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Measurement of the liquid film thickness in micro tube slug flow

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ABSTRACT

Slug flow is one of the representative flow regimes of two-phase flow in micro tubes. 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. In the present study, experiments are carried out to clarify the effects of parameters that affect the formation of the thin liquid film in micro tube two-phase flow. Laser focus displacement meter is used to measure the thickness of the thin liquid film. Air, ethanol, water and FC-40 are used as working fluids. Circular tubes with five different diameters, D = 0.3, 0.5, 0.7, 1.0 and 1.3 mm, are used. It is confirmed that the liquid film thickness is determined only by capillary number and the effect of inertia force is negligible at small capillary numbers. However, the effect of inertia force cannot be neglected as capillary number increases. At relatively high capillary numbers, liquid film thickness takes a minimum value against Reynolds number. The effects of bubble length, liquid slug length and gravity on the liquid film thickness are also investigated. Experimental correlation for the initial liquid film thickness based on capillary number, Reynolds number and Weber number is proposed.

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 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 liquid film thickness is one of the important parameters for the prediction of flow boiling heat transfer in micro tubes (Thome et al., 2004; Kenning et al., 2006).

Many researches on the liquid film thickness in slug flow have been conducted both experimentally and theoretically. Taylor (1961) experimentally obtained the mean liquid film thickness remaining on the wall by measuring the difference of the bubble velocity and the mean velocity. Highly viscous fluids, i.e., glycerine, syrup–water mixture and lubricating oil, were used and thus wide capillary number range was covered. It is reported that the liquid film thickness increases with capillary number and reaches a certain fraction of the tube diameter. Bretherton (1961) suggested an analytical theory on the liquid film thickness and axial pressure drop across the bubble with the lubrication equations. Assuming small capillary number, it is shown that the dimensionless liquid film thickness can be scaled with $Ca^{2/3}$.

Moriyama and Inoue (1996) obtained the liquid film thickness formed by a vapor bubble expansion in a narrow gap by measuring the temperature change of the channel wall, which was initially superheated. In their experiment, it was assumed that whole liquid film on the wall evaporates and the heat is consumed by the evaporation of the liquid film. Their experimental data was correlated in terms of capillary number and Bond number based on the interface acceleration. Heil (2001) investigated the effect of inertial force on the liquid film thickness numerically. It is shown that the liquid film thickness and the pressure gradient are dependent on the Reynolds number.

Aussillous and Quere (2000) measured the liquid film thickness using fluids with relatively low surface tension. It was found that the liquid film thickness deviates from the Taylor's data at relatively high capillary numbers. Visco-inertia regime where the effect of inertial force on the liquid film thickness becomes significant was demonstrated. Kreutzer et al. (2005) investigated the liquid film thickness and the pressure drop in a micro tube both numerically and experimentally. Predicted liquid film thickness showed almost the same trend with that reported by Heil (2001).

Utaka et al. (2007) measured the liquid film thickness formed by a vapor bubble in a narrow gap mini-channel with laser extinction method and investigated the heat transfer characteristics quantitatively. It is concluded that the boiling phenomena are determined by two kinds of characteristic periods, i.e., the microlayer dominant and the liquid saturated periods.

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Nomenclature

Bo	Bond number, $Bo = \rho g D^2/\sigma$
Ca	capillary number, $Ca = \mu U/\sigma$
D	tube diameter [m]
g	acceleration of gravity [m/s^2]
L	length [m]
n	refractive index
Re	Reynolds number, $Re = \rho UD/\sigma$
T	temperature [°C]
U	velocity [m/s]
We	Weber number, $We = \rho U^2 D/\sigma$
y_m	distance of objective lens movement [m]

Greek symbols

α	angle of the cover glass [radian]
δ	liquid film thickness [m]
k	curvature of the bubble nose [1/m]
λ	length of the transition region [m]
μ	viscosity [Pa s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
θ	angle of incidence or refraction [radian]

