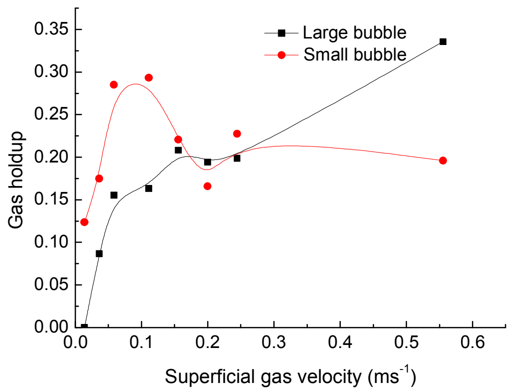
where $\varepsilon_{b,L}$ was the large bubble fraction holdup, and $\varepsilon_{b,sm}$ was the small bubble fraction holdup.

III. Results and Discussion

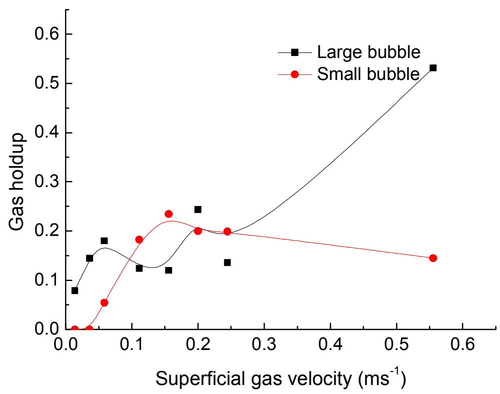
Fig. 2 shows the profiles of large bubble and small bubble gas holdup calculated by the dynamic gas disengagement technique under different particle sizes. It showed obviously that gas holdup value of small bubble reduced gradually when increasing the particle size at low superficial gas velocities, and reached a stable level at high superficial gas velocities. The gas holdup value of small bubble was high at the particle size of 75μm. At low superficial gas velocities, which were at the range of 0–0.2m/s, increasing particle sizes can enhance bubble coalescence rates and decrease small bubble population and therefore the values of the gas holdup of small bubbles decreased. When the superficial gas velocities were greater than 0.2m/s, the values of the small bubble gas holdup were kept around 0.2, whereas the values at the particle size of 75μm were still larger than it at 200μm. At high superficial gas velocity, large bubbles took great volumes at the bulk region which can be observed from the experimental apparatus and therefore the gas holdup value of large bubbles was high around 0.5m/s.



(a) 75µm



(b) 150µm



(c) 200µm

Fig. 2 Gas holdup profiles under different particle sizes

Functions (1) and (2) were utilized to calculate the superficial gas velocities of large and small bubbles, and Fig. 3 shows the superficial gas velocity profiles under different particle sizes. From Fig. 3, it can be observed that the particle sizes effect was not pronounced on the superficial gas velocity values of large and small bubble. The superficial gas velocity of large bubble increased linearly with the superficial gas velocity becoming greater, whereas the superficial gas velocity of small bubble changed little. The superficial gas velocity value of large bubble was greater than that of small bubble. The main reason of the results of Fig. 3 lied in that the superficial gas velocity value of small bubble which was figured out by (1), was low at each superficial gas velocity, and the values were in the range of 0.001m/s–0.02m/s; at the same time, the superficial gas velocity value of this three bubble column system was fixed, and calculated (2) the superficial gas velocity of large bubble were changed little under the conditions of using different particle sizes.

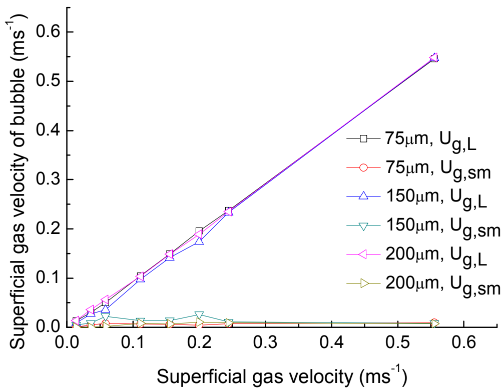


Fig. 3 Superficial gas velocity profiles of large bubble and small bubble at different particle sizes

Fig. 4 presents the comparison of single bubble rise velocity between this study of the three-phase system using particle measuring 150µm in size and the study conducted by Li et al. [10]. The results showed that rise velocities of larger and small bubble fractions in this study were all lower than the results of Li et al. The reasons for the difference may due to that the results of Li et al. were obtained at gas–liquid two phase systems, and the sizes of bubble columns and the gas spargers used were different. Compared with the results of Grund et al. [12], the large bubble rise velocity of Grund et al. was at the range of 0.6m/s–1.1m/s, and that of this study was at 0.6m/s–0.8m/s. The results were similar. Fig. 4 showed that the rise bubble velocity of large bubble was larger than that of small bubble, and it verified the principles of the dynamic gas disengagement technique which was different bubble classes had different rise velocities. Adding particle with diameter of 150µm may decrease the rise velocity of larger bubble fraction compared with that in the gas-liquid two phase bubble column system, and it had the same result with [13], which pointed out that the existence of particles slowed down the bubble rise velocities.

