RISING VELOCITY OF LARGE BUBBLE AND LARGE PARTICLE OF GAS-LIQUID-SOLID THREE-PHASE SLUG FLOW WITH LARGE PARTICLES IN A VERTICAL PIPE

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INTRODUCTION

Whereas the flow situations and flow characteristics of the two-phase flows such as gas-liquid or solid-liquid two-phase flows have widely been studied [1-4], those of gas-liquid-solid three-phase flows have not been clarified so sufficiently. If the diameters of the solid particles as the solid phase are comparably large with the pipe inner diameter, they should cause the deformation and collapse of large bubbles, and their flow situations should be quite complex. Such three-phase flows are encountered, for example, in the air-lifting of large fish from the hold of the fishing boat and in the pipe when they must transport large rocks for dredging or reclamation. However, we have no available data for such flow conditions. The authors, therefore, studied the flow situations and flow characteristics of the gas-liquid-solid three-phase slug flow with large particles in a vertical pipe experimentally [5,6].

In this report, the authors first show the experimental apparatus and method, and then present the images of the flows obtained by a video recorder, and explain about their flow situations. Next, among the important features of their slug characteristics, the rising velocities of large bubbles and large particles are taken up. The measured results are presented. The velocities are divided into some categories according to the flow situations, and their averaged values are compared.

EXPERIMENTAL APPARATUS AND METHODS

The precise of experimental apparatus is reported in refs [5,6]. We therefore explain here briefly. The test section is consisted of a transparent acrylic pipe of D=30.3 mm in inner-diameter round tube, and of 7.5m in total length. The length for three-phase flow part is 6.8m. Air and water at room temperature and atmospheric pressure were used for the gas and liquid phases.

Hydrophilic ceramic spherical solid particles of mean diameter d_S=24.8 mm and density 2370 kg/m^3 were used as the solid phase. The diameter ratio, d_S/D, the particle Reynolds number, the drag coefficient and the terminal settling velocity in the test pipe filled with stagnant water is 0.808, 22100, 0.461 and 0.168 m/s, respectively. The spheroidicities shown by the maximum and minimum deviation from the mean value measured in four quarters of the 45 degree intervals are from -1.52 to 1.33%.

Images of three-phase flow were taken at the position about 5.2 m downstream of the mixing section of air. A part of test section was surrounded by a water-filled rectangular vessel in order to prevent refraction by circular pipe. A Hi-8 video camera was used to record the images. By the processing of the images, the rising velocities of large bubbles and large particles in the 0.910 m flow axial direction were obtained.

The ranges of volumetric fluxes of gas phase $<J_G>$, the liquid phase $<J_L>$ and the solid phase $<J_S>$ were 0.222-1.02, 0.591-1.01 and 0.00302-0.0220 m/s, respectively.

