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The effect of liquid film evaporation on flow boiling heat transfer in a micro tube

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ABSTRACT

Flow boiling in micro channels is attracting large attention since it leads to large heat transfer area per unit volume. Generated vapor bubbles in micro channels are elongated due to the restriction of channel wall, and thus slug flow becomes one of the main flow regimes. In slug flow, sequential bubbles are confined by the liquid slugs, and thin liquid film is formed between tube wall and bubble. Liquid film evaporation is one of the main heat transfer mechanisms in micro channels and liquid film thickness is a very important parameter which determines heat transfer coefficient. In the present study, liquid film thickness is measured by laser focus displacement meter under flow boiling condition and compared with the correlation proposed for an adiabatic flow. The relationship between liquid film thickness and heat transfer coefficient is also investigated. Initial liquid film thickness under flow boiling condition can be predicted well by the correlation proposed under adiabatic condition. Under flow boiling condition, liquid film surface fluctuates due to high vapor velocity and shows periodic pattern against time. Frequency of periodic pattern increases with heat flux. At low quality, heat transfer coefficients calculated from measured liquid film thickness show good accordance with heat transfer coefficients obtained directly from wall temperature measurements.

1. Introduction

Flow boiling in micro channels is an attractive method to dissipate high heat flux from electric chips. As channel size decreases, the ratio of surface area per unit volume increases and thus superior heat and mass transfer can be obtained. The characteristics of flow boiling in micro channels are quite different from those in macro channels. Correlations based on macro channel′ experiments often fail to predict heat transfer performance of flow boiling in micro channels [1].

The effect of mass flow rate on micro channel boiling is not still fully understood, while there is a consensus that heat transfer coefficient is largely affected by heat flux [1]. On this trend, Lazarek and Black [2] explained that nucleate boiling is the dominant heat transfer mechanism in micro channels.

However, it is reported recently by several visualization experiments of flow boiling in micro channels that the evaporation of the thin liquid film formed by elongated vapor bubble suppresses nucleate boiling [3,4]. It is also reported that conduction through the evaporating thin liquid film is the dominant heat transfer mechanism for micro channel boiling [5]. Mukherjee [6] investigated the contribution of liquid film evaporation through numerical simulation under three conditions, i.e., nucleate boiling, moving evaporating meniscus and flow boiling in a micro channel. It is reported that liquid film evaporation is the primary heat transfer mechanism of flow boiling in a micro channel.

Several heat transfer models for flow boiling in micro channels based on the liquid film evaporation have been proposed. Thome et al. [5] proposed a three-zone model for a slug flow. One periodic cell consists of three zones, i.e., liquid slug, thin liquid film and dry out regions. Initial liquid film thickness is one of the three unknown parameters. Kenning et al. [7] proposed confined bubble growth model. They took into account the variation of saturated pressure which was caused by vapor bubble expansion. It was assumed that liquid film thickness is uniform. Model prediction showed good accordance with the experimental results.

Due to the importance of liquid film thickness, many researches have been conducted to measure the liquid film thickness in micro tubes. Taylor [8] experimentally obtained the liquid film thickness from the difference of the bubble velocity and the mean velocity in wide range of capillary number. It is 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 [9] as a function of capillary number:

$$\frac{\delta}{D} = \frac{0.67Ca^{2/3}}{1 + 3.35Ca^{2/3}}, \quad (1)$$

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Nomenclature

Bo	Bond number (–)
Ca	capillary number (–)
C_p	specific heat (kJ/kg K)
D	tube diameter (m)
G	mass flow rate (kg/m^2 s)
h	convection heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity (W/m K)
L	heating length (m)
q''	heat flux (W/m^2)
Re	Reynolds number (–)
T	temperature (°C)
U	bubble velocity (m/s)
V	voltage (V)
We	Weber number (–)
x	quality (–)
z	distance from inlet (m)

Greek symbols

δ	liquid film thickness (m)
μ	viscosity (Pa s)
ρ	density kg/m^3
σ	surface tension coefficient (N/m)

Subscripts

0	initial
in	inner
out	outer
sat	saturated
sub	subcooled

where δ is liquid film thickness and D is tube diameter. Eq. (1) is called Taylor's law.

