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Brief communication

Microgravity effects on the rising velocity of bubbles and slugs in vertical pipes of good and poor wettability

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Abstract

Bubbles and slugs rising in vertical pipes of good and poor wettability were observed with a high-speed video camera in normal gravity as well as in microgravity. The wettability of the pipe did not affect the mean rising velocity of bubbles in microgravity. The same was true for the mean rising velocity of slugs in microgravity. An empirical relation was derived for the mean rising velocity of bubbles and slugs in mirogravity as a function of the superficial velocities of gas and liquid. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Microgravity; Drop tower; Gas–liquid two-phase flow; Wettability; Bubble; Slug; Rising velocity

1. Introduction

In previous studies the flow patterns of air–water two-phase flows in a vertical pipe of poor wettability were investigated in normal gravity and microgravity (Terauchi et al., 1999; Terauchi and Iguchi, 1999; Iguchi and Terauchi, 2000a,b). Particular attention was paid to the bubbly flow regime and slug flow regime. The term "poor wettability" means that the contact angle between a liquid and a solid, θ_c, is greater than 90°. On the other hand, the contact angle of a pipe of good wettability is less than 90°. The behavior of bubbles and slugs in a pipe of poor wettability ($\theta_c = 104°$) was much different from that observed in a pipe of good wettability ($\theta_c = 77°$) in the

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two gravity levels. It should be kept in mind that the vertical length of a bubble is smaller than the inner diameter of the pipe, D, while that of a slug is larger than D.

The mean rising velocity, $\bar{u}_G$, of bubbles and slugs in the vertical pipes of good and poor wettability ($\theta_c = 77°$ and 104°) in microgravity was measured in this study with a high-speed video camera. The microgravity conditions were realized using the drop tower of Japan Microgravity Center (JAMIC). The results were compared with those obtained in the pipes of good and poor wettability in normal gravity to reveal the effects of the gravity level on the mean rising velocity, $\bar{u}_G$.

2. Experimental apparatus and procedure

Although the detail of the experimental apparatus is described in the previous paper (Iguchi and Terauchi, 2000b), some important aspects of the apparatus will be reproduced here. Fig. 1 shows a schematic of the experimental apparatus. The inner diameter of a transparent acrylic pipe, D, was 10.0 mm. The original acrylic pipe had a contact angle θ_c of 77°, and accordingly, it was wetted by water. The contact angle of the pipe was changed from 77° to 104° by coating liquid paraffin on the inner wall of the pipe. Water was circulated with a pump and air was supplied with a compressor through a porous nozzle settled flush on the inner wall of the lower part of each pipe. Experiments were carried out under five different conditions simultaneously for every drop of the apparatus.

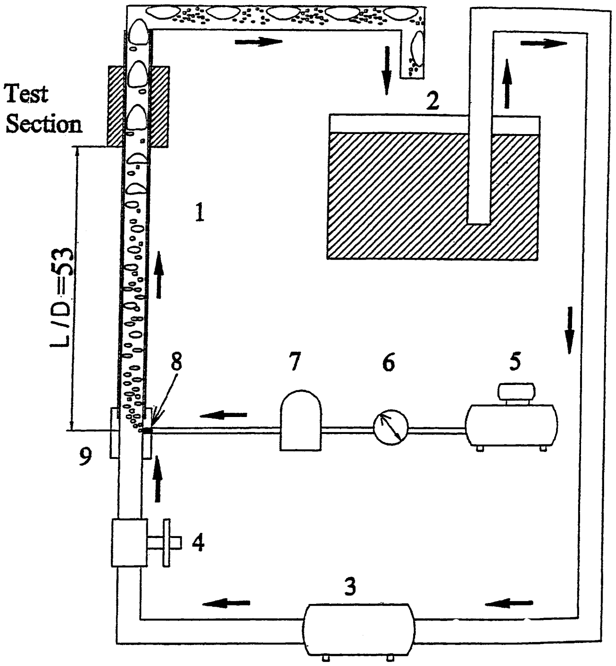

Fig. 1. Experimental apparatus: 1 – acrylic pipe; 2 – water tank; 3 – water pump; 4 – needle valve; 5 – air compressor; 6 – air regulator; 7 – mass flow controller; 8 – porous plug; 9 – connector.

