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The effect of initial flow velocity on the liquid film thickness in micro tube accelerated slug flow

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ABSTRACT

Liquid film thickness is an important parameter for predicting boiling and condensation heat transfer in micro tubes. In the present study, the effect of initial flow velocity on the liquid film thickness in accelerated flows under adiabatic condition is experimentally investigated. The laser focus displacement meter is used to measure the initial liquid film thickness. Circular tube with inner diameter of 1 mm was used for the test tube, and water, ethanol and FC-40 are used as working fluids. When the flow is accelerated from small initial velocities under small Bond number condition, initial liquid film thickness is identical to that of steady flow at small capillary numbers, and then deviates from the steady condition and eventually follows that of accelerated flow from zero initial velocity as capillary number is increased. When the flow is accelerated from large initial velocities, initial liquid film thickness deviates from the steady condition earlier and starts to follow that of accelerated flow from zero initial velocity as capillary number is increased. It is found that the initial flow velocity cannot be neglected in accelerated flows especially at large initial flow velocities and at large Bond numbers. Finally, an empirical correlation is proposed for the initial liquid film thickness of accelerated flows that accounts for the initial flow velocities.

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Introduction

Elongated slug flow is one of the representative flow patterns in micro tubes under the flow boiling condition. It is known that the liquid film thickness is one of the key parameters for predicting boiling heat transfer coefficient in micro tubes (Thome et al., 2004). Evaporation heat transfer coefficient through the liquid film in a steady 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 micro tubes have been conducted (Thome et al., 2004; Kenning et al., 2006; Qu and Mudawar, 2004; Saitoh et al., 2007). Taylor (1961) experimentally obtained the mean liquid film thickness deposited on the wall by measuring the difference of the bubble velocity and the mean velocity. It was reported that the liquid film thickness increases with capillary number and reaches 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):

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

Han and Shikazono (2009a,b) carried out systematic measurements on liquid film thickness in micro two-phase steady flows under the adiabatic condition using laser focus displacement meter. Predictive correlations for the initial liquid film thickness based on capillary number, Reynolds number and Weber number were proposed. Howard and Walsh (2013) examined the liquid film thickness caused by continuous liquid–gas slug train in a small scale tube for a wide range of capillary numbers using an optical measurement technique. Their experimental data were compared with the existing model proposed by Han and Shikazono (2009a) which can be applied the range of capillary numbers up to 0.3. It was reported that their experimental data were found to correlate well with the Han & Shikazono model in a wide range of capillary numbers up to 1.9. Under flow boiling in micro two-phase flow, the bubble velocity is not constant but accelerated. It is necessary to consider this acceleration effect on the liquid film thickness (Kenning et al., 2006). Moriyama and Inoue (1996) measured the liquid film

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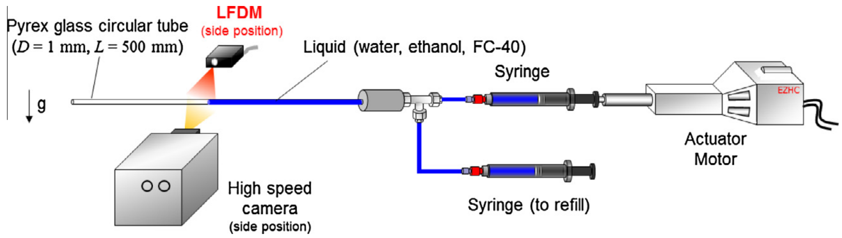

Fig. 1. Schematic diagram of the experimental setup.

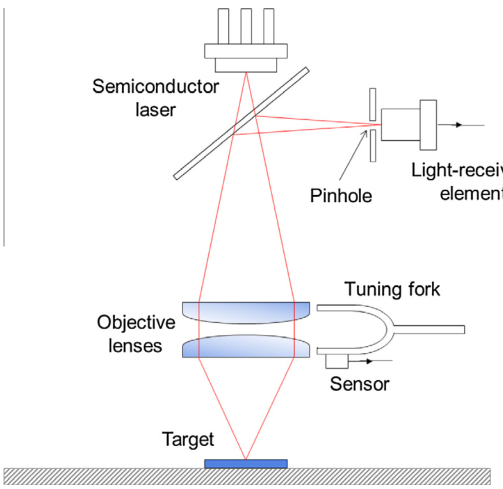

Fig. 2. Principle of the laser focus displacement meter.

