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マイクロ管内スラグ流の液膜厚さに及ぼす加速度の影響
The effect of bubble acceleration on the liquid film thickness in micro tube

＊韓　栄培　（東大院）　伝正　鹿園　直毅　（東大工）

Youngbae HAN and Naoki SHIKAZONO
Dept. of Mech. Eng., The Univ. of Tokyo, 3-1, Honggo 7, Bunkyo-ku, Tokyo 113-8656

It is well known that the thin liquid film formed between the tube wall and the vapor bubble plays an important role in micro scale heat transfer. In the present study, the effects of bubble acceleration on the liquid film thickness are investigated. Under flow boiling condition, bubble velocity is not constant but accelerated. It is necessary to consider this acceleration effect on the liquid film thickness, since it may affect the viscous, surface tension and inertia forces in the momentum equation. In addition, viscous boundary layer develops, and it may also affect the liquid film thickness. Laser focus displacement meter is used to measure the liquid film thickness. Ethanol, water and FC-40 are used as working fluids. Circular tubes with three different diameters, D = 0.5, 0.7 and 1.0 mm, are used. The increase of liquid film thickness with capillary number is restricted by bubble acceleration. An empirical correlation is proposed in terms of capillary number and Bond number based on the bubble acceleration.

Key Words : Liquid film, Two-phase flow, Bubble acceleration, Micro tube

1. Introduction

Micro scale heat transfer attracts large attention due to its many advantages, e.g., high efficiency, miniaturization, etc. It is well known that the thin liquid film formed between the tube wall and the vapor bubble plays an important role in micro tube heat transfer. It is reported that the thickness of the liquid film is one of the important parameters for the prediction of flow boiling heat transfer in micro tubes(1, 2). Although many experiments have been carried out to measure the liquid film thickness in micro tubes, most of the experiments were conducted under adiabatic condition. However, under flow boiling condition, the bubble velocity is not constant but accelerated. It is necessary to consider this acceleration effect on the liquid film thickness, since it may affect the viscous, surface tension and inertia forces in the momentum equation. In addition, viscous boundary layer develops, and it may also affect the liquid film thickness. In the present study, the effect of bubble acceleration on the liquid film thickness is investigated experimentally.

2. Experimental Setup and Method

Circular tubes made of Pyrex glass with inner diameters of 0.5, 0.7 and 1.0 mm were used as test tubes. Table 1 shows the dimensions of micro tubes. Ethanol, water and FC-40 were used as the working fluids. Figure 1 shows the schematic diagram of the experimental setup. One side of Pyrex glass tube is connected to the syringe. Actuator motor (EZHC6A-101, Oriental motor) is used to pull the liquid in the micro tube. High-speed camera (Phantom 7.1) is used to measure the bubble velocity and acceleration. LFDM (Laser focus displacement meter, LT9010M, Keyence) is used to measure the liquid film thickness. LFDM has been used by several researchers for liquid film thickness measurements(3-5). The position of the target surface can be determined by the displacement of objective lens moved by the tuning fork. The intensity of the reflected light becomes highest in the light-receiving element when the focus is obtained on the target surface. Measured liquid film thickness is transformed to DC voltage signal in the range of ±10V. Output signal was sent to PC through GPIB interface and recorded with LabVIEW.

Table 1 Dimensions of the micro tubes.

Circular tube		
I.D. (mm)	O.D. (mm)	Length (mm)
0.995	1.6	250
0.715	1.0	250
0.487	0.8	250

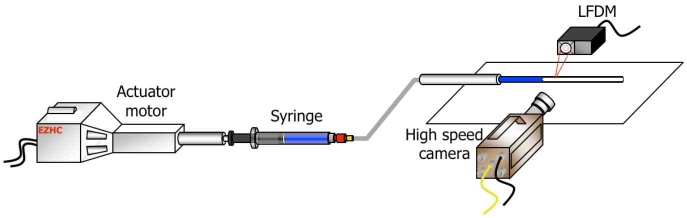

Fig. 1 Schematic diagram of the experimental setup for the adiabatic bubble acceleration.

