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# マイクロチャネルスラグ流の薄液膜厚さに関する研究

# Thickness of Thin Liquid Film Formed in Slug flow in Micro Channel

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Slug flow is the representative flow regime of two-phase flow in micro channels. It is well known that the evaporation of thin liquid film formed between the channel wall and the vapor bubble plays a significant role in micro conduits heat transfer. In the present study, experiments are carried out to clarify the effect of parameters that affect the formation of thin liquid film. Laser focus displacement meter is used to measure the thickness of the thin liquid film. Air, ethanol and water are used as working fluids. Channels with three different heights, $H$=0.1, 0.3, 0.5 mm and circular tubes with two different diameters, $D$=0.3 and 0.5 mm, are used. Experimental results are compared with the Taylor's correlation. The effects of channel height, cross sectional shape and fluid properties on dimensionless thin liquid film thickness are discussed.

*Key Words :* Thin liquid film, Two-phase flow, Micro channel, Micro tube

## 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 tube is quite different from those in conventional tube and they are not fully understood. Flow regime is also different in micro tube due to surface tension, and slug flow becomes the dominant flow pattern. 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. It is reported that the thickness of liquid film is one of the important factors for the prediction of flow boiling heat transfer in micro tubes[(1-2)]. In the present study, a series experiments is conducted to investigate the effects of those parameters that affect the formation of thin liquid film in micro tubes

## 2. Experimental Setup and Method

Rectangular channels made of quartz with large aspect ratio were used. Three kinds of channel height, $H$=0.1, 0.3 and 0.5 mm were used. In addition, circular tubes made of Pyrex glass with 0.3 and 0.5 mm inner diameter were used. Table 1 shows the detailed dimensions of the rectangular channels and the circular tubes. Air, ethanol and water were used as working fluids, and all experiments were conducted under conditions of 20°C and 1atm. Figures 1 and 2 show the schematic of the experimental setup and its real counterparts, respectively. Test channel was connected to syringe. Actuator motor (EZHC6A-101, Oriental motor) was used to move the liquid inside the test conduits. The velocity range of actuator motor is 0 to 0.6 m/s, so syringes with several cross sectional areas were used to control the liquid velocity. The velocity of gas-liquid interface was measured 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 displacement of objective lens moved by tuning fork, when focus is obtained on the target surface. Laser focus displacement meter

**Table 1 Dimensions of micro channel and tube**

| Rectangular channel | | | Circular tube | | |
|---|---|---|---|---|---|
| Height (mm) | Width (mm) | Length (mm) | I.D. (mm) | O.D. (mm) | Length (mm) |
| 0.504 | 10 | 80 | 0.487 | 0.8 | 250 |
| 0.309 | 7 | 80 | 0.305 | 0.5 | 250 |
| 0.116 | 4 | 80 | | | |

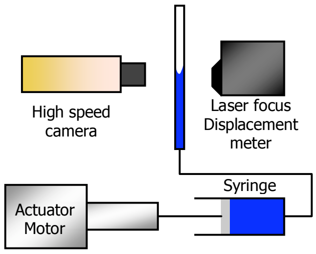


Fig.1 Schematic diagram of experimental setup

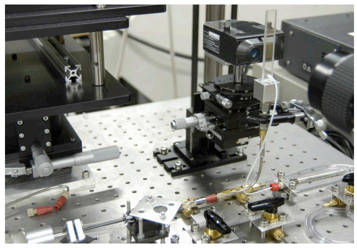

Fig. 2 Real picture of experimental setup

has been used by several researchers for the thin liquid film measurement[(3-4)]. Laser focus displacement meter makes it possible to measure the liquid film thickness very accurately, within 1% error[(4)]. The procedure of measuring liquid film thickness in rectangular channel is as follows. Firstly, the channel height without any liquid is measured, Then, liquid is pulled in by the actuator motor, the interface between liquid and gas is thereby formed. The thickness of liquid film is consequently calculated from the difference of measurements with and without liquid film. As for the micro tube, the method of liquid film thickness measurement is as follows. Cover glass and glycerol were used to remove the focus scattering caused by the outer wall curvature. Refractive index of glycerol is almost the same with that of the Pyrex glass, so the refraction of laser between glycerol and Pyrex glass can be neglected. Figure 3 shows the schematic diagram of the micro tube with cover glass and glycerol. Initially, the distance from cover glass to the inner wall is measured. After liquid film is formed, the thickness including liquid film is measured. The thickness of liquid film is obtained from the difference of those two values. To compensate for the curvature of inner wall,

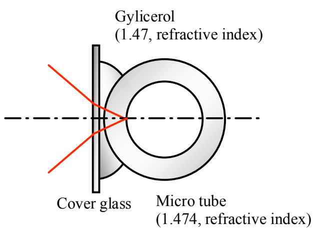


Fig. 3 Schematic diagram of micro tube

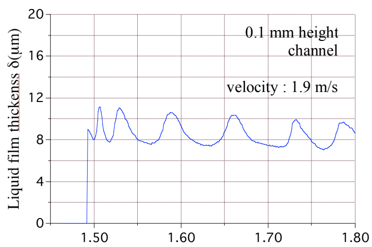


Fig. 4 Example of fluctuation

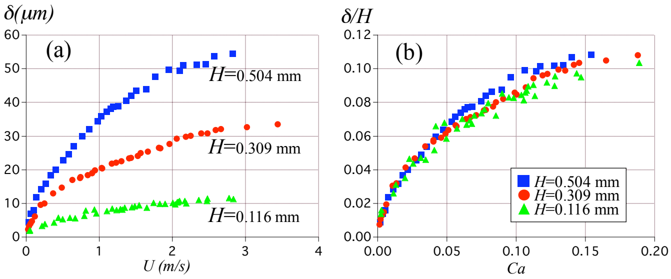


Fig. 5 (a) Thickness of liquid film in micro channel against velocity (b) Dimensionless thickness against Capillary number

correction by Takamasa and Kobayashi[3] was used.

