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LIQUID FILM THICKNESS OF OSCILLATING FLOW IN A MICRO TUBE

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ABSTRACT

Oscillating flow is encountered frequently in many two-phase flow systems such as pulsating heat pipe, refrigerator with reciprocating compressor, etc. Thickness of liquid film formed between the tube wall and the vapor bubble is one of the crucial parameters to develop two-phase flow systems using micro tubes. However, liquid film formation and variation of oscillating flows are very complicated phenomena coupled with acceleration, deceleration, evaporation, condensation, etc. In the previous research, liquid film thickness in accelerating flow under adiabatic conditions was measured and compared with the correlation developed under steady condition [5]. In the present study, liquid film thickness in decelerating flow in a micro tube is investigated under adiabatic condition. Circular tubes with diameter, D = 1.0 mm, is used. Laser focus displacement meter is used to measure the liquid film thickness. Two-phase flow is obtained by introducing air from the open end of the test tube. Ethanol is used as a working fluid. At small capillary numbers, the effect of deceleration is negligible similar to the trend under accelerated condition. As capillary number increases, liquid film thicknesses in decelerated conditions become larger than the predictions of adiabatic steady correlation. However, liquid film thickness does not exceed the critical thickness at $Re > Re_{\mathrm{crit}}$. It is considered that liquid film thickness is affected by the altered velocity profiles in the liquid slug ahead of air-liquid interface according to accelerated or decelerated condition.

1. Introduction

Micro-scale heat transfer attracts large attention due to its many advantages, e.g., high efficiency, miniaturization, etc. However, the characteristics of two-phase flow in micro tubes are quite different from those in conventional tubes and they are not fully understood. Flow regimes are also different in micro tubes due to surface tension, and slug flow becomes one of the dominant flow patterns. It is well known that the thin liquid film formed between the micro tube wall and the vapor bubble plays an important role in heat transfer performance. Characteristics of liquid film thickness in micro-scale two-phase flow have been investigated extensively for the last several decades [1-6].

Although many researches on the liquid film thickness in micro-scale two-phase flow have been conducted, most of them dealt with steady flow. However, two-phase flow becomes unsteady in many real applications. Oscillating flow is encountered frequently in many two-phase flow systems such as pulsating heat pipe, refrigerator with reciprocating compressor, etc. In oscillating flow, liquid film formation and variation of oscillating flow are very complicated phenomena coupled with acceleration, deceleration, evaporation, condensation, etc.

Moriyama and Inoue [3] measured the thickness of the liquid film formed by a vapor bubble expansion in a narrow gap. It was stated that liquid film thickness was determined mainly by two basic mechanisms. i.e., boundary layer development in the liquid slug and the balance between surface tension/viscous forces. It was reported that when acceleration becomes large, liquid film thickness was affected by the viscous boundary layer. Their experimental data was correlated in terms of dimensionless boundary layer thickness, capillary number and Bond number.

Han and Shikazono [7] investigated the effect of bubble acceleration on liquid film thickness under adiabatic condition. It was observed that the increase of liquid film thickness with capillary number was restricted when bubble acceleration became large. It was explained that liquid film thickness decreased because the curvature at bubble nose and transition region was affected by the flow acceleration. New correlation for the liquid film thickness in accelerated condition was proposed.

Recently, Han et al. [8] measured liquid film thicknesses in a micro tube under flow boiling condition and compared them with the adiabatic correlation. At the same bubble velocity, liquid film thickness showed large scattering according to bubble acceleration. Adiabatic correlation proposed by Han and Shikazono [7] could predict liquid film thickness well also under flow boiling condition.

In the present study, liquid film thickness in decelerated flow in a micro tube is investigated under adiabatic condition as a basic research. Instantaneous and local liquid film thickness is measured by laser focus displacement meter. Finally, the effects of acceleration and deceleration on liquid film thickness in oscillating flow are discussed.