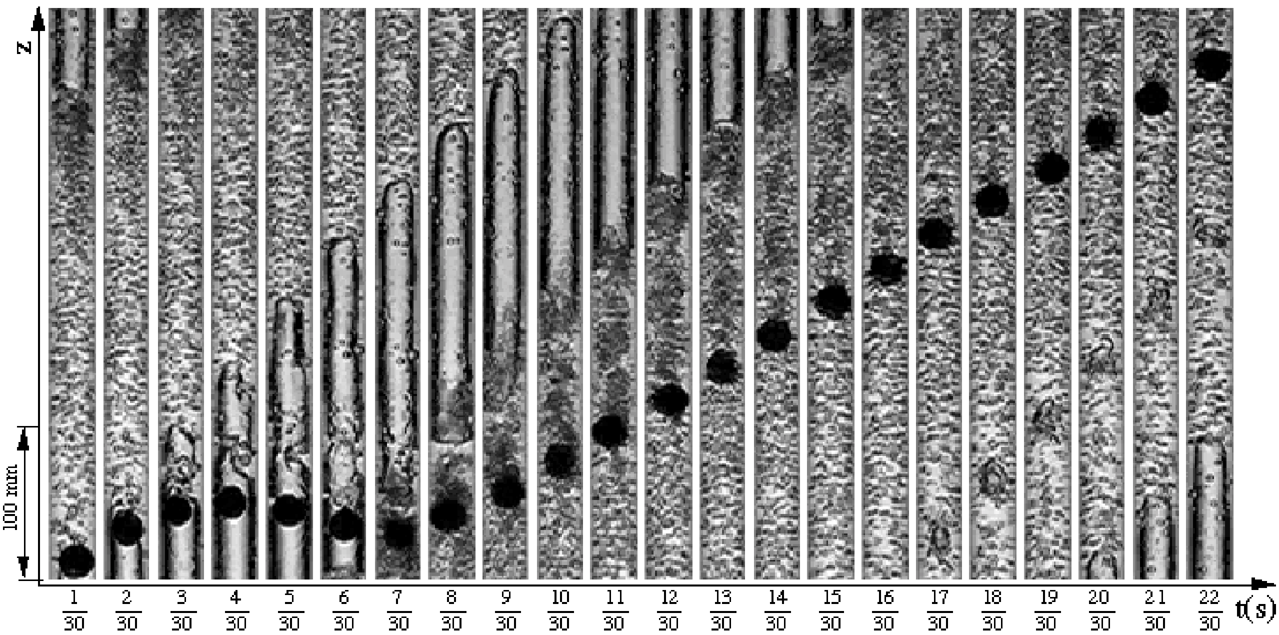
FLOW SITUATION OF THREE-PHASE SLUG FLOW WITH LARGE PARTICLE

Flow situation of large particles

We can recognize strong interaction between large bubbles and large particles including destruction or strong deformation of large bubbles and drastic dynamic behavior of large particles through liquid slugs and large bubbles as shown in Fig.1. In this figure, time series video images are arranged every 1/30 second. The black circles are the images of a large particle. The rising velocity of the large particle can be estimated by the slope of the images. Just after a large particle is overtaken by a large bubble (1/30 sec in Fig.1), it reduces its rising velocity, and after it stops (4/30 sec), it begins to fall in the large bubble. It's supposed to be because of weak acting force on the particle only from the liquid film around and gas phase in the large bubble. It draws a parabolic line just before the nose of adjacent liquid slug reaches (7/30 sec). After that, it begins to move upwards with large value of acceleration caused by the liquid slug. The velocity of the large particle gradually reaches to the value that it takes just before it is caught by the adjacent large bubble. Large particle thus repeats the upward motion in liquid slug and the downward motion in large bubble.

Flow situation of large and small bubbles

The movement of the large bubble in the liquid slug is almost similar to that of the gas-liquid two-phase slug flow. However, the passage of a large particle causes the deformation and the collapse on a large bubble as shown from 2/30 sec to 6/30 sec in Fig.1. Some small or middle size bubbles are produced, which are compounded to the large bubble again to become a bullet shaped immediately after the large particle passes.



D=30.3mm, d_S=24.8mm, ρ_S =2370kg/m^3, d_S/D=0.818

$<J_G>$=0.409 m/s, $<J_L>$=0.613 m/s, $<J_S>$=0.00307 m/s

Fig.1 Interaction between a large bubble and a large particle

The number density of small bubbles in the liquid slug is higher than that of gas-liquid two-phase slug flow because the large particle promotes the production of small bubbles due to the break up of large bubbles caused by the direct interaction. Usually, small bubbles produced at the tail of large bubble are absorbed into the large bubble again. However, the large particles prevent this absorption. Thus, most of the produced small bubbles have a long life time in the liquid slug.

RISING VELOCITY OF LARGE BUBBLES AND LARGE PARTICLES

Large bubble velocity

The plotted symbols in the lower section of Fig.2 are based on the images shown in Fig.1. They denote the positions of a large bubble nose, $Z_{BN}(t)$, of a large bubble tail, $Z_{BT}(t)$, and of a large particle, $Z_P(t)$ as a function of time, t. The lines in the lower section are drawn using the least squares method as linear or parabolic lines. In the upper section of Fig.2, the velocities of a large bubble nose, $V_{BN}(t)$, of a large bubble tail, $V_{BT}(t)$, and of a large particle, $V_P(t)$, are plotted, which were calculated as the slope of each position for every 1/30 sec. Moreover, the straight lines in the upper section are obtained using the slopes of the lines in the lower section. We adopt the velocity of nose of large bubbles, $V_{BN}(t)$, as the representative velocity of large bubbles because the tail of large bubbles is so much disturbed and therefore the measuring precision becomes bad. During the direct interaction (black symbols in Fig.2), the velocity of large bubble nose (▲) once increases and decreases later. Except for this period, the velocity of large bubble nose (□, ▲)is almost constant. Hereafter, the average velocity of large bubble nose for all period for many large bubbles is denoted by $\overline{V}_B$, whereas that during the period of direct interaction is denoted by $\overline{V}_{BwithP}$, and that during the period when large bubbles rise in the liquid slugs without the direct effect of large particles is denoted by $\overline{V}_{BinL}$.

