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The effect of bubble deceleration on the liquid film thickness in microtubes

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ABSTRACT

Liquid film thickness is an important parameter for predicting boiling and condensation heat transfer coefficients in microtube slug flows. In the present study, the effect of bubble deceleration on the liquid film thickness is experimentally investigated under adiabatic condition. The laser focus displacement meter is used to measure the liquid film thickness. Circular tubes with three different inner diameters, $D = 0.7$, 1.0 and 1.3 mm, are used. Measurement is carried out using a microtube with one open end and the other connected to an actuator motor. Water, ethanol and FC-40 are used as working fluids. It is found that deceleration makes the liquid film thicker than that in the steady flow, and it deviates from the steady case as the deceleration rate is increased. Liquid film thickness remains nearly unchanged just after the onset of deceleration, and then gradually decreases and eventually converges to the steady thickness as the velocity is further decreased. Finally, an empirical correlation is proposed to predict initial liquid film thickness in decelerated flows.

1. Introduction

Slug flow is one of the representative flow patterns in microtube two phase flows, which is important in many thermal and chemical engineering applications such as heat pipes and microreactors, etc. It is known that the liquid film thickness is one of the key parameters for predicting flow boiling and flow condensation heat transfer coefficients in microtubes (Thome et al., 2004; Qu and Mudawar, 2004; Kenning et al., 2006; Saitoh et al., 2007; Wu et al., 2010; Odaymet et al., 2012). Evaporation or condensation heat transfer coefficient through the liquid film in a steady laminar slug flow is represented as follows:

$$h = \frac{k}{\delta} \tag{1}$$

where h is the heat transfer coefficient, k is the thermal conductivity of the liquid and δ is the liquid film thickness. Many investigations on liquid film thickness in microtubes have been conducted. Taylor (1961) experimentally obtained the mean liquid film thickness by measuring the difference between mean and bubble velocities. It was reported that the liquid film thickness increases with capillary number and asymptotes to a certain fraction of the tube diameter. Taylor's experimental data were correlated by Aussillous and Quere (2000) as a function of capillary number Ca as follows:

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

In a steady slug flow, Han and Shikazono (2009a, 2009b) carried out systematic measurements on liquid film thickness under the adiabatic condition using laser focus displacement meter. Predictive correlations for the initial liquid film thickness based on capillary number Ca, Reynolds number Re and Weber number We were proposed. On the other hand, under flow boiling in microtwo-phase flow, the bubble velocity is not constant but accelerated, and the flow pattern becomes very complicated (Kenning et al., 2006; Rao et al., 2013; Rao et al., 2015). Moriyama and Inoue (1996) measured the thickness of the liquid film formed by a vapor bubble expansion in a narrow gap. It was reported that liquid film thickness is affected by the viscous boundary layer in the preceding liquid flow. Their experimental data was correlated in terms of dimensionless boundary layer thickness, capillary number and Bond number based on flow acceleration. Han and Shikazono (2010) investigated the effect of acceleration on the liquid film thickness in microtubes. It was reported that the liquid film thickness becomes thinner than the steady case under flow acceleration. New correlation for the initial liquid film thickness in accelerated condition was proposed. However, their experiments were limited to cases with zero velocity at the initial state.

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Nomenclature

a	flow deceleration (m/s^2)
Bo	Bond number based on flow deceleration, $Bo = \rho\lvert a\rvert D^2/\sigma$
Ca	capillary number, $Ca = \mu U/\sigma$
D	tube inner diameter (m)
h	heat transfer coefficient (W/m^2-K)
k	thermal conductivity (W/m-K)
n	refractive index
Re	Reynolds number, $Re = \rho UD/\mu$
T	time (s)
U	flow velocity (m/s)
We	Weber number, $We = \rho U^2 D/\sigma$
Z	axial distance from the decelerating start-point (m)

Greek symbols

Δ	liquid film thickness (m)
λ	transition region length (m)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

0	initial
1	through Z axis in Fig. 4
2	through X axis in Fig. 4
decel	decelerated condition
steady	steady condition

Youn et al. (2015) and Muramatu et al. (2015) experimentally and numerically investigated the effect of initial flow velocity on the liquid film thickness in accelerated flows. It was found that the effect of initial flow velocity cannot be neglected in accelerated flows especially at large initial flow velocities and large acceleration Bond numbers. A predictive correlation was proposed for the initial liquid film thickness of accelerated flows that takes into account the initial flow velocity effect.