A high-speed video camera was used to observe the behavior of bubbles and slugs in the axial region of $L/D \geqslant 53$. That is, the distance from the porous nozzle to the measurement position, L, was 530 mm, and the observations were carried out in the following 100 mm region. This region is considered to be located in the fully developed region. The rising velocity of a bubble or a slug, u_G, was calculated by dividing its vertical displacement by a prescribed time interval. The mean rising velocity, $\bar{u}_G$, in normal gravity was determined by averaging more than 50 data on u_G, the over-bar representing the ensemble-averaged value. In microgravity, bubbles passing through the measurement region were used to determine the mean rising velocity. The number of bubbles used for the determination of $\bar{u}_G$ therefore depends on the flow condition. The measurement uncertainty of rising velocity data in microgravity varied from ±15% to ±25% as the gas flow rate increased.

3. Experimental results and discussion

3.1. Histories of gravity level, water flow rate and gas flow rate

The histories of gravity level, g/g_0, and the water flow rate, Q_L, in each pipe are shown in Fig. 2 for a better understanding of the performance of the drop tower and the flow establishment time of air–water two-phase flows in microgravity. The start of the drop is indicated by $t = 0$. Just after the drop of the apparatus the acceleration in the gravitational direction, g, decreases suddenly from g_0 (= 9.8 m/s^2) to 2.0×10^{-2} m/s^2. The water flow rate, Q_L, slightly decreased due to the weightlessness but approached a new steady state value again. The flow establishment time is

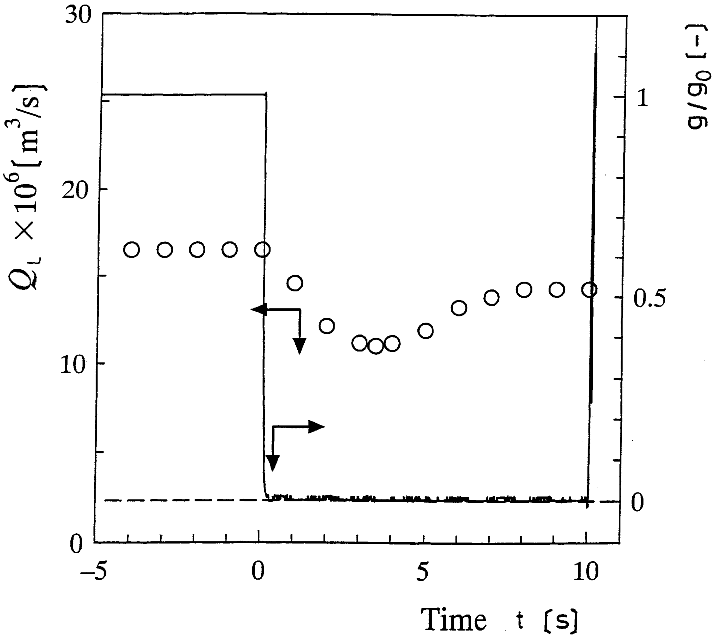

Fig. 2. Histories of water flow rate and gravity level.

