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Brief communication

Boundaries among bubbly and slug flow regimes in air–water two-phase flows in vertical pipe of poor wettability

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1. Introduction

Much effort has been devoted to understand the characteristics of gas–liquid two-phase flows in vertical and horizontal pipes used in a variety of engineering fields such as mechanical, chemical and atomic energy engineering (Wallis, 1965; Akagawa, 1980; Hetsroni, 1982; Ueda, 1989; Jpn. Soc. Mech. Eng.,1989). Most researchers have paid their attention to pipes of good wettability, i.e., pipes wetted with liquid. Information on the flow patterns, velocities of liquid and gas, pressure losses, heat transfer in the pipes of good wettability have been extensively accumulated. On the other hand, investigations on the effects of wettability on the characteristics are very limited (Barajas and Panton, 1993), although pipes of poor wettability have been widely used in materials engineering (Sugita, 1998) and atomic energy engineering. This lack of research is partly because the liquids i.e., molten metals used in these engineering fields are not transparent, and partly because the melting temperatures of the molten metals are usually very high, so that measurements of the aforementioned characteristics are dangerous. Accordingly, adequate sensors for measuring the characteristics under such severe conditions are absent at the present stage.

Model experiments, therefore, are expected to be carried out, but it is not easy to control and keep the wettability of a pipe for a long time even in the model experiments. Surface treatment is commonly applied to change the wettability of the pipe wall. The advancing contact angle, which is used to quantitatively represent the wettability (Iida and Guthrie, 1988), rapidly decreases due to contamination and in most cases, the pipe becomes wetted with liquid in a relatively short time. Accordingly, long-range experiments are difficult except in very rare cases.

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In this study, the advancing contact angle, θ_c, of an acrylic pipe was changed by coating a hydrophilic substance or liquid paraffin on the inner wall of an acrylic pipe. Three different values of θ_c were realized; $\theta_c = 36°, 77°$ and 104°. The flow pattern was observed with a still camera and a high-speed video camera to understand the effects of the wettability of the pipes on it.

2. Experimental apparatus and procedure

Fig. 1 shows a schematic of the experimental apparatus. The inner diameter of a transparent acrylic pipe, D, was 5.0, 10.0 or 15.0 mm. The original acrylic pipe had an advancing contact angle θ_c of 77°, and accordingly, it was wetted with water. The wettability of the pipe was changed by coating a hydrophilic substance or liquid paraffin. The advancing contact angle θ_c was 36° for the hydrophilic substance coating and 104° for the liquid paraffin coating. The former and the latter pipes are classified into a pipe of good wettability and a pipe of poor wettability, respectively. The lifetime of each coating was long enough to carry out systematic experiments. Although purified water was initially used, measurements were carried out after the water was fully contaminated. The water was circulated with a pump, and air was supplied through a porous nozzle settled flush on the inner wall of the lower part of each pipe. The diameter of the nozzle, d_p was 4.0 mm and it had a pore diameter of 270 μm and porosity of 25%. Pulsation arising from the compressor was satisfactorily suppressed with a filter, though it is not drawn in the figure. The shape and size of

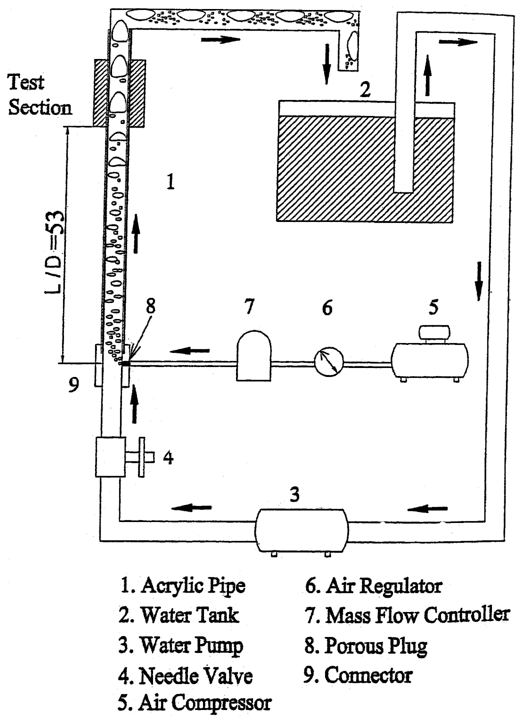

Fig. 1. Experimental apparatus.

bubbles and slugs rising in the fully developed region of $L/D \geqslant 53$ for the three kinds of pipes were recorded with a still camera and a high-speed video camera at 200 frames/s.