Moriyama and Inoue [10] measured liquid film thickness formed by a vapor bubble expansion in a narrow gap from the temperature change of the channel wall. Their experimental data were correlated in terms of dimensionless boundary layer thickness, capillary number and Bond number as follows:

$$\frac{\delta}{D} = \begin{cases} 0.10(\delta^*)^{0.84} & (Bo > 2), \\ 0.07Ca^{0.41} & (Bo \le 2), \end{cases} \tag{2}$$

where δ^* is the dimensionless viscous boundary layer thickness and Bo is the Bond number based on the vapor–liquid interface acceleration. Eq. (2) was employed in the three-zone model proposed by Thome et al. [5] for the initial liquid film thickness.

Han and Shikazono [11,12] measured local and instantaneous liquid film thickness in micro channels under adiabatic condition with laser focus displacement meter. The effect of inertial force on the liquid film thickness was investigated using several working fluids in micro channels with different diameters. Empirical correlations based on capillary number, Reynolds number and Weber number were proposed. They also investigated the effect of bubble acceleration on liquid film thickness [13]. It was observed that the increase of liquid film thickness with capillary number was suppressed when bubble acceleration is large. It was explained that liquid film thickness decreased because the curvature between bubble nose and transition region was affected by flow acceleration.

Although many experiments have been carried out to measure liquid film thickness in micro tubes, most of the experiments were conducted under adiabatic condition. However, under flow boiling condition, the bubble velocity is not constant but accelerated due to phase change. Thus, it is necessary to consider how flow boiling affects liquid film thickness. Although several models for flow boiling heat transfer in micro tubes based on liquid film evaporation are proposed, the effect of liquid film evaporation on flow boiling heat transfer in micro tubes is not fully understood. In the present study, liquid film thicknesses are directly measured under flow boiling condition and compared with those under adiabatic condition. The relationship between liquid film thickness and heat transfer coefficient is also investigated.

2. Experimental setup and procedures

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. In Fig. 1, working fluid is degassed by the degasser and pumped at a uniform flow rate with the plunge pump. In the preheater, working fluid is heated up to the desired temperature. Pyrex glass tube of D = 0.5 mm inner diameter is used as a test tube.

Fig. 2 shows the schematic diagram of the test section. Flow direction is horizontal. Acryl blocks are used for connection and thermal insulation. Test tube is coated by ITO, which is a transparent conductive film for Joule heating. ITO film is connected to DC power supply. Total length of the test tube is 100 mm and heating length is 85 mm. Outer wall temperatures at eight positions are measured by K-type thermocouples calibrated within ±0.2 °C error. Two thermocouple probes and two pressure sensors are used to measure the temperatures and pressures at the inlet and the outlet as shown in Fig. 2. The data for measured temperature, pressure, voltage and current are collected by data acquisition system and recorded by PC.

The velocity of the vapor bubble is measured from the images of vapor–liquid interface captured by the high-speed camera (Photron SA1.1). Frame rate was varied according to the bubble velocity and was increased up to 5000 frames per second.

2.2. Laser focus displacement meter

Laser focus displacement meter (LT9010M, Keyence, LFDM hereafter) is used to measure the liquid film thickness. LFDM has been used by several researchers for liquid film thickness measurements [11–15]. It is reported that the laser focus displacement meter can measure the liquid film thickness in a circular tube very accurately within 1% error [15].

As the laser beam passes through the tube wall, focus is scattered within a certain range due to the difference of curvatures between axial and azimuthal directions. Cover glass and glycerol are used to remove the curvature effect caused by the outer wall. Refractive index of glycerol is almost the same with that of the Pyrex glass, thus the refraction of laser between glycerol and Pyrex glass can be neglected. The effect of inner wall curvature is corrected by the equation suggested by Takamasa and Kobayashi [14].

The interface between the glass wall and liquid film cannot be detected by the present LFDM because of similar refractive indexes. Therefore, liquid film thickness is obtained as following procedures. First, the thickness from the outer cover-glass surface to the glass inner wall is measured without liquid film. Then, the whole thickness from the outer cover-glass surface to the vapor–liquid interface is measured including liquid film thickness. Liquid film thickness is calculated from the difference of those two values.

Interferometer is another method to measure the liquid film thickness. Liquid film thickness measured with LFDM in micro