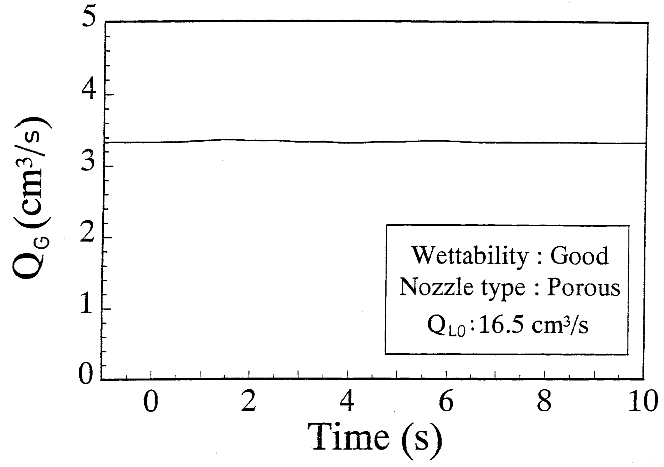

Fig. 3. History of gas flow rate.

defined as the period from the start of drop to the moment at which a new steady state is established in microgravity. This time is estimated to be approximately 7 s under the present experimental conditions. The gas flow rate, Q_G, was not affected by the gravity level, as can be seen in Fig. 3 because it was controlled by a mass flow controller. In this figure Q_{L0} denotes the water flow rate in the initial state in normal gravity.

3.2. Behavior of bubbles and slugs

Figs. 4(a)–(f) show examples typical of bubbles and slugs in the transient period from normal gravity to microgravity, where j_{L0} is the initial superficial velocity of water. Video images of bubbles and slugs taken under five different conditions are presented altogether in every figure. There is a great difference between the behavior of bubbles and slugs in the pipe of good wettability and that in the pipe of poor wettability both in normal gravity and microgravity. In the pipe of good wettability the corners of bubbles and slugs were rounded in microgravity due to the prevailing effect of the surface tension force. On the other hand, when the wettability of the pipe was poor, most bubbles and slugs rose in the pipe attaching to and detaching from the pipe wall. In particular, disk-like bubbles and slugs appeared for $Q_G = 8.62 \times 10^{-6}$ m^3/s ($j_G = 11.0$ cm/s) in the pipe of poor wettability in microgravity. Here, j_G is the superficial velocity of gas. The transient time was estimated to be approximately 7 s, as suggested from Fig. 2. The disk-like bubbles and slugs is more clearly seen in Figs. 5(a) and (b).

3.3. Correlation of mean rising velocity of bubbles and slugs

3.3.1. Normal gravity

The mean rising velocity of bubbles and slugs could be correlated by the following empirical relation (Nicklin et al., 1962) within a scatter of ±30% regardless of the wettability of the pipe (Iguchi and Terauchi, 2000a).

