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Liquid film thicknesses of oscillating slug flows in a capillary tube

Young Jik Youn [a,*], Youngbae Han [b], Naoki Shikazono [c]

[a] Energy Efficiency and Materials Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 34129, Republic of Korea
[b] Korea Military Academy, 574 Hwarangro, Nowon-gu, Seoul P.O. Box 77-2, Republic of Korea
[c] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 151-0041, Japan

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ABSTRACT

Liquid film thickness is an important parameter for predicting boiling and condensation heat transfer coefficients in a microscale slug flow. In the present study, liquid film thickness of oscillating slug flow in a capillary tube is experimentally investigated under adiabatic condition. Laser focus displacement meter is used to measure the initial liquid film thickness. Circular tube with inner diameter of 1 mm is used for the test tube, and water and ethanol are used as working fluids. Measurement is carried out using a capillary tube with one open end and the other connected to a stepping motor. Driving frequency is ranged from 1 to 10 Hz at equivalent slug stroke of 31.7 mm and 51.2 mm. As the frequency and equivalent slug stroke are increased, the liquid film thickness deviates from that in the steady condition and becomes thinner or thicker under flow acceleration or deceleration, respectively. The empirical correlations for the initial liquid film thickness under acceleration and deceleration conditions proposed in the previous study (Youn et al., 2015, 2016) well predict the liquid film thicknesses of the oscillating flows within 15% accuracy.

1. Introduction

Oscillating slug flow is encountered in many thermal and chemical engineering applications such as heat pipes, steam engine and micro reactors. It is known that the liquid film thickness is one of the key parameters for predicting heat transfer coefficients in micro tubes [1–6]. Liquid film evaporation or condensation heat transfer coefficient 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 micro tubes have been conducted. In a steady slug flow, Han and Shikazono [7], Han and Shikazono [8] conducted extensive measurements on liquid film thickness under adiabatic condition using laser focus displacement meter, and proposed predictive correlations for the initial liquid film thickness. Under flow boiling conditions, the bubble velocity is not constant but accelerated, and the flow pattern becomes very complicated. Han and Shikazono [9] investigated the effect of acceleration on the liquid film thickness in micro tubes. It was reported that the liquid film thickness becomes thinner than the steady case under flow acceleration. Youn et al. [10] and Muramatsu et al. [11] experimentally and numerically investigated the effect of initial flow velocity on the liquid film thickness in accelerated slug flows. It was found that the effect of initial flow velocity becomes important at large initial flow velocities and at 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. On the other hand, the bubble velocity is decelerated under condensation conditions. Youn et al. [12] investigated the effect of deceleration on the liquid film thickness in a micro tube. It was found that deceleration makes the liquid film thicker than that in the steady flow, and it deviates from the steady case as the deceleration Bond number is increased. An empirical correlation is proposed to predict initial liquid film thickness in decelerated flows. In actual two-phase flow applications such as oscillating heat pipe [13–16], and oscillating steam engine [17], oscillating slug flow is often encountered. During the oscillation, the velocity and the acceleration of the slug change periodically. Therefore, it is important to consider both acceleration and deceleration effects on the liquid film thickness in oscillating systems such as heat pipes and oscillating steam engines. There are several experimental results on liquid film thickness under either accelerated or decelerated slug

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[*] Corresponding author.
E-mail address: yjyoun@kier.re.kr (Y.J. Youn).

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Nomenclature

a	flow acceleration or deceleration (m/s^2)
Bo	Bond number based on flow deceleration, $Bo = \rho|a|D^2/\sigma$
Ca	capillary number, $Ca = \mu U/\sigma$
D	diameter (m)
f	frequency (Hz)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	stroke (mm)
n	refractive index
Re	Reynolds number, $Re = \rho UD/\mu$
t	time (s)
U	flow velocity (m/s)
We	Weber number, $We = \rho U^2 D/\sigma$

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
accel	accelerated condition
decel	decelerated condition
steady	steady condition

flow [9,10,12]. However, research on liquid film thickness in oscillating flow has not been conducted.