The liquid film thickness, δ varies slightly as time passes after it is formed on the wall. The reason maybe due to the effect of shear force on the interface caused by gas velocity. The liquid film thickness shows fluctuation of about ±1.5μm in relatively high velocity cases. Averaged value during first one cycle was taken as the thickness data. Figure 4 shows an example of liquid film thickness.

## 3. Results and Discussions

### 3.1 Micro Rectangular Channel

Figure 5 shows the measured liquid film thickness in rectangular channels. Liquid film thickness increases with velocity. It is known that the liquid film thickness is mainly determined by the force balance between the viscous force and surface tension force, which can be represented by Capillary number, $Ca=\mu U/\sigma$. Figure 5 (b) shows the dimensionless liquid film thickness, $\delta/H$ against *Ca*. It is considered that the effect of viscous force dominates as velocity increases. The liquid film thickness converges to a constant value. In the region of low *Ca* number, the results from three channels become nearly identical. However, as *Ca* number increases, the liquid film thickness in larger channel shows slightly larger values. This is considered to be due to the effect of inertia force. The inertia force is usually neglected in micro scale, but there is still some inertia effect left at high *Ca* numbers.

### 3.2 Micro Circular Tube

Figure 6 shows the comparison of the liquid film thickness between rectangular channels and circular tubes. In Figure 6 (b), tube diameter, *D* is used for the dimensionless thickness of the micro tube. The general trend on the thickness of liquid film in the circular micro tube is almost the same as that in the micro rectangular channel. In the region of low velocity, the thickness of liquid film both in micro rectangular channel and circular tube shows almost the same value. But as velocity increases, the thickness of liquid film in micro circular tube shows slightly smaller value. Bretherton[5] carried out a scaling analysis about the liquid film thickness behind the bubble tip. He divided a bubble in to three regions, spherical cap region, transition region and flat film region. In his scaling analysis, pressure drop term is in a inverse proportion to the square thickness of liquid film. Although pressure drop in the transition region is not same as the single

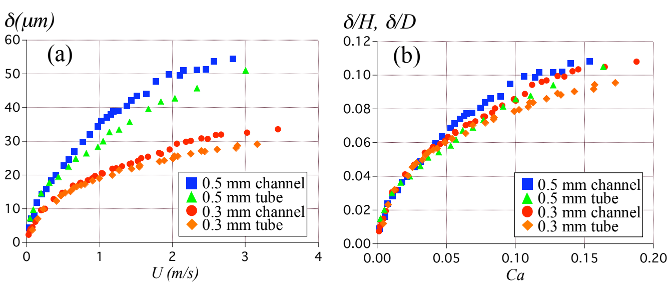


Fig. 6 (a) Thickness of liquid film against velocity (b) Dimensionless thickness against Capillary number

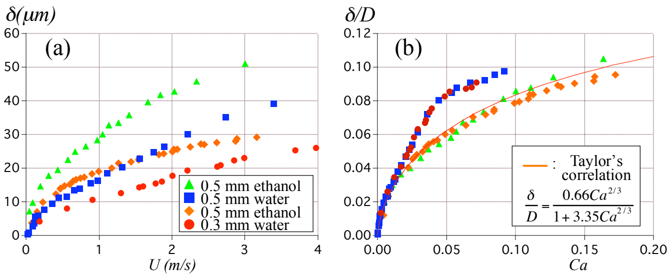


Fig. 7 (a) Thickness of liquid film against velocity (b) Dimensionless thickness against Capillary number

phase laminar flow, we can infer that pressure drop of transition region in micro tube is larger than that in micro channel. More careful analysis is necessary to clarify the effect of geometry on the liquid film thickness.

To understand the effect of inertia force, experiments using water as working fluid were conducted. The *Re* number of water is about 6 times larger than that of ethanol at same *Ca* number. Figure 7 shows the results. The line in Figure 7 (b) is the experimental correlation suggested by Taylor[6]. He measured the averaged thickness of liquid film in circular tubes of 2 and 3 mm diameters. The fluids in his experiment were highly viscous such as glycerol and lubricating oil, therefore the *Re* number in his experiment was less than 1. The dimensionless liquid film thickness of water shows much larger value than that of ethanol and Taylor's correlation. Reynolds number of water and ethanol at 0.05 *Ca* number are about 1800 and 300, respectively in 0.5 mm diameter tubes. Tube diameter was used as the characteristic length for *Re* number, $Re=\rho UD/\mu$. Although *Re* number of ethanol is larger than that of Taylor's correlation, the dimensionless thickness of liquid film of ethanol is slightly smaller than the Taylor's correlation. It is considered that inertia force does not always contribute to thickening liquid film, but it makes the thickness of liquid film decrease and tend to increase after *Re* number becomes larger than a certain value. This trend of liquid film thickness against Reynolds number is also reported by several numerical simulations[6-7].

## 4. Conclusion

The liquid film thickness in micro rectangular channel and circular tube was investigated experimentally. It is confirmed that the liquid film thickness increases as velocity increases and converges to a constant value. The thickness of liquid film in micro rectangular channel shows slightly larger value than that in micro circular tube at high *Ca* number. The liquid film thickness is determined mainly by the force balance between viscous force and surface tension. If the velocity is large, but the effect of inertia force can not be neglected. To clarify the effect of inertia force on the liquid film thickness, more experiments are necessary.


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