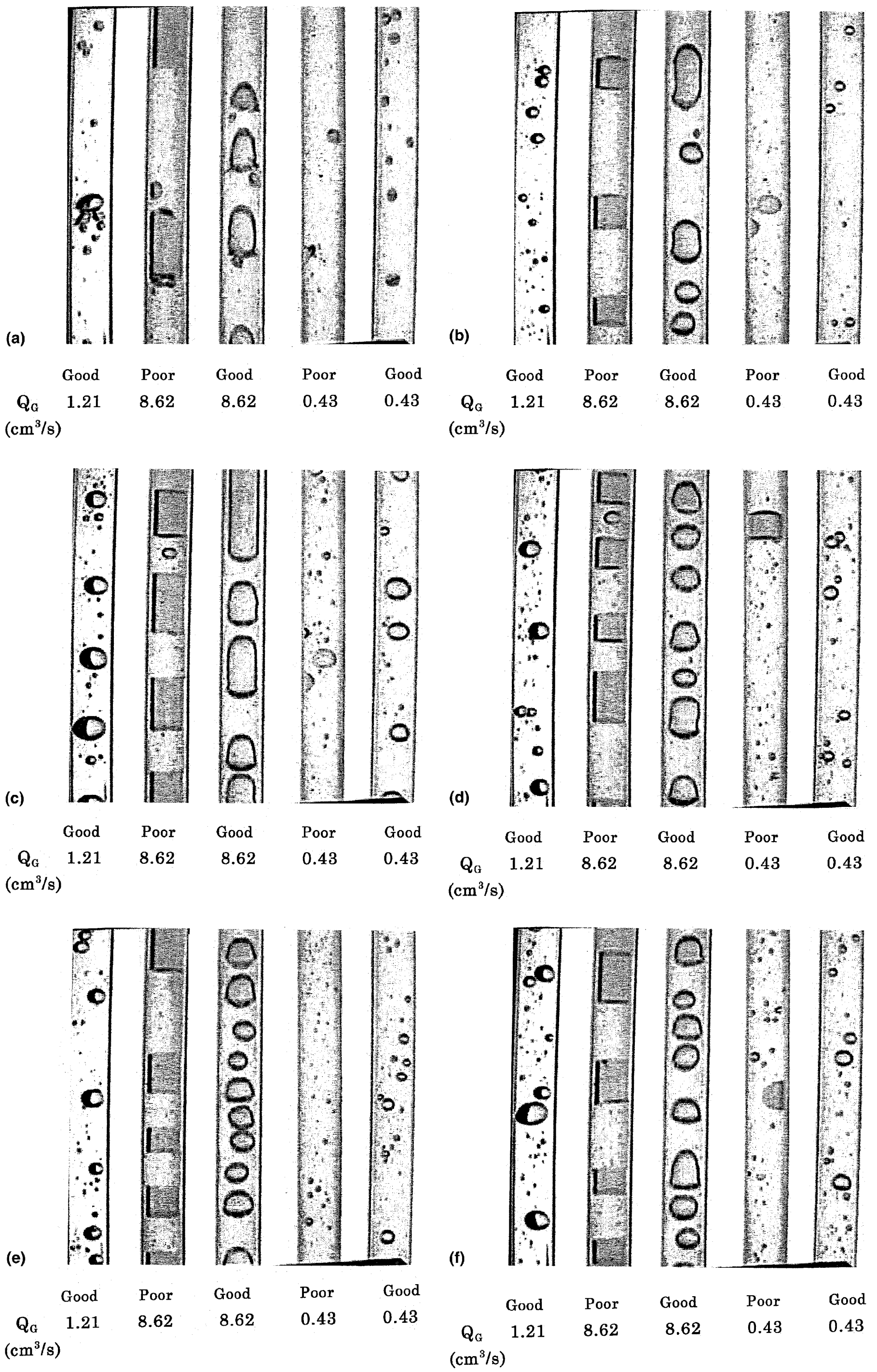

Fig. 4. Behavior of bubbles and slugs in vertical pipes of different wettability ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s, the subscript 0 means a value in normal gravity): (a) $t = -0.9$ s, (b) $t = 1.0$ s, (c) $t = 3.0$ s, (d) $t = 5.0$ s, (e) $t = 7.0$ s and (f) $t = 9.0$ s.

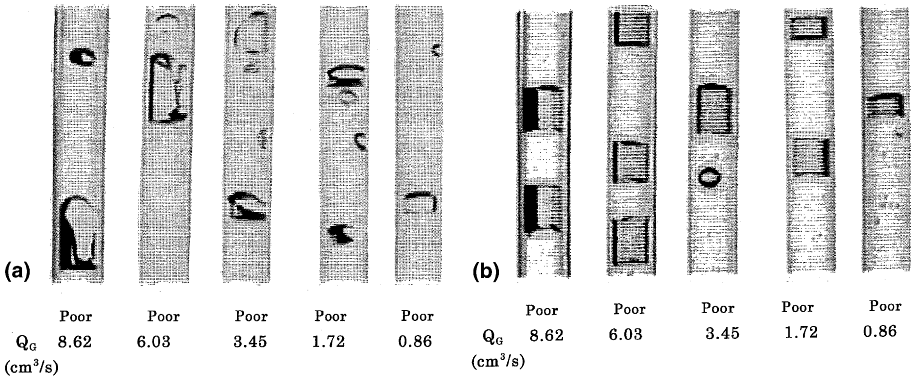

Fig. 5. Behavior of bubbles and slugs in vertical pipes of poor wettability ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s): (a) $t = -0.9$ s and (b) $t = 9.0$ s.