3. Experimental results and discussion

3.1. Flow pattern

The changes in the flow patterns of air–water two-phase flows in the three pipes of different contact angles are shown in Fig. 2, where j_G and j_L denote the superficial velocities of air and water, respectively. This figure was reproduced from a previous paper (Terauchi et al., 1999). Each shaded portion appearing in the upper row in Fig. 2 indicates a part of a bubble or a slug being in contact with the pipe wall. The flow pattern of air–water two-phase flows in the pipe of $\theta_c = 36°$ was almost the same as that in the pipe of $\theta_c = 77°$. This fact means that the flow pattern of air–water two-phase flows in a vertical pipe of good wettability is hardly influenced by the contact angle at least for θ_c from 36° to 77°. For the sake of simplicity, only the experimental results obtained for the pipes of $\theta_c = 77°$ and 104° will be presented to discuss the effects of the wettability of the pipe on the flow pattern.

When the wettability of a pipe was poor and j_L was lower than a certain critical value, $j_{L,cr}$, bubbles and slugs frequently attached to the pipe wall. They did not remain there, but ascended in the pipe repeating attachment to and detachment from the pipe wall. Such a behavior has never been observed in the pipe of good wettability. Accordingly, bubbly flows in the pipe of

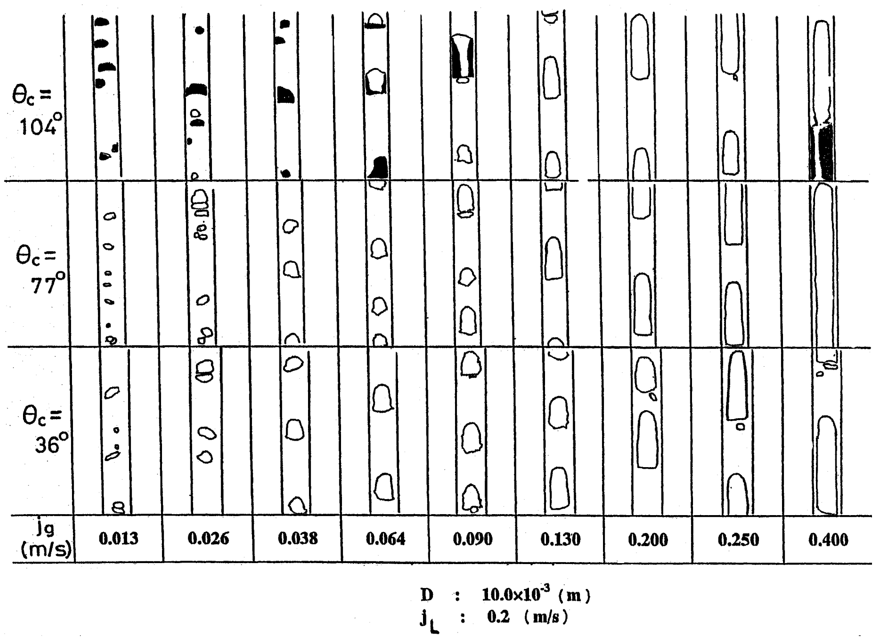

Fig. 2. Flow patterns in pipes with different contact angles.

poor wettability for $j_L < j_{L,cr}$ were classified further into two categories, and slug flows in the same pipe for $j_L < j_{L,cr}$ were classified further into three types, as shown in the previous paper (Terauchi et al., 1999). However, detailed discussion on the boundaries among the bubbly and slug flow regimes was not given there. For a better understanding of the flow patterns in a vertical pipe of poor wettability, the definitions of the bubbly and slug flows will be explained below. Discussion on the critical superficial velocity of water, $j_{L,cr}$, will also be given in a later section.

3.1.1. Classification of bubbly flows in the pipe of poor wettability for $j_L < j_{L,cr}$

Two types of bubbly flows were observed in the pipe of $\theta_c = 104°$.

(1) *Bubbly flow a*: Small bubbles of almost ellipsoidal shape ascend repeating attachment to and detachment from the pipe wall.