In order to investigate the effect of bubble acceleration, the measuring point is positioned at L = 5, 10 and 20 mm away from the air-liquid interface as shown in Fig. 2. Figure 3 shows a typical measurement example. After the initial quick decreasing part, liquid film thickness decreases with time due to the shear force of gas flow.

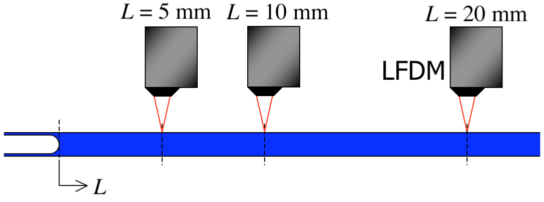

Fig. 2 Initial bubble location L = 0 and the measuring points, L = 5, 10 and 20 mm.

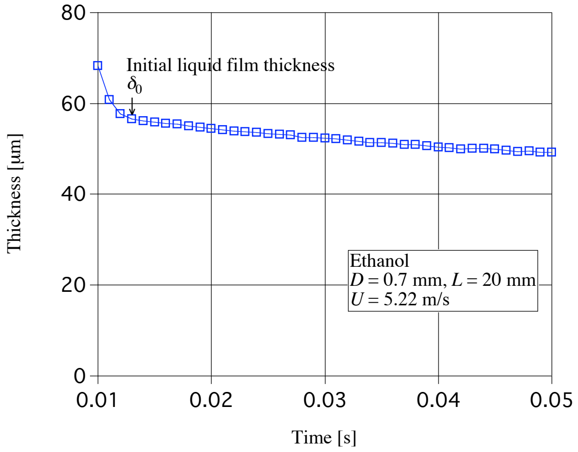

Fig. 3 Liquid film thickness against time, ethanol, D = 0.7 mm, L = 20 mm, U = 5.22 m/s.

3. Results and Discussions

3.1 The effect of bubble acceleration

Figure 4 shows the dimensionless liquid film thickness against capillary number using ethanol, D = 0.7 mm. Acceleration is larger for larger capillary numbers. Liquid film thickness is identical with the zero acceleration curve at small capillary number. However, as capillary number increases, liquid film thickness becomes constant and is much smaller than the zero acceleration case. It is considered that viscous boundary layer developed by bubble acceleration affects the liquid film thickness. Liquid film thickness is governed by two different modes. If the viscous boundary layer is thick, liquid film is identical to the zero acceleration case. If the viscous boundary layer is thin, force balance is affected by the viscous boundary layer, and liquid film thickness deviates from the zero acceleration case. Figure 5 shows dimensionless liquid film thickness against dimensionless viscous boundary layer thicknesd . In Fig. 5, it is shown that experimental values approach asymptotic lines when the viscous boundary layer thickness is thin. These lines correspond to the restriction on the liquid film thickness caused by the viscous boundary layer. These restriction lines are different depending on the working fluids. At the same viscous boundary layer thickness, liquid film thickness becomes thinner for water.

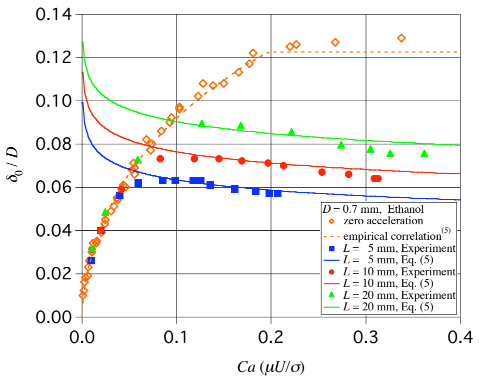

Fig. 4 Dimensionless liquid film thickness (δ_0/D) against capillary number (Ca = $\mu U/\sigma$) at different measuring points using ethanol, L = 5, 10 and 20 mm, D = 0.7 mm.