$$\bar{u}_G = 1.2(j_G + j_L) + 0.35[gD]^{1/2}. \tag{1}$$

The presently measured values of $\bar{u}_G$ in the pipes of good and poor wettability in normal gravity are also predicted by Eq. (1), as demonstrated in Fig. 6 with open symbols. Consequently, the attachment of bubbles and slugs to the pipe wall of poor wettability hardly affects the rising behavior of them under the experimental conditions considered.

3.3.2. Microgravity

Fig. 6 also shows the measured values of $\bar{u}_G$ in the steady state in microgravity ($t = 7$–10 s) against the gas flow rate, Q_G. Eq. (1) overestimates $\bar{u}_G$ in microgravity. The measured values of $\bar{u}_G$

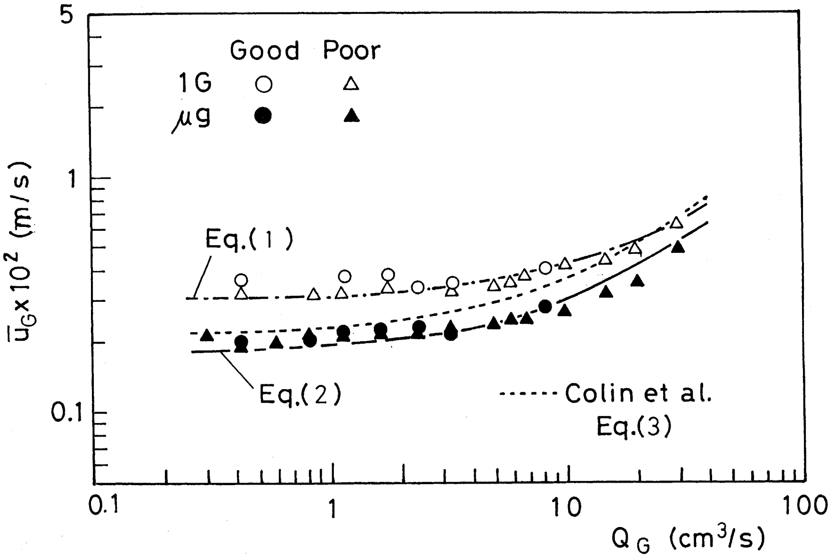

Fig. 6. Mean rising velocity of bubbles and slugs in normal gravity and microgravity ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s).

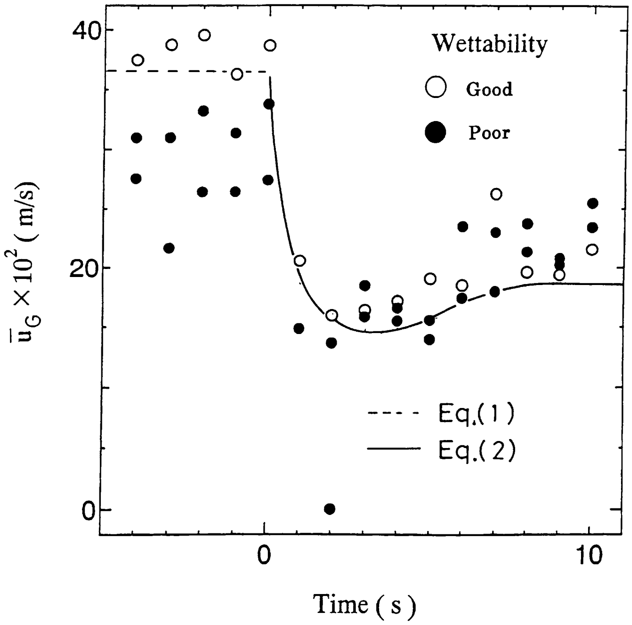

Fig. 7. Mean rising velocity of bubbles and slugs in transient period from normal gravity to microgravity ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s, $Q_G = 0.417$ cm^3/s, $j_G = 0.531$ cm/s).