(2) *Bubbly flow b*: When relatively large bubbles attach to the pipe wall, they spread in the circumferential (horizontal) direction and sometimes become piston-like bubbles or donut-like bubbles. However, these bubbles never remain on the pipe wall. The vertical length of these is less than the pipe diameter.

3.1.2. Classification of slug flows in pipe of poor wettability for $j_L < j_{L,cr}$

(1) *Slug flow a*: Bullet-like slugs spread on the pipe wall when they attach to the pipe wall and become bullet-like in shape again as they detach from the pipe wall. Such slugs resemble bubbles classified into the aforementioned bubbly flow b when they are in contact with the pipe wall, but their sizes are much larger than those bubbles.

(2) *Slug flow b*: Bullet-like slugs rise without attaching to the pipe wall, but small bubbles behind them repeat attachment to and detachment from the pipe wall.

(3) *Slug flow c*: Bullet-like slugs ascend as their rear parts repeat attachment to and detachment from the pipe wall.

3.2. Determination of boundaries among bubbly and slug flow regimes

3.2.1. Pipe of good wettability

Many empirical equations have been proposed to describe the boundary between the bubbly flow and slug flow regimes in a vertical pipe of good wettability (Wallis, 1965; Taitel et al., 1980; Weisman and Kang, 1981; Mishima and Ishii, 1984). The boundary for the good wettability pipe, determined in this study, is drawn by a solid line in Fig. 3. It is approximately described by the following empirical equation proposed by Taitel et al. (1980):

$$j_L = 3.0\, j_G - 1.15(\sigma g \Delta\rho/\rho_L^2)^{1/4}, \tag{1}$$

where σ is the surface tension of the liquid, g the acceleration due to gravity, $\Delta\rho$ the density difference, and ρ_L is the density of the liquid.

3.2.2. Pipe of poor wettability

Fig. 4 shows the boundaries among the three types of bubbly flows and four types of slug flows. The boundary between the bubbly flow regimes denoted by open symbols and the slug flow regimes denoted by solid symbols is represented by a solid line. This boundary is found to be almost

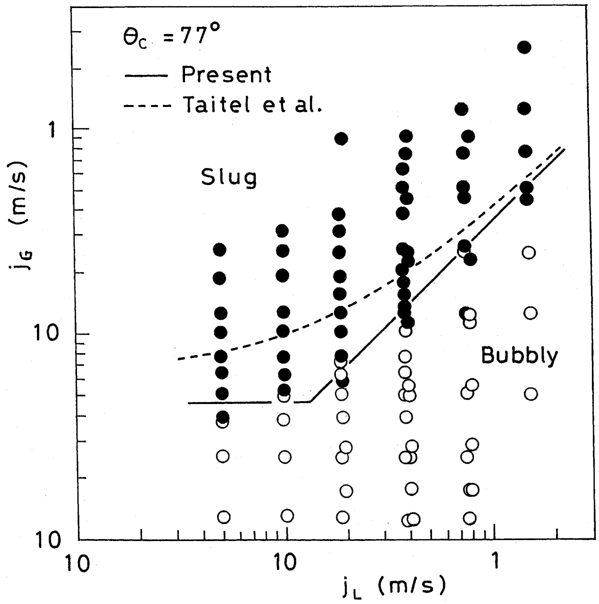

Fig. 3. Boundary between bubbly flow and slug flow regimes in pipe of good wettability.

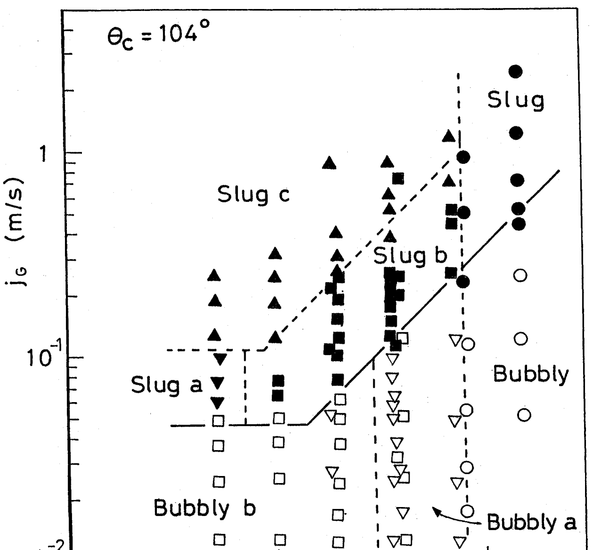

Fig. 4. Boundaries among bubbly and slug flow regimes in pipe of poor wettability.

the same as that for the good wettability pipe shown in Fig. 3 and accordingly, it is hardly affected by the wettability of the pipe. For $j_L > 0.8$ m/s, the behavior of bubbles and slugs is almost independent of the wettability of the pipe.