In the present study, liquid film thickness in oscillating slug flow is experimentally investigated under adiabatic condition. The liquid film thickness in micro circular tubes is measured using laser focus displacement meter for two different working fluids, i.e. water and ethanol. Driving frequency is ranged from 1 to 10 Hz at equivalent slug stroke of 31.7 mm and 51.2 mm.

2. Experimental setup and procedures

2.1. Experimental setup

Circular tube made of Pyrex glass with an inner diameter of D = 1.0 mm and a length of 500 mm was used as a test tube. Water and ethanol were used as working fluids and air was used as the gas phase. Fig. 1 represents the schematic diagram of the experimental setup. Stepping motor and controller (Oriental motor, ARL66AA and EMP401, maximum torque of 1.2 N·m) were used to pull and push the liquid to make an oscillating flow. Instantaneous bubble velocities and acceleration and deceleration rates were obtained from the high-speed camera images (Photron SA1.1). The liquid film thicknesses were measured by laser focus displacement meter (LFDM; LT 9010M, Keyence). The tube is vertically 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 the liquid film thickness in capillary tube slug flow [7–10,12,18,19]. Fig. 2 shows the principle of the LFDM. The position of the target surface can be determined by the displacement of the 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 spot diameter

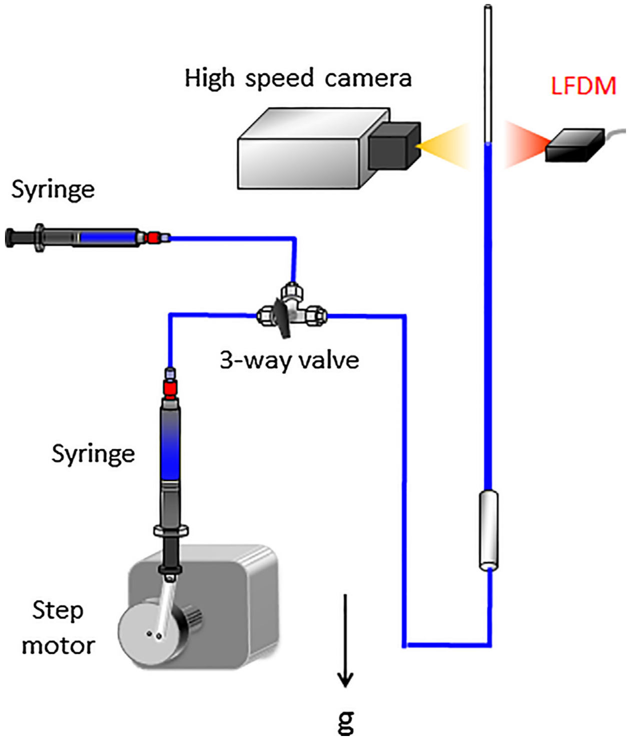

Fig. 1. Schematic diagram of the experimental setup.

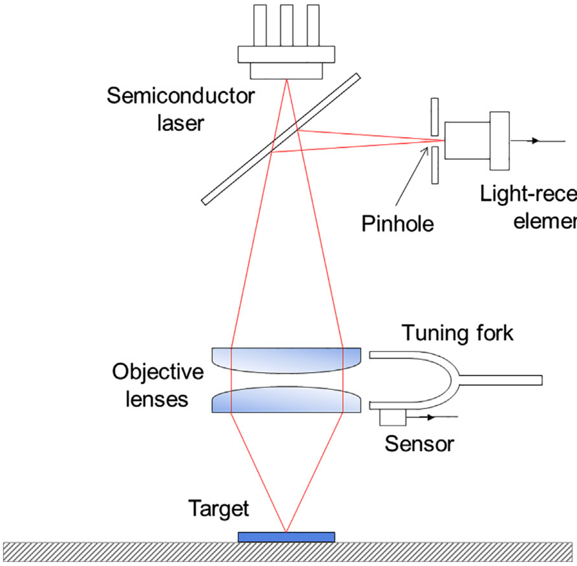

Fig. 2. Principle of the laser focus displacement meter.