Rising Behavior of Air–Water Two-phase Flows in Vertical Pipe of Poor Wettability

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Bubbles and slugs rising in vertical pipes of good and poor wettability were observed with a high-speed video camera. The mean rising velocity of bubbles on the pipe center line was slightly smaller in the poor wettability pipe than that in the good wettability pipe because the attachment of bubbles to the pipe wall took place in the former pipe, while that of slugs was hardly dependent on the wettability of the pipe. The mean vertical length of bubbles on the pipe center line was slightly larger in the pipe of poor wettability than that in the pipe of good wettability due to the coalescence of bubbles on the wall of the pipe of poor wettability. However, the mean vertical length of slugs was not dependent on the wettability of the pipe. An empirical equation was proposed for the mean vertical length of slugs.

KEY WORDS: gas–liquid two-phase flow; wettability; bubble; slug; bubble rising velocity; bubble length; vertical pipe.

1. Introduction

The wettability of materials used for the refractories and pipes in the current metal processing systems is usually very poor in order to avoid contamination of molten metals due to chemical reactions with the materials. According to previous studies on the behavior of bubbles rising along a flat plate and rising in a vertical pipe, the bubbles were found to frequently attach to the walls of the plate and pipe. Such a phenomenon would cause changes in the momentum, heat, and mass transfer from the walls. Information on the interaction between bubbles and walls of poor wettability therefore is of practical importance for the design of metal processing systems. The poor wettability means that the walls are not wetted with liquid, i.e., the advancing contact angle \( \theta_i \) falls between 90 deg. and 180 deg.

In the previous study, the flow patterns of air–water two-phase flows in a vertical pipe of poor wettability were experimentally investigated. The advancing contact angle of the pipe, \( \theta_i \), was 104 deg. Before discussing the rising behavior of bubbles and slugs, the result will be briefly reviewed below for a better understanding of the air–water two-phase flows in the poor wettability pipe. When the superficial velocity of water, \( j_w \), is higher than a certain critical value, \( j_w,c \), bubbles and slugs just like those appearing typically in a good wettability pipe were observed in the pipe of poor wettability, too. On the other hand, bubbles and slugs in the pipe of poor wettability ascended repeating attachment to and detachment from the pipe wall for \( j_w \leq j_w,c \).

Accordingly, the bubbly flows for \( j_w \leq j_w,c \) were classified further into two types and the slug flows for \( j_l \leq j_l,c \) were classified further into three types. The boundary between the bubbly flow regime and the slug flow regime, however, was hardly dependent on the wettability of the pipe.

In this study the mean rising velocity, \( \bar{u}_{ic} \), and mean vertical length, \( L_{vc} \), of bubbles and slugs in the pipe of poor wettability are measured with a high-speed video camera. The results are compared with those obtained in a pipe of good wettability \( (\theta_i = 77 \text{ deg.}) \). An empirical equation is proposed for \( L_{vc} \) in the slug flow regime.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic of the experimental apparatus. The inner diameter of a transparent acrylic pipe, \( D \), was 5.0 mm, 10.0 mm, or 15.0 mm. The original acrylic pipe had an advancing contact angle \( \theta_i \) of 77 deg., 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 \( \theta_i \) was 36 deg. for the hydrophilic substance coating and 104 deg. for the liquid paraffin coating. According to the aforementioned criterion, the former and the latter pipes are classified into a pipe of good wettability and a pipe of poor wettability, respectively.

The life time of each coating was long enough to carry out systematic experiments. Water was circulated with a pump and air was supplied with a compressor through a porous nozzle placed flush on the inner wall of the lower part of each pipe. The diameter of the nozzle, \( d_{np} \), was 4.0 mm, and it had a pore diameter of 270 \( \mu \text{m} \) and porosity of 25%.
A still camera and a high-speed video camera were used to observe the behavior of bubbles and slugs in the fully developed region in the pipe. The rising velocity of a bubble or a slug was calculated by dividing its vertical displacement by a prescribed time interval. The mean rising velocity was determined by averaging more than 50 rising velocity data. The vertical length of a bubble or a slug was determined from its image recorded on the high-speed video camera.