2. Experimental setup and procedures

2.1 Experimental setup

Figure 1 shows the schematic diagram of the experimental setup. In Fig. 1, one end of the test tube is connected to the syringe and the actuator motor (EZHC6A-101, Oriental Motor). The other end of the test tube is open to air. Figure 2 shows the schematic diagram of the test tube. In order to obtain stable decelerating flow, test tube should be sufficiently long. The test tube is lengthened using silicone tube of the same diameter, D = 1.0 mm.

Syringes (1700 series, Hamilton) with several cross sectional areas are employed to control the interface velocity in the test channel. Ethanol is used as a working fluid. The movement of air-liquid interface is captured by the high-speed camera. Images are taken at several frame rates according to the air-liquid interface velocity. For the maximum interface velocity, frame rate is 2000 frames per second.

Laser focus displacement meter (hereafter LFDM; LT9010M, Keyence) are employed to measure the liquid film thickness. On the principle and uncertainty analysis of LFDM, refer to the authors' previous paper [5]. Liquid film thickness measured by LFDM is transformed to DC voltage signal in the range of ±10 V. Output signal was sent to PC through GPIB interface and recorded with LabVIEW.

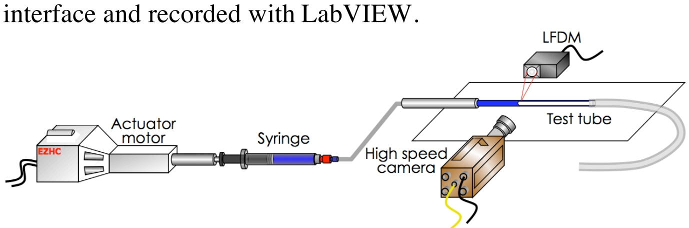

Fig. 1 Schematic diagram of the experimental setup.

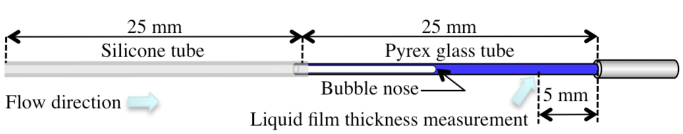

Fig. 2 Schematic diagram of the test section.

2.2 Experimental procedures

Ethanol is injected into the syringe and the piston of syringe is connected to the actuator motor. After the inner wall of test channel is purged with pressurized dry air for several minutes, the test channel is connected to the syringe. Working fluid is moved by the actuator motor until the air-liquid interface is located near the open end of the silicone tube. Then, working fluid is pulled by the actuator motor and liquid film is formed on the wall. Movement of air-liquid interface is controlled by actuator motor to make decelerating flow around the measurement point. Liquid film thickness measurement is synchronized with the high-speed camera.

2.3 Measurement example

Figure 3 shows captured images of decelerated flow. Liquid film thickness is measured at the center of images. It is observed that bubble nose becomes blunter as interface velocity decreases. Liquid film also becomes thinner with deceleration.

Figure 4 shows the measured interface velocities in decelerating flow shown in Fig. 3. Interface velocity and the deceleration at the measurement point are obtained from the fitting line of several measured velocities around the measurement point. Interface position has approximately ±2 pixels error in each captured image. Thus, the error in the displacement of interface position is ±4 pixels. In the present experiment, the displacement of interface position is approximately 80 pixels. Thus, the uncertainties of velocity and deceleration are ±5% and ±10%, respectively. Deceleration is not constant for the whole deceleration process. For example, interface velocity and deceleration for the case shown in Fig. 4 are U = 0.569 m/s and a = -119.8 m/s^2, respectively.

Figure 5 shows time variation of liquid film thickness in the case of Fig. 4. After the air-liquid interface passes by the measurement point, signal for liquid film thickness is sent to experimental PC. If the angle of interface to LFDM is larger than approximately 11°, intensity of the reflected light becomes weak and the interface position cannot be detected. Therefore, it is not possible to measure the whole shape of the bubble nose. Initial decrease in Fig. 5 is the transition region between the bubble nose and the flat film region. The liquid film thickness after the rapid decrease is defined as the initial liquid film thickness δ_0 as shown in Fig. 5. Initial liquid film thickness in Fig. 5 is δ_0 = 70. 9 μm.