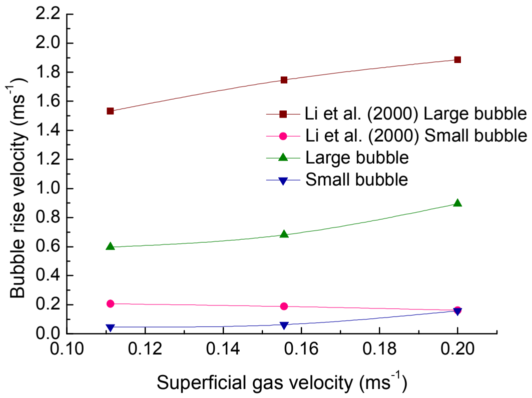
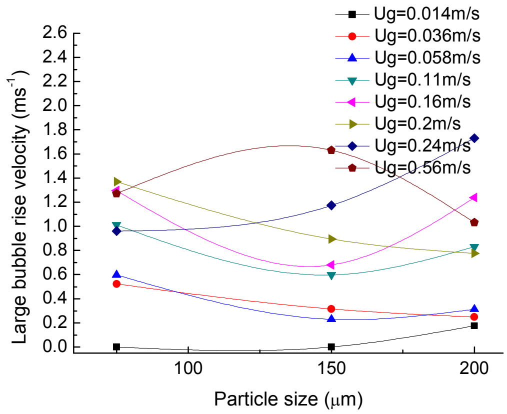


Fig. 4 Bubble rise velocity profiles of large bubble and small bubble

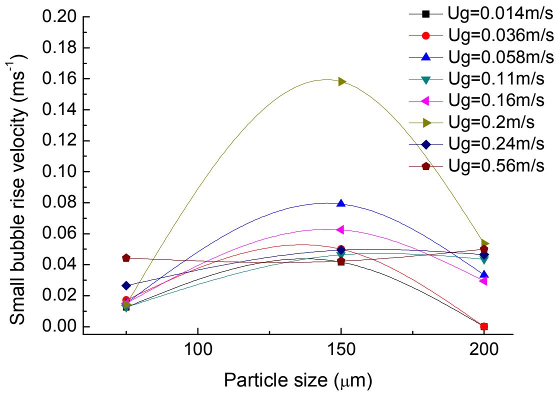
Whether treating liquid-solid two-phases as a pseudo-homogeneous phase or heterogeneous phase was always a research question when discussing the bubble rise velocity [8]. We treated the liquid-solid phases as a heterogeneous phase and considered the effect of particle size. Fig. 5 shows the effect of particle sizes on the rise velocity of larger and small bubble fractions obtained for air-water-glass bead powders system. The data in Fig. 5 were collected from the pressure tap one and the pressure tap two, and only represented the bubble behaviors near the sparger region. All these shifting behaviors of bubble rise velocity curves only represented the bubble characteristics in the region between the two taps. Bubble rise velocities were calculated by (3) and (4).

In Fig. 5, when particle sizes shifted from 75μm to 150μm, the large bubble rise velocities decreased at low superficial gas velocities which ranged from 0.036 m/s to 0.2m/s, whereas the rise velocities of small bubble fractions became greater. When particle sizes shifted from 150μm to 200μm, the rise velocity of larger bubble fraction had no obvious changing tendency and that of small bubble fraction decreased at low superficial gas velocities. From Fig. 5 (b), at low superficial gas velocity ranges, small bubble rise velocity became larger at particle size of 150μm and then decreased at 200μm; at high superficial gas velocities such as at 0.24 m/s and 0.56m/s, particle size had little effect on the rise velocity of small bubble fraction. Therefore, small bubble behaviors differently at low superficial gas velocities and at high ones. Refer to (4), the rise velocity of small bubble fraction was related with the small bubble fraction holdup and the superficial gas velocities of small bubble. The superficial gas velocities of small bubble were similar at different particle sizes as shown in Fig. 3; the difference of single large bubble velocity mainly came from the values of small bubble fraction holdup. For example, at low superficial gas velocities, high values of small bubble fraction holdup were observed at particle size of 75μm in Fig. 2, and it caused low values of small bubble rise velocities as shown in Fig. 5 (b) at 75μm.

The main forces acting on bubbles consist of the upward forces (buoyancy and gas momentum force) and the downward forces (liquid drag, surface tension force, Basset force, bubble inertial force, the particle–bubble collision force and the suspension inertial force) [7]. All the forces contributed to the bubble movements and velocities. The existence of particles can affect the flow regimes and liquid flow, and then all these factors acted on the bubble flow. Rabha et al. [11] found out that particle size effect had greater influence on the average bubble diameter and average gas holdup when particle size was greater than 100μm, and this particle size effect can affect the rise bubble velocity further.



(a) Single large bubble velocity



(b) Single small bubble velocity

Fig. 5 Bubble rise velocities as a function of particle sizes

IV. Conclusions

1) The effect of particle size on the rise velocities of larger and small bubble fractions in gas-liquid-solid bubble column systems was studied.
2) The superficial gas velocity of large bubble increased linearly as increasing the superficial gas velocity, whereas that of small bubble changed little. Particle size had no pronounced influence on the superficial gas velocity of large and small bubbles.
3) The rise velocity of larger bubble fraction was larger than that of small bubble fraction. Adding particle may decrease the rise velocity of larger bubble fraction compared with that in the air-water systems studied by Li et al. and Grund et al.

4) Particle size effects on bubble rise velocity showed distinguished results under two conditions which were at low superficial gas velocities and at high ones. More work is needed in the future research.

NOMENCLATURE

C	volume concentration
U	superficial velocity, m/s
V	single bubble velocity, m/s
Greek letter	
ρ	density of phases, kg/m^3
ε_g	gas hold-up
ε_b	bubble fraction holdup
Subscripts	
b	bubble
g	gas
l	liquid
L	large bubbles
s	solid
sm	small bubbles

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