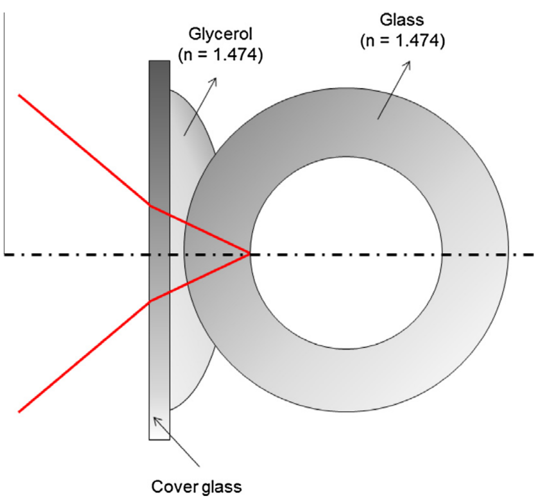

Fig. 3. Correction for the outer wall curvature.

Table 1
Properties of the working fluids at 20 °C and 25 °C.

	Temperature (°C)	Water	Ethanol	FC-40
ρ (kg/m^3)	20	998	789	1860
	25	997	785	1849
μ (μPa s)	20	1001	1196	3674
	25	888	1088	3207
σ (mN/m)	20	72.7	22.8	16.3
	25	72.0	22.3	15.9
n		1.33	1.36	1.29

thickness formed by a vapor bubble expansion in a narrow gap through temperature change of the channel wall. It was reported that when acceleration becomes large, liquid film thickness is affected by the viscous boundary layer. A predictive correlation was suggested in terms of dimensionless boundary layer thickness, capillary number and Bond number. Han and Shikazono (2010) investigated the effect of acceleration on the liquid film thickness in micro tubes. It was reported that the increase of liquid film thickness with capillary number is restricted by the acceleration. A predictive correlation was proposed for the initial liquid film thickness based on capillary number and Bond number. However, their experiments were limited to cases with zero velocity at the initial state. Qu and Mudawar (2003) investigated flow characteristics of two-phase micro-channel heat sinks in which the highest inlet liquid Reynolds number (Re_0) is 303, corresponding capillary number (Ca_0) is 0.01. Chen et al. (2014) experimentally investigated flow condensation in microchannels in which the inlet vapor Reynolds number (Re_0) ranges from 408 to 1042, correspondingly capillary number (Ca_0) is ranged from 0.03 to 0.076. Considering the real phase change phenomena, liquid and vapor bubbles are supplied to the heating or cooling section with a certain flow velocity. Therefore, it is essential to consider the effect of initial flow velocity on liquid film thickness in accelerated flow.

In the present study, the liquid film thicknesses in accelerated flows under adiabatic condition are experimentally investigated with various initial flow velocities. The liquid film thickness is measured in a micro circular tube for several working fluids using

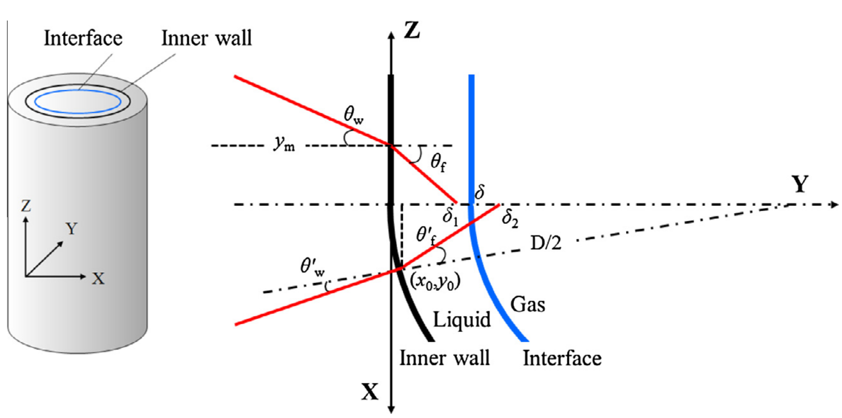

Fig. 4. Correction for the inner wall curvature.

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