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MICRO-LIQUID-LAYER BEHAVIOR AND HEAT TRANSFER CHARACTERISTICS OF BOILING IN A MICRO-CHANNEL VAPORIZER

Yoshio Utaka
Yokohama National University, Tokiwadai, Hodogaya, Yokohama, Kanagawa 240-8501, Japan
e-mail utaka@ynu.ac.jp

Yutaka Tasaki
Nissan Motor Co., Ltd., Natsushima-cho, Yokosuka-shi, Kanagawa 237-8523, Japan
e-mail y-tasaki@mail.nissan.co.jp

Shuhei Okuda
Yokohama National University, Tokiwadai, Hodogaya, Yokohama, Kanagawa 240-8501, Japan
e-mail okushu55@ybb.ne.jp

Abstract *To elucidate the mechanism and characteristics of boiling heat transfer in a micro-channel vaporizer, it is important to investigate experimentally the micro-layer thickness that forms between the heating surface and generated vapor. In this study, the micro-layer thickness was measured by the laser extinction method for channel gap sizes of 0.5, 0.3 and 0.15 mm. It was clarified that the gap size, the rate of bubble growth and the distance from the incipient bubble site have an effect on the micro-layer thickness in a micro-channel boiling system. The initial micro-layer thickness increased with increasing velocity of the bubble forefront and had the effect of moderating the velocity. In the region of higher velocity, the thickness was constant for each gap. Distributions of the initial thickness of the micro-layer on the heat transfer surface are shown.*

Keywords*. boiling, micro-channel, micro-layer thickness, laser extinction method*

1. Introduction

The objective of the present investigation is to clarify the characteristics of the micro-layer that forms between the heating surface and bubbles during boiling in a micro-channel vaporizer by using a laser extinction method to measure the micro-layer thickness. The micro-channel refers to the section for the entrance of the bulk liquid in a plate-shaped vapor generator the gap of which is narrowed by the heating plates. The reformer fuel cell vehicle requires high heat exchange efficiency and low heat capacity to meet powertrain requirements for quick response and compactness. The use of a micro-channel type of vapor generator for the reformer is one possible approach to meeting these requirements. In this case, the gap of the micro-channel must be made as small as possible to obtain high heat-transfer characteristics.

In the boiling process, the bulk liquid, superheated thin liquid layer (micro-layer) and the bubbles generally affect boiling characteristics in complicated ways. In the particular case of a restricted flow path such as a micro-channel, vapor bubbles have a depressed shape because they are pushed and crushed by the heating plates and rapidly spread over the heating plates. Therefore, the rate of evaporation at the micro-layer between the plates and the bubbles plays an important role in determining the heat-transfer rate. Thus, the characteristics of boiling heat transfer in the micro-channel differ from those of pool boiling as reported by Katto and Yokoya (1966) and Fujita et al (1988).

A previous report by some of the authors (Tasaki & Utaka, 2004) described observations of the aspects of the vapor behaviors and heat transfer measurements in the micro-channel. The effect of the gap size between the heating plates and the wettability of the heating surface of a micro-channel on heat-transfer characteristics was experimentally studied. It was pointed out that the heat-transfer characteristics were mainly governed by these factors. In the case of a gap size between 0.25 and 10 mm, wettability was changed from hydrophilic to hydrophobic by applying coatings of titanium oxides and silicon resin to the lapped copper heating surfaces. The effects of surface wettability on the boiling curve were investigated by observing various factors affecting boiling. It was found that hydrophilic surface reduced heat transfer with a 10 mm gap size. On the other hand, with a gap size between 0.25 mm and 1.0 mm, heat transfer was enhanced. It was concluded that the enhancement of heat transfer was due to the formation and sustaining of a micro-liquid-layer on the heating plate with a highly wetting surface.

The boiling curves measured for various gap sizes with a titanium oxide-coated surface in our previous work are shown in Fig. (1). Two regions are seen for boiling or vaporization in the micro-channel, namely a micro-layer-dominant region and a dryout region. Intermittent formation of the micro-layer due to the generation of vapor bubble is observed in the first region. In the other region, periodical forward and backward movements of the liquid at the entrance of the channel and the appearance of dryout at the exit are observed. The dotted line in the figure divides the two regions. For all cases of a gap size of less than 0.5 mm, the maximum heat flux occurs in the dryout region.