3. Experimental Results and Discussion

3.1. Flow Pattern

Although the flow patterns of air–water two-phase flows in the pipe of poor wettability are described in detail in the previous paper, we shall summarize them here again. The boundary between the bubbly and slug flow regimes was hardly dependent on the wettability of the pipe. Among many existing empirical equations, the following empirical equation proposed by Taitel et al. was the most adequate to predict the boundary observed in this study, as discussed in the previous paper.

\[ j_L = 3.0 j_G - 1.15 (\sigma g \Delta \rho / \rho_L)^{1/4} \]  

where \( j_L \) and \( j_G \) denote the superficial velocities of water and air, respectively, \( \sigma \) is the surface tension of water, \( g \) is the acceleration due to gravity, \( \Delta \rho = \rho_a - \rho_L \) is the density difference, \( \rho_a \) is the density of air and \( \rho_L \) is the density of water. The two superficial velocities are defined as

\[ j_G = Q_G / (\pi D^2/4) \]  
\[ j_L = Q_L / (\pi D^2/4) \]  

where \( Q_G \) and \( Q_L \) are the air flow rate and the water flow rate, respectively.

The behavior of bubbles and slugs in the vertical pipe of poor wettability (\( \theta_c = 104 \) deg.) was much different from that observed in the pipe of good wettability (\( \theta_c = 77 \) deg.) when the superficial velocity of water, \( j_L \), was lower than a certain critical value \( j_{L,cr} \). Re-examination of the data on the critical value yields

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

Bubbles and slugs in the pipe of poor wettability frequently attached to the pipe wall while rising in the pipe. They did not remain there, but ascended repeating attachment to and detachment from the pipe wall. Accordingly, the bubbly flows in the pipe of poor wettability for \( j_L < j_{L,cr} \) were classified further into two categories, and the slug flows under the same condition were also classified further into three types, as presented already in Introduction. On the other hand, the movements of bubbles and slugs for \( j_L > j_{L,cr} \) were hardly influenced by the wettability of the pipe.

3.2. Mean Rising Velocity of Bubbles and Slugs on the Pipe Center Line

Measured values of mean rising velocity \( \bar{u}_G \) are shown in Figs. 2 through 4. Three arrows in each figure denote the boundaries between the bubbly and slug flow regimes for three different \( j_L \) values calculated from Eq. (1). In the slug flow regime there is no difference between the values of \( \bar{u}_G \) measured in the good and poor wettability pipes, while the
mean rising velocity $\bar{u}_G$ in the bubbly flow regime for $j_L \geq j_{L,cr}$ is slightly smaller in the poor wettability pipe than that in the good wettability pipe. This is because bubbles in the poor wettability pipe are likely to attach to the pipe wall and, as a result, the vertical movements of them are suppressed.

Figures 5 and 6 show the measured values of mean rising velocity $\bar{u}_G$ in the good and poor wettability pipes, respectively. If we allow a scatter of $\pm 30\%$, the measured values of $\bar{u}_G$ both in the bubbly flow and slug flow regimes can be approximated by the following equation,\(^9\) irrespective of the wettability of the pipe.

$$\bar{u}_G = 1.2(j_G + j_L) + 0.35(gD)^{1/2} \text{....................(5)}$$

In the slug flow regime the following empirical equation proposed by Kariyasaki et al.\(^9\) is also valid.

$$\bar{u}_G = 1.2(j_G + j_L) \text{....................(6)}$$

Further discussion on the effect of the wettability on the rising velocity of bubbles in the whole pipe cross section must be left for a future study.

### 3.3. Mean Vertical Length of Bubbles and Slugs on the Pipe Center Line

Figures 7 through 9 show measured values of the mean vertical length of bubbles and slugs in the good and poor wettability pipes. The measured values of $L_G$ in the bubbly flow regime are larger in the pipe of poor wettability than those in the pipe of good wettability. This is because bubbles generated in the pipe of poor wettability are likely to coalesce on the pipe wall while ascending in the pipe.
Further discussion will be given separately on $L_G$ of slugs in the good and poor wettability pipes.

3.3.1. Mean Vertical Length of Slugs in Pipe of Good Wettability

Akagawa and Sakaguchi\(^\text{10,11}\) proposed the following empirical equation.

$$ L_G = 69.7 \text{ cm/s} / 1.5 \text{ cm} \approx 1.5 \text{ cm} $$(7)

Also, Street and Tek\(^\text{11}\) derived the following equation.\(^\text{12}\)

$$ L_G = 0.29 j_{G} / \sqrt{j_{L}} \approx 0.29 j_{G} / (j_{L} + 0.12) \approx 0.29 j_{G} / (j_{L} + 0.12) $$

The units of $L_G$, $j_G$, and $j_L$ in Eqs. (7) and (8) are m, m/s, and m/s, respectively. Equations (7) and (8) however could not approximate the presently measured values of $L_G$. For example, the measured value of $L_G$ is approximately 1.5 cm in case of $D=1.0$ cm, $j_G=20.0$ cm/s, and $j_L=38.2$ cm/s, while Eqs. (7) and (8) yield 12.1 cm and 11.6 cm, respectively. Accordingly, we shall try to derive an empirical equation for $L_G$ in the slug flow regime.