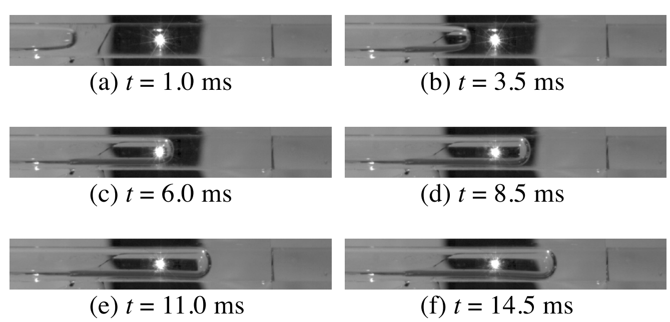

Fig. 3 Captured images in decelerated flow.

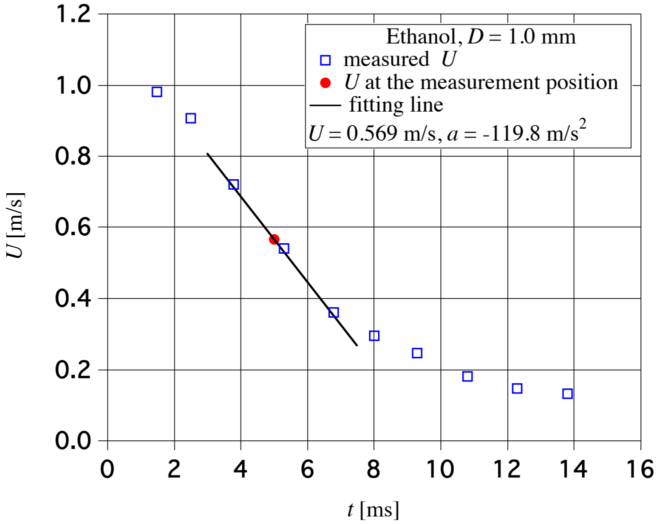

Fig. 4 Measured interface velocities in decelerated flow.

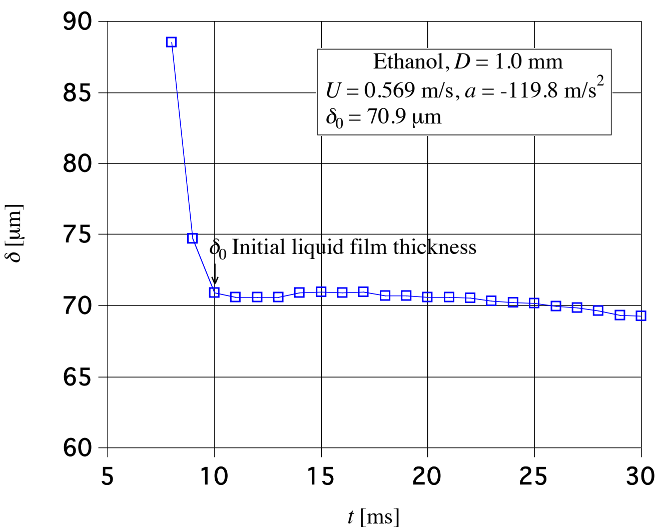

Fig. 5 Time variation of liquid film thickness.