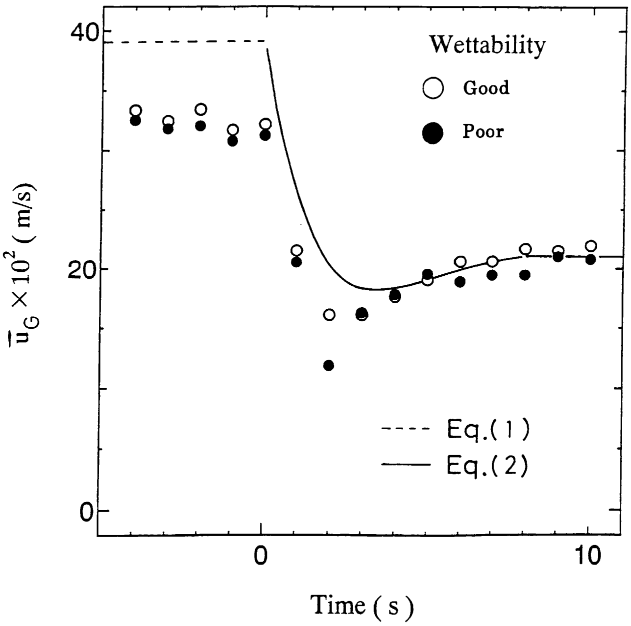

Fig. 8. Mean rising velocity of bubbles and slugs in transient period from normal gravity to microgravity ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s, $Q_G = 2.33$ cm^3/s, $j_G = 2.97$ cm/s).

in microgravity denoted by solid symbols can be satisfactorily predicted by the following equation regardless of the wettability of the pipe:

$$\bar{u}_G = j_G + j_L. \tag{2}$$

This is because the buoyancy force acting on bubbles and slugs disappears in microgravity.

Colin et al. (1991, 1996) assumed the following relation for $\bar{u}_G$ in microgravity:

$$\bar{u}_G = 1.2(j_G + j_L). \tag{3}$$

The coefficient, 1.2, reflects the radial distribution of fluid flow velocity in the pipe. This relation is drawn by a broken line in Fig. 6. Eq. (3), however, overestimates the rising velocity $\bar{u}_G$ for a higher gas flow rate in microgravity. These results collectively suggest that the radial distribution of fluid flow velocity is flattened in microgravity especially in the slug flow regime because of the disappearance of the buoyancy force.

If we focus only on the gas flow rate regime ranging from 0.3 to 3 cm^3/s ($j_G = 0.38$–3.8 cm/s), the following equation is more adequate, although it is not shown in order to avoid crowding in the figure:

$$\bar{u}_G = 1.1(j_G + j_L). \tag{4}$$

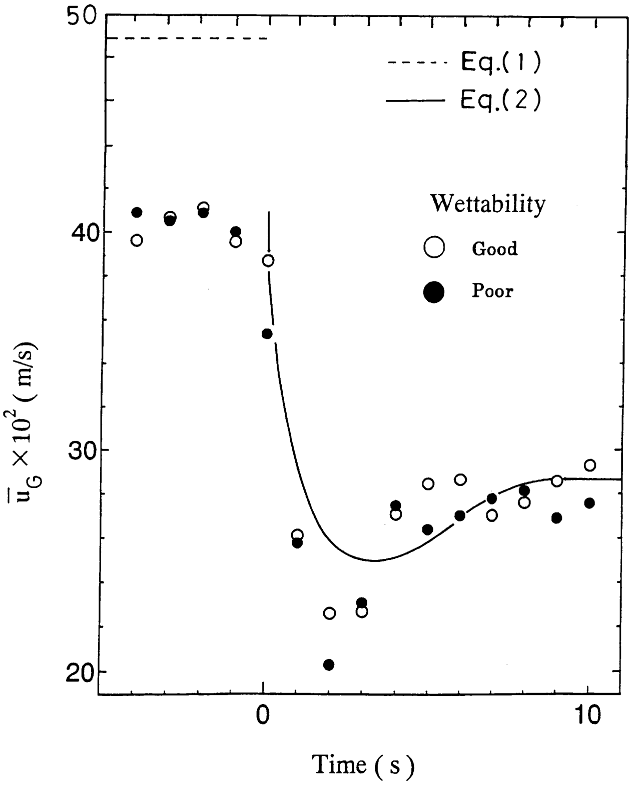

Fig. 9. Mean rising velocity of bubbles and slugs in transient period from normal gravity to microgravity ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s, $Q_G = 8.33$ cm^3/s, $j_G = 10.6$ cm/s).

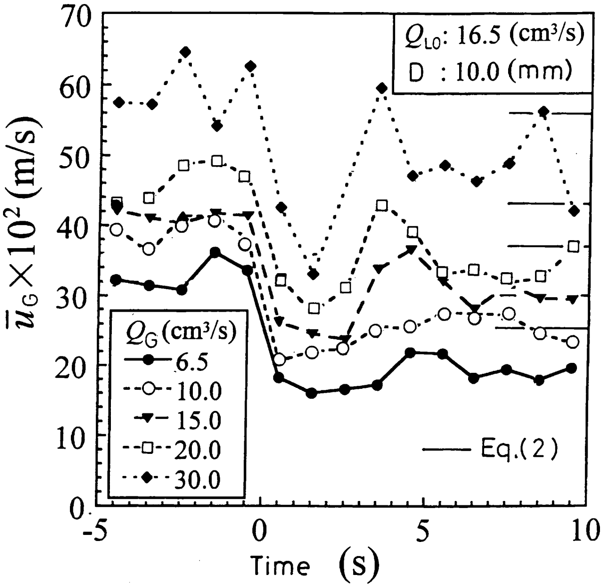

Fig. 10. Mean rising velocity of bubbles and slugs in transient period from normal gravity to microgravity ($D = 10.0$ mm, $Q_{L0} = 16.5$ cm^3/s, $j_{L0} = 21.0$ cm/s, $Q_G = 6.5$–30 cm^3/s, $j_G = 8.3$–38 cm/s).

As a difference between Eqs. (2) and (4) is at most 10%, we will use Eq. (2) under the subsequent discussion.

3.3.3. Transient period from normal gravity to microgravity

The change in the mean bubble rising velocity, $\bar{u}_G$, for lower gas flow rates during the drop of the experimental apparatus is shown in Figs. 7–9. The measurement uncertainty is ±15%. The data on $\bar{u}_G$ in the pipes of good and poor wettability, represented by open and solid symbols, respectively, agree with each other for every gas flow rate. Consequently, the wettability effect on $\bar{u}_G$ is small. Eq. (2) can predict the mean rising velocity $\bar{u}_G$ in the transient period from normal gravity to microgravity.

Fig. 10 shows data on $\bar{u}_G$ mainly for higher gas flow rates. The measurement uncertainty varied from ±15% to ±25% as Q_G increased. The histories of $\bar{u}_G$ with respect to time is nearly the same as those shown in Figs. 7–9.The measured values of $\bar{u}_G$ are satisfactorily predicted by Eq. (2) for the five gas flow rates.

4. Conclusions

Experiments were carried out in normal gravity and microgravity to understand the effects of the wettability of the pipe walls on the mean rising velocity of bubbles and slugs. The mean rising velocity in the steady state in microgravity ($t = 7$–10 s) was satisfactorily predicted by the following equation regardless of the wettability of the pipe under the experimental conditions considered:

$$\overline{u}_G = j_G + j_L.$$

This equation was valid also in the transient period from normal gravity to microgravity.

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