In the slug flow regime specified by Eq. (1) the mean vertical length of slugs, $\bar{L}_G$, is proportional to $j_G$ (see Fig. 8) but inversely proportional to $j_L^{3/4}$ (see Fig. 11). The relationship between the length $\bar{L}_G$ and the pipe diameter $D$ in the slug flow regime is shown in Fig. 9. It is evident that $\bar{L}_G$ is proportional to $D^{7/8}$. These results collectively suggest that $\bar{L}_G$ is proportional to $DFr_G/DFr_L^{3/4}$ in the slug flow regime because $DFr_G/DFr_L^{3/4}$ is expressed by

$$ DFr_G/DFr_L^{3/4} = j_G / \sqrt{j_L} \approx j_G / \sqrt{j_L} $$

$$ Fr_G = j_G / (gD)^{1/2} \approx j_G / (gD)^{1/2} \approx j_G / (gD)^{1/2} $$

$$ Fr_L = j_L / (gD)^{1/2} \approx j_L / (gD)^{1/2} \approx j_L / (gD)^{1/2} $$

The presently measured values of $\bar{L}_G/D$ are plotted against $Fr_G/DFr_L^{3/4}$ in Fig. 13 together with those obtained by Akagawa and Sakaguchi.\(^\text{10}\) All the measured values in the slug flow regime can be correlated by this arrangement method, and accordingly, the following empirical equation is proposed.

$$ \bar{L}_G/D = 4.7[Fr_G/DFr_L^{3/4}]^{17} \approx 4.7[Fr_G/DFr_L^{3/4}]^{17} $$

This equation can approximate the measured values within a scatter of $\pm 30\%$. It should be noted that the dependence of $\bar{L}_G$ on $j_G$, $j_L$, and $D$ described by Eq. (12) is slightly different from that described by Eq. (9). The derivation of empirical equation of $\bar{L}_G$ in the bubbly flow regime must be left for a future study.
3.3.2. Mean Vertical Length of Slugs in Pipe of Poor Wettability

In the slug flow regime, $L_G/ D$ was hardly influenced by the wettabiliy of the pipe and approximated by Eq. (12), as demonstrated in Fig. 14.

4. Conclusions

The effects of the wettability of a vertical pipe on the characteristics 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 wetted with water, the measured values of the mean rising velocity of slugs, $u_G$, were approximated by an empirical equation proposed previously by Nicklin et al. Also, when a pipe was not wetted with water, i.e., the wettability of the pipe was poor, that empirical equation was valid. The mean rising velocity of bubbles was slightly smaller in the pipe of poor wettability than in the pipe of good wettability. However, if we allow a scatter of $±30\%$, the mean rising velocity of bubbles can be predicted by the empirical equation proposed by Nicklin et al.

An empirical equation was newly proposed for the mean vertical length of slugs, $L_G$, in the pipe of poor wettability. This equation could satisfactorily approximate measured values of $L_G$ reported by previous researchers. The measured value of $L_G$ in the slug flow regime in the pipe of poor wettability almost agreed with those in the pipe of good wettability. On the other hand, the mean vertical length of bubbles in the pipe of poor wettability was slightly larger than that in the pipe of good wettability. This is because bubbles are likely to coalesce on the wall of the pipe of poor wettability.

In this study the mean rising velocity and mean vertical length of bubbles and slugs were measured only on the pipe center line. Further experimental investigations on the distributions of these quantities in the whole cross section must be required for full understanding of the effects of the wettability of the pipe on the characteristics of bubbles and slugs.

Nomenclature

- $D$: pipe diameter
- $d$: nozzle diameter
- $F_{RG}$: Froude number based on superficial velocity of gas $=j_G/(gD)^{1/2}$
- $F_{RL}$: Froude number based on superficial velocity of liquid $=j_L/(gD)^{1/2}$
- $g$: acceleration due to gravity
- $L_G$: mean vertical length of bubbles and slugs on pipe center line
- $Q_G$: gas flow rate
- $Q_L$: liquid flow rate
- $u_G$: mean rising velocity of bubbles and slugs on pipe center line
- $\sigma$: surface tension
- $\theta_c$: contact angle

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