Figure 3 shows the relations between $\overline{V}_B$, $\overline{V}_{BwithP}$ and $\overline{V}_{BinL}$. All of them are larger than the value of the total volumetric flux, $\langle J_T \rangle$ ($=\langle J_G \rangle + \langle J_L \rangle + \langle J_S \rangle$), and increase with the volumetric flux of each phase. Among three averaged velocities, $\overline{V}_{BwithP}$ is the largest and $\overline{V}_{BinL}$ is the smallest. $\overline{V}_B$ is medium because it is the average of $\overline{V}_{BwithP}$ and $\overline{V}_{BinL}$. It is also recognized that the increasing rates of these velocities when the solid volumetric flux is increased under constant volumetric fluxes of the other phases are much larger than when the gas or liquid phase volumetric flux is increased..

Large particle velocity

It is found from Fig.2 that the particle velocity is almost constant in the period that the particle is not under direct interaction with a large particle (○ in Fig.2). The particle velocity, however, suddenly decreases to negative values after it begins a direct interaction with a large bubble (● in Fig.2). The decelerations seems almost constant during the direct interaction. After the direct interaction, the particle accelerate intensely, and its rising velocity approaches to the value for without direct interaction (● in Fig.2). Hereafter, the average velocity of large particles for all period for many large particles is denoted by $\overline{V}_P$, whereas that during the period of direct interaction is denoted by $\overline{V}_{PinB}$, and that during the period when large particles rise in the liquid slugs without the direct effect of large bubbles is denoted by $\overline{V}_{PinL}$.

Figure 4 shows their relations. All of them are smaller than the value of $\langle J_T \rangle$, and increase with the volumetric flux of each phase. Among three averaged velocities, $\overline{V}_{PinL}$ is the largest and $\overline{V}_{PinB}$ is the smallest. $\overline{V}_P$ is medium because it is their average. The values of $\overline{V}_{PinL}$ are almost along a straight line, whereas those of $\overline{V}_{PinB}$ forms a distorted and flat diamond shape.

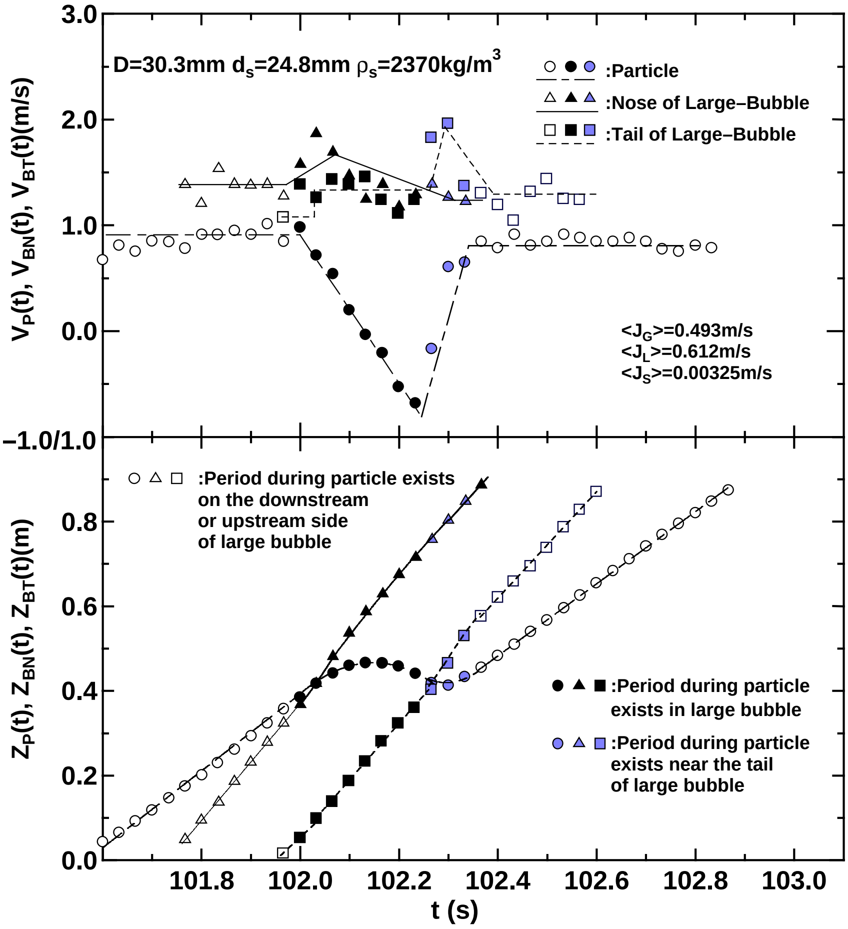


Fig.2 Time series positions and velocities of a large bubble and a large particle