On the other hand, the bubble velocity is decelerated in two-phase flows with condensation. For example, it is important to consider both acceleration and deceleration effects on the liquid film thickness in oscillating heat pipes (Rao et al., 2013, 2015). In the present study, the effect of bubble deceleration on the liquid film thickness in microtubes under adiabatic condition is experimentally investigated. The liquid film thickness in microcircular tubes is measured using laser focus displacement meter for three different working fluids, i.e. water, ethanol and FC-40. The flow visualization using high speed camera is carried out to observe the bubble shape change. Finally, an empirical correlation is proposed to predict initial liquid film thickness in decelerated microtube slug flows.

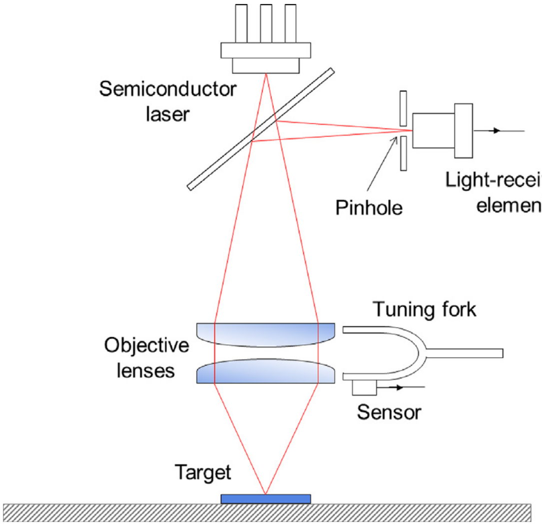

Fig. 2. Principle of the laser focus displacement meter.

2. Experimental setup and procedures

2.1. Experimental setup

Circular tubes made of Pyrex glass with inner diameter of $D = 0.7$, 1.0 and 1.3 mm were used as test tubes. Water, ethanol and FC-40 were used as working fluids and air was used as the gas phase. Tube length is 500 mm for 0.7 and 1.0 mm tubes and 700 mm for 1.3 mm tube to ensure fully developed flows before deceleration. Fig. 1 represents the schematic diagram of the experimental setup. Actuator motor (EZHC6A-101, Oriental motor) was used to pull the liquid and to decelerate the flow. Instantaneous bubble velocities and deceleration rates were obtained from the images obtained by a high-speed camera (Photron SA1.1). Laser focus displacement meter (LFDM; LT 9010 M, Keyence) was used to measure the liquid film thickness. The tube is horizontally oriented, and the instantaneous bubble velocities and liquid film thicknesses are measured from the side of the tube. LFDM has been already used by several researchers to measure liquid film thickness (Takamasa and Kobayashi, 2000; Hazuku et al., 2005; Han and Shikazono, 2009a, 2009b, 2010; Youn et al., 2015). Fig. 2 shows the principle of the LFDM. The position of the target surface can be determined by the displacement of objective lens connected to the tuning fork. The intensity of the reflected light in the light-receiving element becomes the highest when the focus is obtained on the target surface. Objective lens is vibrated continually in the range of ±0.3 mm. Relative distance between interfaces can be detected during one cycle of the objective lens vibration. The resolution of the present LFDM is 0.01 µm, the laser

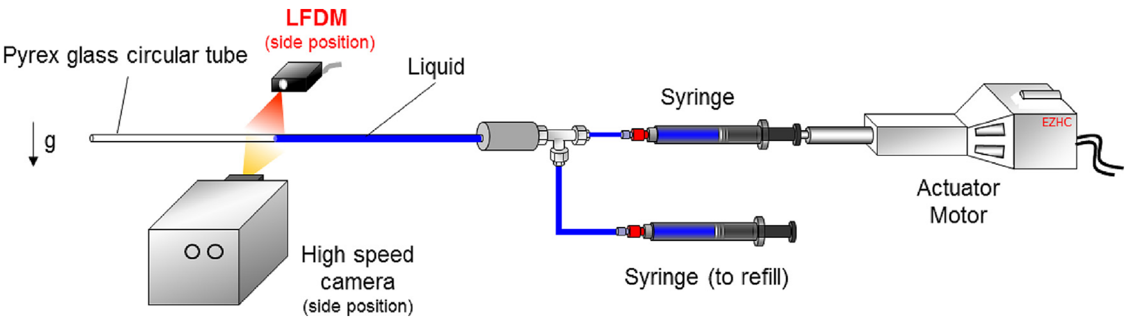

Fig. 1. Schematic diagram of the experimental setup.