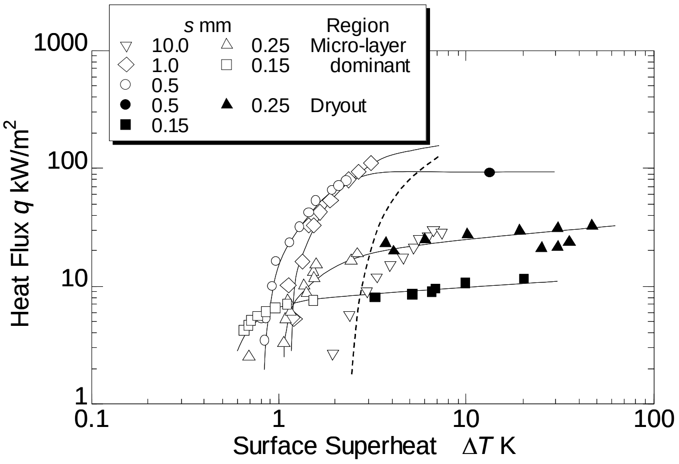


Figure 1 Effect of gap sizes on boiling curves on titanium oxide-coated copper surface

However, the micro-layer-dominant region occupies approximately 70 to 80% of the maximum heat flux. Hence, it is seen that the micro-layer-dominant region represents the principal form of heat transfer in the micro-channel boiling. For instance, in the region of relatively low superheat, a narrower gap size results in a higher heat-transfer coefficient. However, with increasing superheat, the trend tends to change oppositely. Therefore, clarifying the behavior of the micro-layer is a very important factor in elucidating the mechanism and characteristics of boiling heat transfer in a micro-channel vaporizer.

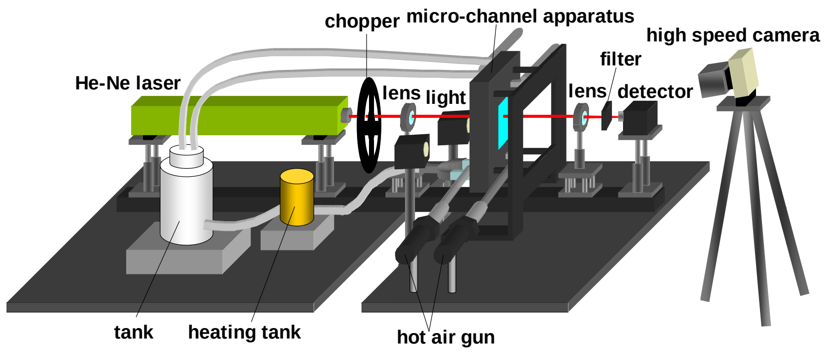
Cooper and Lloyd (1969) generated relatively large-size bubbles in low-pressure nucleate boiling and predicted the thickness of the micro-layer from their experimental results. They also proposed a simple fluid dynamics model for predicting the micro-layer thickness. In recent years, application of a theoretical model to evaporation characteristics taking into account intermolecular force was proposed for investigating more general evaporation phenomena (Wayner, 1998; Stephan, 2002). Research has also been done concerning micro-layer evaporation in an extended meniscus region, including from liquid meniscus, which is easily created on an evaporation surface, to the micro-layer. However, even though the distribution and time-related behavior of the thickness of the micro-layer formed on the heating surface play important roles in boiling in the micro-channel, sufficient information concerning the micro-layer thickness has yet to be reported. Therefore, it is considered very significant to clarify these aspects.

As mentioned above, the purpose of the present investigation is to examine the relation between boiling characteristics and aspects of the micro-layer by observing the formation of bubbles and the progress of their growth and by measuring the thickness of the micro-layer, based on our previous study. High response and non-contact measurement are required to be able to measure an extremely thin film. To satisfy those requirements, a laser extinction method was fitted to the apparatus of the micro-channel used.