3. Experimental results and Discussion

3.1 Liquid film thicknesses under decelerated and accelerated conditions

Han and Shikazono [5] proposed an experimental correlation for the initial liquid film thickness in a micro tube under adiabatic condition as follows:

$$\left(\frac{\delta_0}{D}\right)_{steady} = \frac{0.670Ca^{2/3}}{1+3.13Ca^{2/3}+0.504Ca^{0.672}Re^{0.589}-0.352We^{0.629}}\left(Re<Re_{crit}\right), \quad (1)$$

where δ_0, ρ and σ are initial liquid film thickness, liquid density and surface tension, respectively. Equation (1) is valid only for laminar flow and liquid film thickness becomes constant for turbulent flow. Re_{crit} is critical Reynolds number at which flow changes from laminar to turbulent. Re_{crit} = 2000 is used in Ref. [5].

Figure 6 shows measured initial liquid film thicknesses in decelerating and accelerating air-liquid flows. Experimental data in Han and Shikazono [7] are used for accelerated condition. Solid line is the predicted line using Eq. (1). Properties of ethanol at T = 24°C are used for dimensionless numbers. Dotted line is Taylor's law that is fitting curve proposed by Aussillous and Quere [4] using Taylor's experimental data.

In Fig. 6, measured liquid film thicknesses are in good accordance with the prediction at small capillary numbers Ca < 0.025. The effect of deceleration on liquid film thickness is negligible. This is the consistent feature of liquid film thickness also under accelerated condition. It was observed that acceleration effect became negligible at small capillary numbers and liquid film thickness was determined only by capillary number [7].

However, liquid film thickness becomes larger than the predicted value as deceleration increases. Liquid film thickness does not exceed the predicted value of constant thickness region at Re > 2000. On the other hand, liquid film thickness becomes smaller than predicted value as acceleration increases.

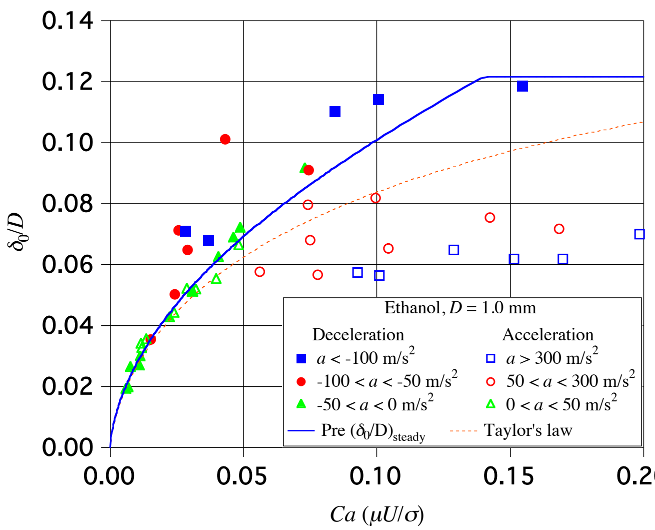

Fig. 6 Initial liquid film thickness in decelerating flow.

In order to express the bubble acceleration and deceleration effects, Bond numbers based on the bubble acceleration and deceleration are introduced as follows:

$$Bo_{accel} = Bo_{decel} = \frac{\rho|a|D^2}{\sigma}, \quad (2)$$

where a is bubble acceleration or deceleration. Absolute value of a is used for Bond number. Moriyama and Inoue used the same dimensionless number for liquid film thickness [3].

Figure 7 shows the ratio of measured liquid film thickness to predicted values in decelerating and accelerating flows. At

Bo < 2, the ratio is almost unity for both decelerating and accelerating flows. The effects of deceleration and acceleration are negligible. Liquid film thickness can be predicted well by the steady correlation Eq. (1). The criteria Bo = 2 was reported also by Moriyama and Inoue [3]. In their correlation, liquid film thickness is determined by viscous boundary layer thickness at Bo > 2. In Fig. 7, the ratio in accelerating flow decreases linearly as Bond number increases, while the ratio in decelerating flow increases initially and then decreases. It is attributed that liquid film thickness cannot be larger than the constant thickness of Eq. (1) at Re > 2000.