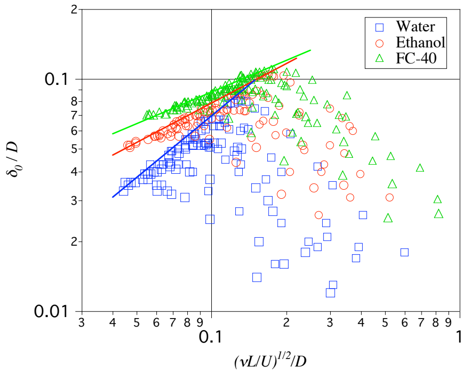

Fig. 5 Dimensionless liquid film thickness (δ_0/D) against dimensionless viscous boundary layer thickness $(\nu L/U)^{1/2}/D$.

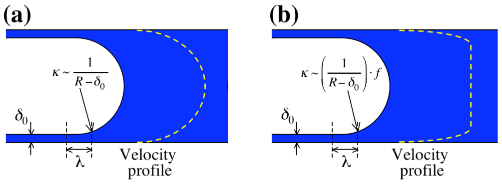

Fig. 6 Schematic diagram of velocity profiles: (a) steady condition - zero acceleration (b) acceleration condition.

3.2 Scaling analysis for the bubble acceleration

Figure 6 shows the schematic diagram of velocity profiles under steady and acceleration conditions. Bubble nose curvature is affected by the thin viscous boundary layer. Under acceleration, the bubble nose curvature is modified as:

$$\kappa \sim \left(\frac{1}{R-\delta_0}\right)\cdot f. \tag{1}$$

If the bubble nose curvature is replaced with Eq. (1), relation of dimensionless liquid film thickness is changed as follows:

$$\frac{\delta_0}{D} \sim \frac{Ca^{2/3}\cdot f^{-1}}{1+Ca^{2/3}\cdot f^{-1}}. \tag{2}$$

In order to obtain a relation for f, Eq. (2) is rewritten as(6) :

$$f \sim \frac{0.67Ca^{2/3}}{\delta_0/D} - 3.35Ca^{2/3}. \tag{3}$$

In order to express the bubble acceleration effect, Bond number based on the bubble acceleration is introduced. The bubble acceleration is simply expressed with the assumption of uniform acceleration as follows:

$$Bo = \frac{\rho a D^2}{\sigma}, \quad a = \frac{U^2}{2L}. \tag{4}$$

Figure 7 shows the relationship between R.H.S. of Eq.(3) and the Bond number. Only the experimental data that deviate from the zero acceleration case are used. All the data are well correlated with a single line, $0.692Bo^{0.414}$. Therefore, this line is adopted for the expression of f. Finally, an experimental correlation of the liquid film thickness under bubble acceleration becomes as follows:

$$\frac{\delta_0}{D} = \frac{0.968Ca^{2/3}Bo^{-0.414}}{1+4.838Ca^{2/3}Bo^{-0.414}}. \tag{5}$$

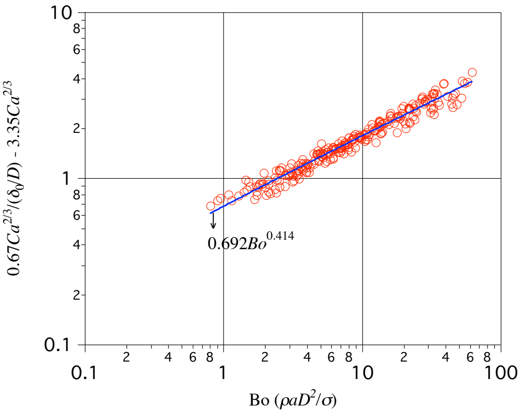

Fig. 7 R.H.S of Eq. (3) against Bond number ($\rho aD^2/\sigma$).

4. Conclusion

Liquid film thickness in micro tubes under bubble acceleration is investigated. If the viscous boundary layer is thin, liquid film thickness is restricted by the viscous boundary layer. Experimental correlation on the liquid film thickness under bubble acceleration condition is proposed in terms of capillary number and Bond number based on the bubble acceleration.

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References

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