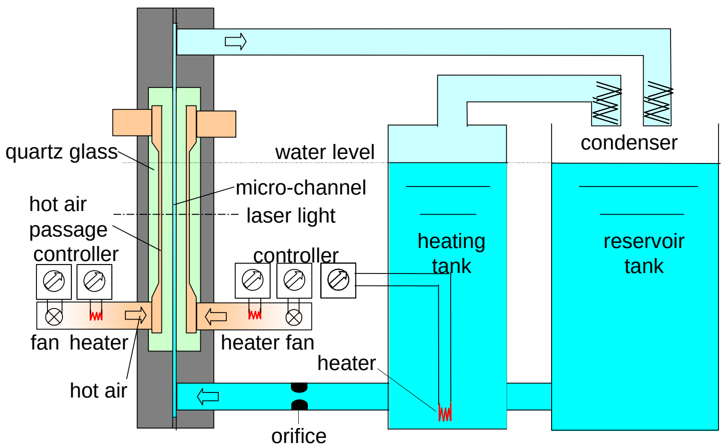
2. Experimental apparatus and procedure

The experimental apparatus consisting of a boiling section in the micro-channel vaporizer and a section for measuring the micro-layer thickness by laser extinction is shown in Fig. (2(a)). The vaporizer is located between a He-Ne laser emitter and a Pb-Se detector. Figure (2(b)) shows the micro-channel system, which is the same as the one used in the previous study with the exception of the micro-channel section. A brief explanation of the experimental apparatus follows.

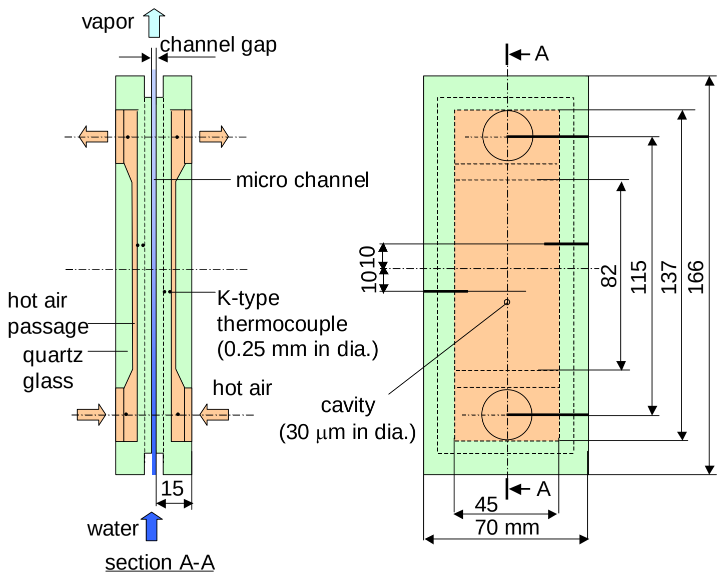
A water reservoir and a heating tank were placed upstream in the micro-channel test apparatus. The cross-sectional area of the water reservoir was large enough to maintain a constant water level in the micro-channel. The water supplied to the micro-channel apparatus was boiled in the heating tank that was open to the atmosphere. Vapor generated from the micro-channel vaporizer and the heating tank flowed through a condenser and back to the water reservoir. The details of the micro-channel test apparatus are shown in Fig. (2(c)). A quartz glass having high transparency for the infrared light used was mainly used for the test apparatus to enable more accurate measurement of the micro-layer thickness. The micro-channel was formed by two quartz glass plates. The passages for high temperature air that supplied heat to the micro-channel were located at the back and the front of the micro-channel. The central part of the 82-mm-high passages was narrowed to enhance heat transfer in this area that essentially served as the heating area. The width of the passages was 45 mm. The heat flux into the micro-channel was varied by controlling the temperature of the air from 110 to 300°C. A cavity of 30 μm in diameter was located 12 mm below the center of the micro-channel to provide an incipient bubble site on the heating plate. Two thermocouples were embedded at different depth in the quartz glass at points of 12 mm above and below the center, respectively, to measure the heat flux through this component.