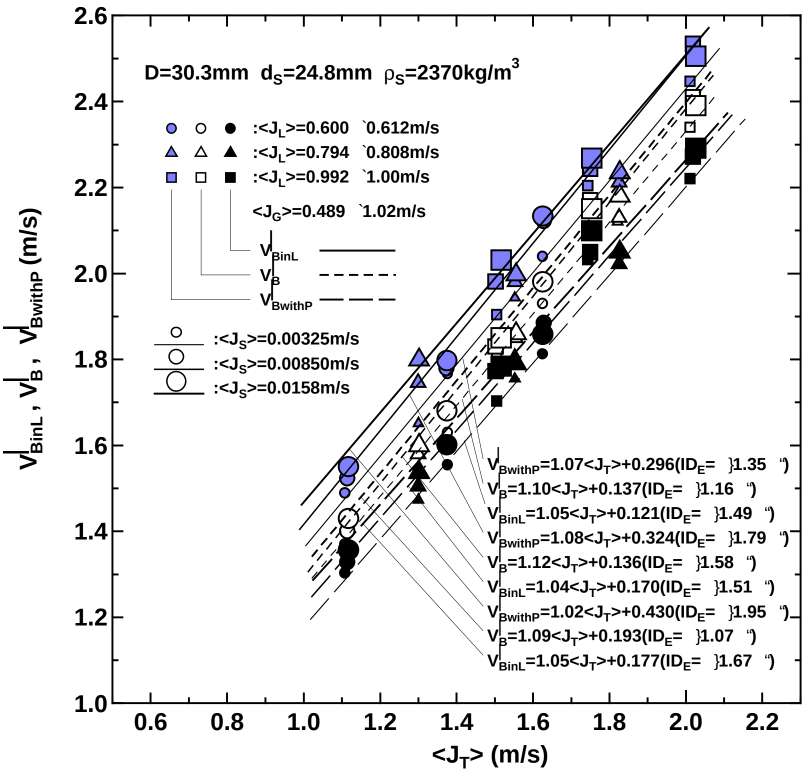


Fig.3 Averaged large bubble velocities

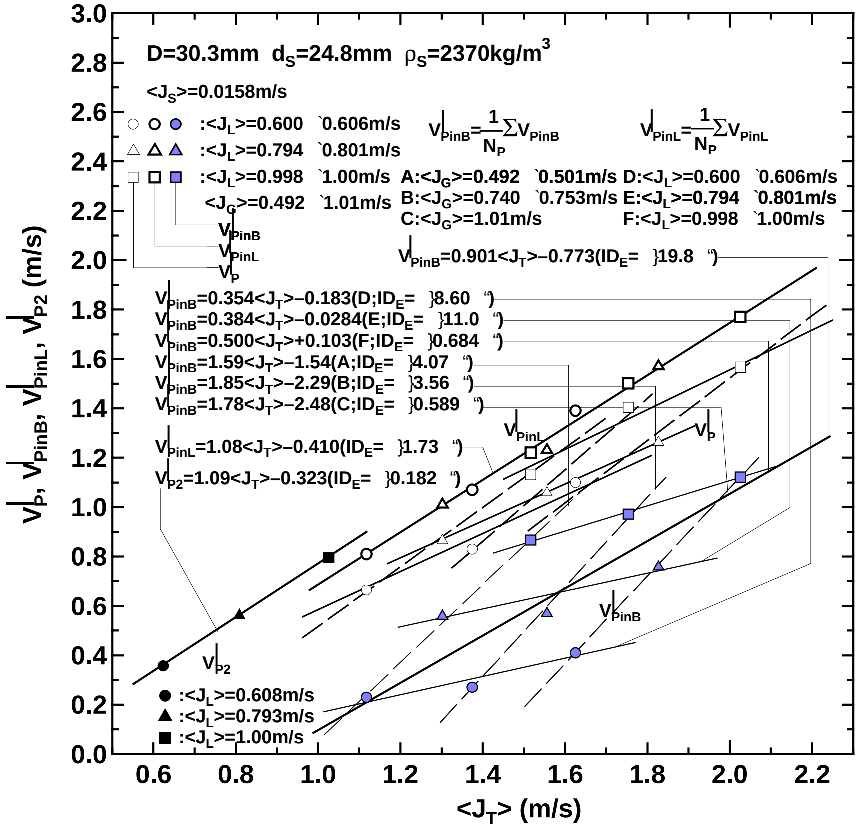


Fig.4 Averaged large particle velocities

CONCLUSIONS

In this report, the authors presented the images of the flows obtained by a video recorder, and explained about the flow situations of gas-liquid-solid three-phase slug flow with large particles of the diameter ratio 0.818. Strong interaction between large bubbles and large particles including destruction or strong deformation of large bubbles and drastic dynamic behavior of large particles through liquid slugs and large bubbles were recognized. The rising velocity of large bubbles and large particles were divided into some categories according to the flow situations especially to the direct interaction. Their averaged values were compared with each other.

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