Subscripts

0	initial
1	through *Z* axis in Fig. 5
2	through *X* axis in Fig. 5
actuator	actuator
bottom	tube bottom in horizontal flow direction
bubble	bubble
f	fluid
side	tube side in horizontal flow direction
slug	liquid slug
w	wall

Although, many experiments have been carried out to measure the liquid film thickness in micro tubes, quantitative data of local and instantaneous liquid film thicknesses are still limited. To develop a precise heat transfer model in a micro tube, it is crucial to know the characteristics of the liquid film thickness. In the present study, local and instantaneous liquid film thicknesses are measured directly with laser focus displacement meter. Series of experiments is conducted to investigate the effects of capillary number and Reynolds number on the formation of liquid film in micro tubes.

2. Experimental setup and procedure

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. Circular Pyrex glass tubes with inner diameters of 0.3, 0.5, 0.7, 1.0 and 1.3 mm were used as test tubes. Tube diameter was measured with a microscope and the averaged value of inlet and outlet inner diameters was used. Table 1 and Fig. 2 show the dimensions and the photograph of 0.487 mm inner diameter tube. The differences of inlet and outlet inner diameters are less than 1% for all tubes. One edge of Pyrex glass tube was connected to the syringe. Actuator motor (EZHC6A-101, Oriental motor) was used to control the velocity of liquid in the micro tube. The velocity range of the actuator motor is from 0 to 0.2 m/s. Syringes with several cross sectional areas were used to control the liquid velocity in the test section. The range of liquid velocity in the present experiment was varied from 0 to 7 m/s. The velocity of gas–liquid interface was measured from the images captured by the high speed camera (Phantom 7.1). Images were taken at several frame rates according to bubble velocity. For the maximum bubble velocity, frame rate was 10000 frames per second with a shutter time of 10 μs. Laser focus displacement meter (LT9010M, Keyence) was used to measure the liquid film thickness. Laser focus displacement meter has been used by several researchers for the measurement of the liquid film thickness (Takamasa and Kobayashi, 2000; Hazuku et al., 2005). It is reported that the laser focus displacement meter can measure the liquid film thickness very accurately within 1% error (Hazuku et al., 2005). Fig. 3 shows the principle of the laser focus displacement meter. 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. Objective lens is vibrated continually in the range of ±0.3 mm. Liquid film thickness is obtained from those values. The resolution for the present laser focus displacement meter is 0.01 μm, the laser spot diameter is 2 μm and the response time is 640 μs. Measured liquid film thickness is transformed to DC voltage signal in the range of ±10 V. Output signal was sent to PC through GPIB interface and recorded with Lab VIEW.

Table 1
Dimensions of the test tubes

ID (mm)	OD (mm)	Length (mm)
1.305	1.6	250
0.995	1.6	250
0.715	1.0	250
0.487	0.8	250
0.305	0.5	250

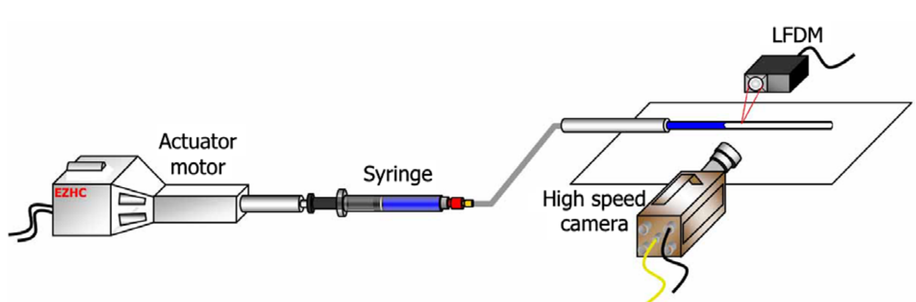

Fig. 1. Schematic diagram of the experimental setup.