As the pipe diameter decreases, capillary forces become dominant, especially in a pipe of poor wettability. We therefore introduced the Weber number similitude in order to correlate the boundaries among the bubbly and slug flow regimes. The two kinds of Weber numbers are defined as follows:

$$We_{SG} = \rho_G D j_G^2 / \sigma, \tag{2}$$

$$We_{SL} = \rho_L D j_L^2 / \sigma, \tag{3}$$

where ρ_G is the density of gas.

The boundaries among the three types of bubbly flows and four types of slug flows are shown in Fig. 5. This arrangement is satisfactory for correlating the boundaries too. The effect of the wettability of the pipe on the behavior of bubbles and slugs disappears when the Weber number, We_{SL}, exceeds approximately 100.

$$We_{SL,cr} = \rho_L D j_{L,cr}^2 / \sigma = 100. \tag{4}$$

Therefore, the critical superficial velocity of water, $j_{L,cr}$, is approximated by

$$j_{L,cr} = 10[\sigma/(\rho_L D)]^{1/2}. \tag{5}$$

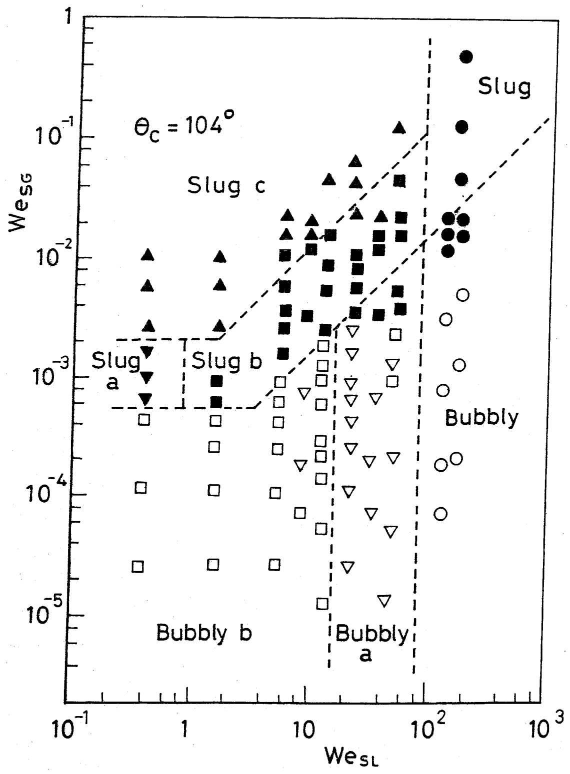

Fig. 5. Correlation of boundaries among bubbly and slug flow regimes in terms of Weber number similitude.

It is not clear whether this equation is valid or not under experimental conditions beyond the presently mentioned conditions. Further discussion on the adequacy of this equation must be left for a future study.

4. Conclusions

The effects of the wettability of a vertical pipe on the flow pattern of air–water two-phase flows in the pipe were experimentally investigated. Main findings obtained in this study are summarized as follows.

When a pipe was not wetted with water, ($\theta_c = 104°$) and the superficial velocity of water, j_L, was lower than a critical value, $j_{L,cr}$, bubbles and slugs ascended repeating attachment to and detachment from the pipe wall. Such a phenomenon never took place in the pipe of good wettability for $j_L < j_{L,cr}$. Accordingly, bubbly flows in the pipe of poor wettability were classified further into two types and slug flows in the same pipe were classified further into three types. When the superficial velocity of water was higher than the critical value, the bubbly and slug flows typical of two-phase flows in the pipe of good wettability were observed. The boundary between the bubbly flow and slug flow regimes was hardly dependent on the wettability of the pipe. Also, the boundaries among three types of bubbly flows and four types of slug flows were determined as shown in Figs. 4 and 5. An empirical equation, Eq. (5), was proposed for the critical superficial velocity, $j_{L,cr}$.

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