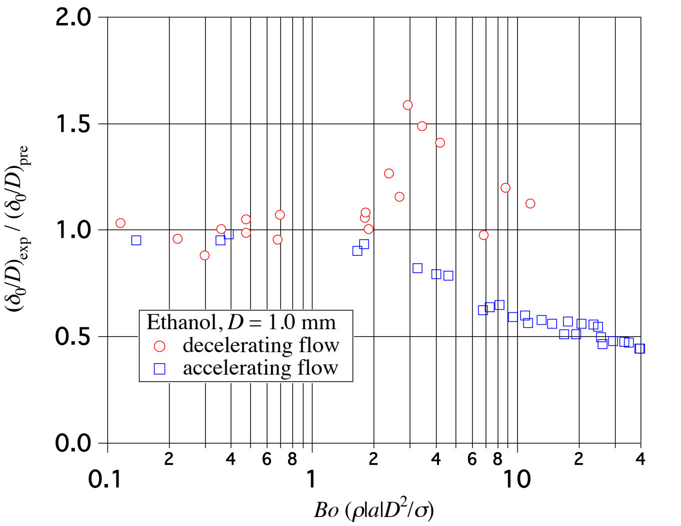

Fig. 7 Ratio of measured liquid film thickness to predicted values in decelerating and accelerating flows.

3.2 Scaling analysis

Aussillous and Quere [4] made a scaling analysis on the liquid film thickness based on Bretherton's theoretical analysis [2]. The momentum balance and the curvature matching between the bubble nose and the transition region are expressed as follows:

$$\frac{\mu U}{\delta_0^2} \sim \frac{1}{\lambda}\left\{\frac{\sigma}{R-\delta_0}\right\}, \tag{3}$$

$$\frac{\delta_0^2}{\lambda^2} \sim \frac{1}{R-\delta_0}, \tag{4}$$

where λ is transition region length and R is tube radius. The relation δ_0/D is deduced as follows:

$$\frac{\delta_0}{D} \sim \frac{Ca^{2/3}}{1+Ca^{2/3}}. \tag{5}$$

Based on Eq. (5), Taylor's experimental data was fitted as follows [4]:

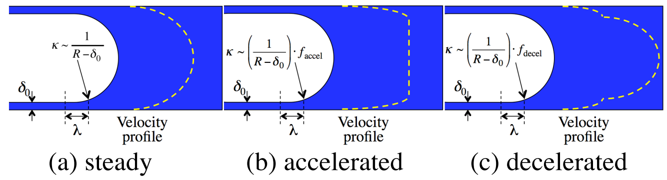

Fig. 8 Schematics of velocity profile inside liquid slug under steady, accelerated and decelerated conditions.

$$\frac{\delta_0}{D} = \frac{0.67Ca^{2/3}}{1+3.35Ca^{2/3}}. \tag{6}$$

Equation (6) is called the Taylor's law.

Figure 8 shows the schematic diagram of velocity profiles under steady, accelerated and decelerated conditions. Under accelerated and decelerated conditions, bubble nose curvature is affected by the altered velocity profile ahead of bubble nose. This is considered to be the reason for the deviation of the liquid film thickness from the steady correlation. Under decelerated or accelerated condition, the bubble nose curvature is modified as:

$$\kappa \sim \left(\frac{1}{R-\delta_0}\right)\cdot f. \tag{7}$$

If the bubble nose curvature is replaced with Eq. (7), Eq. (5) is changed as follows:

$$\frac{\delta_0}{D} \sim \frac{Ca^{2/3}}{f+Ca^{2/3}}. \tag{8}$$

Eq. (8) can be rewritten using Eq. (6) as:

$$f \sim \frac{0.67Ca^{2/3}}{\delta_0/D} - 3.35Ca^{2/3}. \tag{9}$$

In the previous research [7], it was shown that all the experimental data under accelerated condition are well correlated with a single line as:

$$f_{accel} = 0.629Bo_{accel}^{0.414}. \tag{10}$$

Using the relation Eq. (10), experimental correlation for the liquid film thickness under accelerated condition was proposed as follows:

$$\left(\frac{\delta_0}{D}\right)_{accel} = \frac{0.968Ca^{2/3}}{Bo_{accel}^{0.414}+4.838Ca^{2/3}}. \tag{11}$$

