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Thickness of Liquid Film Formed in Micro Channel Slug Flow

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Abstract: Slug flow is the representative flow regime of two-phase flow in micro tubes and channels. It is well known that the evaporation of thin liquid film formed between the tube wall and the vapor bubble plays a significant role in micro channel heat transfer. In the present study, experiments are carried out to clarify the effects of parameters that affect the formation of thin liquid film. Laser focus displacement meter is used to measure the thin liquid film thickness. Air, ethanol and water are used as working fluids. Circular tubes with two different diameters, 0.3 and 0.5 mm, and square channels with two different dimensions, 0.3 × 0.3 and 0.5 × 0.5 mm, are used. The effects of capillary number, Reynolds number and geometry on liquid film thickness are investigated.

1. INTRODUCTION

Micro scale evaporation heat transfer attracts much attention due to its many advantages, e.g., high efficiency, microgravity, miniaturization, etc. However, the characteristics of flow boiling in micro channels are quite different from those in large channels and they are not fully understood. Slug flow becomes the dominant flow pattern in micro channels due to surface tension. It is known that the evaporation of thin liquid film formed between the tube wall and the vapor bubble plays a significant role in micro tube heat transfer. In the present study, a series of experiments is conducted to investigate the effects of those parameters that affect the formation of thin liquid film in micro circular tubes and square channels.

2. EXPERIMENTAL SETUP AND PROCEDURE

Square channels made of quartz and circular tubes made of Pyrex glass were used. Table 1 shows the detailed dimensions of micro tubes and channels. In square channels, liquid film thickness is not uniform along the perimeter. To measure the liquid film thickness at the channel corner, one corner of the square channel is modified as shown in Fig. 1. Air, ethanol and water were used as working fluids, and all experiments were conducted under conditions of room temperature and 1 atm.

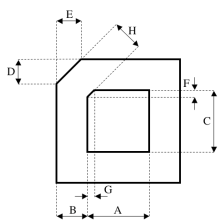

Figure 1. Cross section of the micro channel

Table 1. Dimensions of micro channels and tubes

	A (mm)	B (mm)	C (mm)	D (mm)
Channel 1	0.559	0.240	0.571	0.229
Channel 2	0.294	0.198	0.283	0.192
	E (mm)	F (mm)	G (mm)	H (mm)
Channel 1	0.234	0.044	0.041	0.197
Channel 2	0.188	0.019	0.014	0.170

Tube 1	I.D. (mm)	0.485	O.D. (mm)	0.8
Tube 2	I.D. (mm)	0.305	O.D. (mm)	0.5

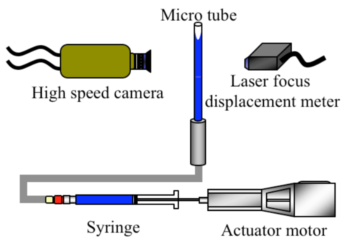

Figure 2. Schematic of the experimental setup

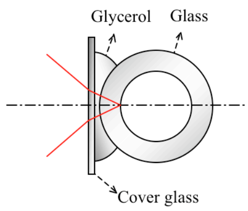

Figure 3. Schematic of the micro tube

Figure 2 shows the schematic of the experimental setup. Actuator motor (EZHC6A-101, Oriental motor) was used to move the liquid inside the test conduits. The velocity of gas-liquid interface was measured from the images captured by high-speed camera (Phantom 7.1). Laser focus displacement meter (LT9010M, Keyence) was used to measure the thickness of liquid film. The displacement of target surface can be determined by the objective lens moved by the tuning fork. Laser focus displacement meter has been used by several researchers for the measurement of the liquid film thickness [1][2].

For circular tubes, cover glass and glycerol were used to remove the focus scattering caused by the outer wall curvature. Figure 3 shows the schematic of the micro tube with cover glass and glycerol. To compensate for the inner wall scattering, correction suggested by Takamasa and Kobayashi[1] was used.

Figure 4 shows a typical measurement example in horizontal flow direction. There is no signal before the air-liquid interface reaches the measuring position. After air-liquid interface passes by the measuring position, liquid film is formed on the wall and signal is obtained. In Fig. 4, liquid film thickness decreases initially. This initial decrease corresponds to the transition region between the bubble nose and the flat film region. Initial liquid film thickness δ_i after the initial decrease is collected as experimental data.