In the same way, the relation between f_{decel} and Bo_{decel} can be investigated. Figure 8 shows the relation between f_{decel} and Bo_{decel}. Except three points on the right side, all the data can be correlated qualitatively with a single line as follows:

$$f_{\text{decel}} = 1.285 Bo_{\text{decel}}^{-0.753}. \tag{12}$$

As for the three points on the right side in Fig. 8, it is attributed that liquid film thickness cannot exceed the constant thickness of the steady correlation at $Re > 2000$. Even at large Bond number, liquid film thickness does not becomes larger but converges to the constant thickness of steady correlation. On the contrary, liquid film thickness becomes smaller without limitation as acceleration increases.

In order to make more accurate correlation on the liquid film thickness in decelerating flow, experiments under various conditions, i.e, different tube diameters and working fluids are necessary.

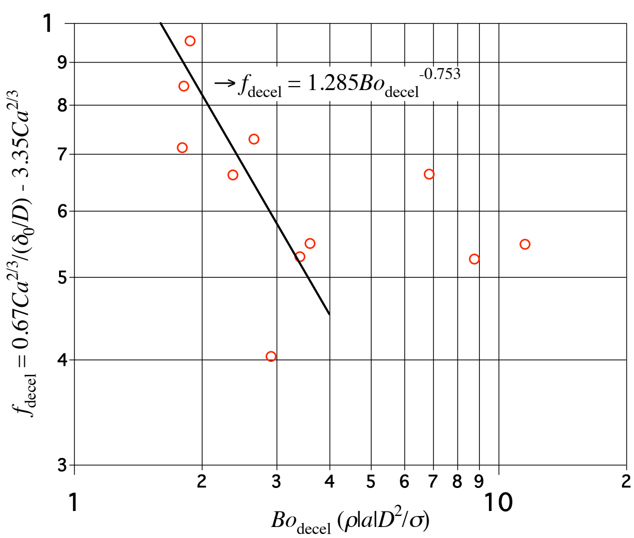

Fig. 8 Relation between f_{decel} and Bo_{decel}.

3.3 Liquid film thickness oscillating flow

Oscillating flow is produced using step motor and syringe as shown in Fig. 9. Water is used as a working fluid. Oscillating frequency is ranged from 2 to 12 Hz. At one fixed frequency, liquid film thickness is measured at various positions. Thus, liquid film thicknesses under various accelerated and decelerated conditions can be obtained.

Figure 10 shows dimensionless liquid film thickness versus capillary number. Critical Reynolds number is $Re_{\text{crit}} = 2600$ for steady condition prediction. At small capillary number, liquid film thickness is almost identical with prediction for steady condition and the effects of acceleration and deceleration are negligible. However, as capillary number increases, the effects of acceleration and deceleration become larger. As discussed above, it is observed that liquid film in decelerated flow is thicker than steady condition prediction, while liquid film in accelerated flow is thinner. More parametric experiments are necessary to understand the characteristics of liquid film in oscillating flow quantitatively.

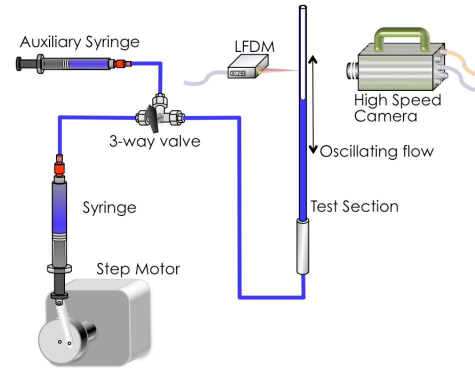

Fig. 9 Schematic diagram of the experimental setup for oscillating flow.

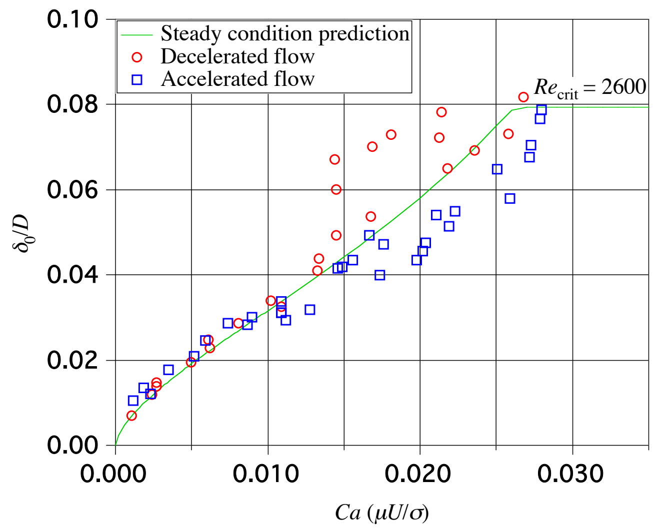

Fig. 10 Dimensionless liquid film thickness versus capillary number in oscillating flow.

4. Conclusions

In the present study, liquid film thickness in oscillating flow in a micro tube is investigated. The effect of deceleration on liquid film thickness is compared with that of acceleration. At small capillary numbers, the effect of deceleration is negligible like the trend under accelerated condition. As capillary number increases, liquid film thickness of larger deceleration becomes larger than predicted value using steady correlation. However, liquid film thickness does not exceed the predicted value of constant thickness region at $Re > 2000$. On the contrary, liquid film thickness becomes smaller without limitation as acceleration increases. It is considered that liquid film thickness is affected by the velocity profiles in the liquid slug ahead of air-liquid interface according to accelerated or decelerated condition.

NOMENCLATURE

Symbol	Description	Unit
Bo	Bond number	-
Ca	capillary number	-
D	tube diameter	m
f	modification factor	-
R	tube radius	m
Re	Reynolds number	-
T	temperature	°C
U	bubble velocity	m/s
We	Weber number	-

Greek Symbols

δ	liquid film thickness	m
κ	curvature	m^{-1}
λ	transition region length	m
μ	viscosity	Pa·s
ρ	density	kg/m^3
σ	surface tension coefficient	N/m

Subscripts

0	initial
accel	accelerated
decel	decelerated

ACKNOWLEDGMENTS

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REFERENCES

[1] Taylor, G. I., 1961, "Deposition of a viscous fluid on the wall of a tube," J. Fluid Mech., **10**, pp. 161-165.

[2] Bretherton, F. P., 1961, "The motion of long bubbles in tubes," J. Fluid Mech., **10**, pp. 166-188.

[3] Moriyama, K. and Inoue, A., 1996, "Thickness of the liquid film formed by a growing bubble in a narrow gap between two horizontal plates," Trans. of the ASME, **118**, pp. 132-139.

[4] Aussillous, P. and Quere, D., 2000, "Quick deposition of a fluid on the wall of a tube," Phys. Fluids, **12**, pp. 2267-2371.

[5] Han, Y. and Shikazono, N., 2009, "Measurement of the liquid film thickness in micro tube slug flow," Int. J. Heat Fluid Flow. **35**, pp. 896-903.

[6] Han, Y., Shikazono, N., 2009, "Measurement of liquid film thickness in micro square channel," Int. J. Multiphase Flow, **30**, pp. 842-853.

[7] Han, Y. and Shikazono, N., 2010, "The effect of bubble acceleration on the liquid film," Int. J. Heat Fluid Flow, **31**, pp. 630-639.

[8] Han Y., Shikazono N. and Kasagi, N., 2010 "The effect of liquid film evaporation on heat transfer coefficient in a micro tube, " Int. Heat Transfer Conf., Washington, DC, USA.