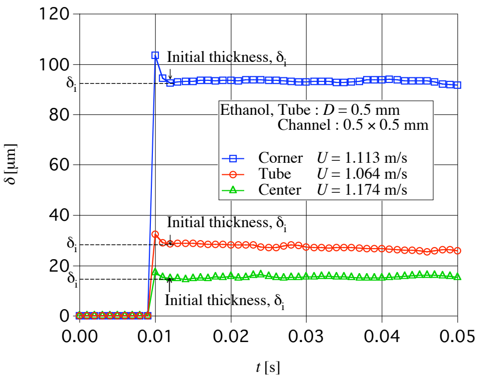

Figure 4. Measured liquid film thickness against time

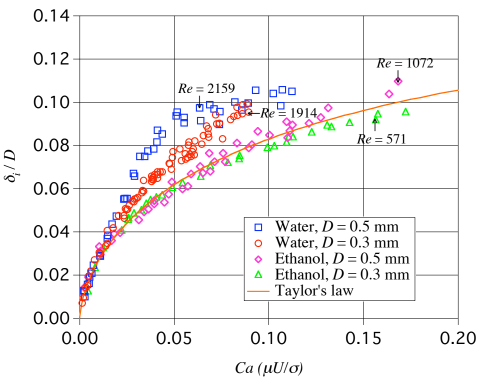

Figure 5. Dimensionless liquid film thickness (δ_i/D) against capillary number ($Ca = \mu U/\sigma$) in micro tube

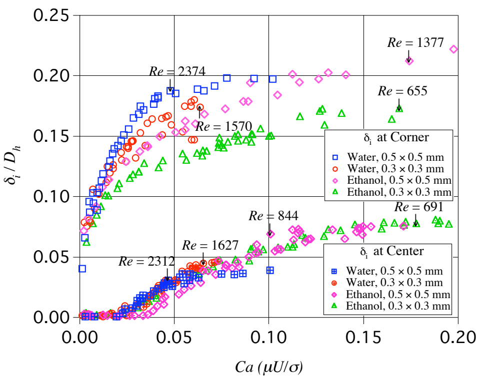

Figure 6. Dimensionless liquid film thickness (δ_i/D_h) against capillary number ($Ca = \mu U/\sigma$) in micro channel

3. EXPERIMENTAL RESULT AND DISCUSSION

3.1 Circular tube

Figure 5 shows the dimensionless liquid film thickness δ_i/D in micro circular tube against capillary number $Ca = \mu U/\sigma$. It is known that the liquid film thickness is determined by the force balance between viscous and surface tension forces, which can be represented by capillary number. The solid line in Fig. 5 is an empirical curve fitting of Taylor's experimental data[3] proposed by Aussillous and Quere[4]:

$$\frac{\delta}{R} = \frac{1.34Ca^{2/3}}{1 + 2.5 \times 1.34Ca^{2/3}}. \qquad (1)$$

Equation (1) is called Taylor's law. The working fluids in Taylor's experiments were highly viscous. Therefore, Reynolds number in his experiment is quite small and the inertia force is negligible.

In Fig. 5, at low capillary number, dimensionless liquid film thicknesses become nearly identical regardless of working fluids and tube diameters. However, as capillary number increases, the liquid film thicknesses of water and larger diameter tube become thicker. It is considered that the inertia force makes liquid film thicker as capillary number increases. The trend of liquid film thickness changes when Reynolds number $Re = \rho UD/\mu$ becomes larger than roughly 2000. For $Re > 2000$, the liquid film thickness against capillary number remains nearly constant with some scattering. It is considered that this is due to the flow transition from laminar flow to turbulent flow.

3.2 Square channel

Figure 6 shows the dimensionless liquid film thickness in micro square channel. In Fig. 6, hydraulic diameter D_h of square channel is used for the dimensionless liquid film thickness. Liquid film thickness δ_i at channel center is almost zero for $Ca < 0.03$. However, δ_i at channel corner increases from $Ca = 0$. It is found that the effect of inertia force becomes more distinct at channel corner than at channel center. Inertia force makes liquid film thicker as the trend found in micro circular tubes. The dependence of δ_i on inertia force is qualitatively the same, but δ_i for given capillary number is much thicker at channel corner than that in circular tubes. The liquid film thickness remains nearly constant also in square channel, for Re > 2000.

4. CONCLUSIONS

The liquid film thickness in micro circular tubes and square channels is measured by laser focus displacement meter. The liquid film thickness is determined only by capillary number at small capillary number. However, as capillary number increases, the effect of inertia force cannot be neglected and inertia force makes liquid film thicker in both circular tubes and square channels. Liquid film thickness at channel center is almost zero for Ca < 0.03, while the liquid film thickness at channel corner increases from $Ca = 0$. The effect of inertia force is more distinct at channel corner than at channel center. For Re > 2000, the liquid film thicknesses in both circular tubes and square channels remains nearly constant with some scattering due to the flow transition.

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