(a) Entire system



(b) Micro-channel system



(c) Details of micro-channel and quartz glass heating plates

Figure 2 Experimental apparatus

The contact angle of the pure water on the quartz glass used as the heating plates was 26 ° and the real gap size of the narrower micro-channel measured with a plasti-gauge was in the range of 0.147 ~ 0.158 mm for a 0.15 mm gap size as a test Therefore, it was confirmed that the heating surface had sufficient wettability and that the gap size was constant and sufficiently accurate with respect to the target value.

A laser ray having a diameter of 3 mm and a wavelength of 3.39 μm was launched from a He-Ne laser through the micro-channel via a chopper. A convex lens, one side of which was flat, narrowed the laser ray to 0.6 mm in diameter. After passing through the convex lens and an optical filter, the laser ray was introduced into a Pb-Se infrared detector (optical conducting element) having a light-receiving surface 3×3 mm^2 in area. The laser signals were recorded in synchronization with the process of bubble growth, which was recorded with a high-speed camera placed in front of the micro-channel. The relative location of the incident laser ray on the heating surface was adjusted to vary the incipient bubble site and the distance from the measuring point.

The principle of the laser extinction method used for measuring the micro-layer thickness is shown in Fig. (3). I_0 and I denote the light intensities at the detector under the condition that the micro-channel being measured is filled with steam and with water and steam, respectively. The micro-layer thickness was found by applying Lambert's law shown in Eq. (1) below to the measured laser signal.

$$\delta = -\left(1/A\right)\ln\left(I/I_0\right) \qquad (1)$$

where δ and A are the micro-layer thickness and extinction coefficient, respectively. The extinction coefficient for water was shown and the precision of measurement was investigated in (Utaka and Nishikawa, 2003a,b). The values of I/I_0 varied from 0.2 to 0.9 in relation to a range of 2 to 30 μm for the thickness of the micro-layer of water. This method is sufficiently accurate to measure the micro-layer thickness of water on a micron scale.

An example of consecutive measurements ((a) → (c)) for the process of bubble growth and the laser signal is shown in Fig. 4. The dots at the center and in the lower part of the pictures show the measuring point for the micro-

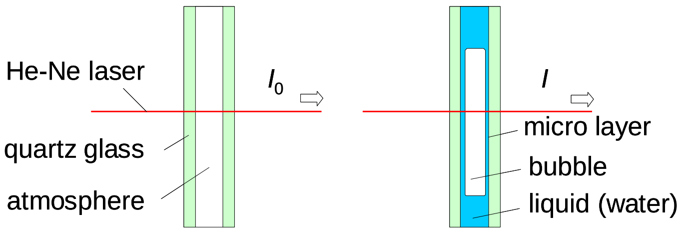


Figure 3 Laser extinction method applied for measuring micro-layer thickness

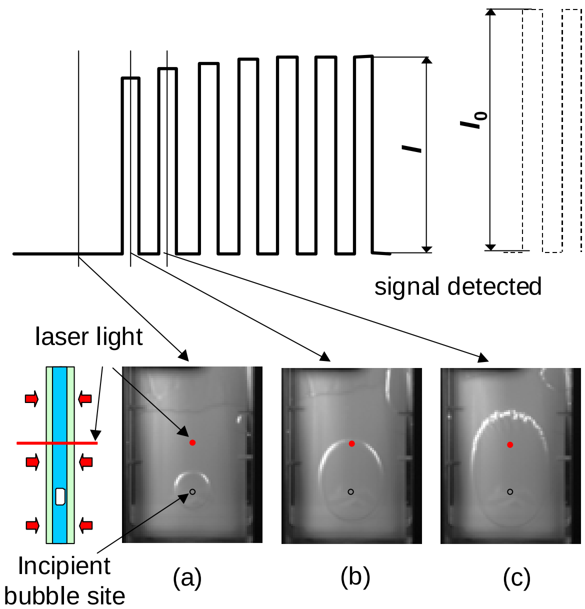


Figure 4 Example of micro-layer thickness measurement

layer thickness and the incipient bubble site, respectively. As seen in picture (b), the micro-layer was formed after the bubble forefront reached the measuring point and the micro-layer thickness was found in accordance with the correlation between it and the laser ray intensity.

3. Results and discussion

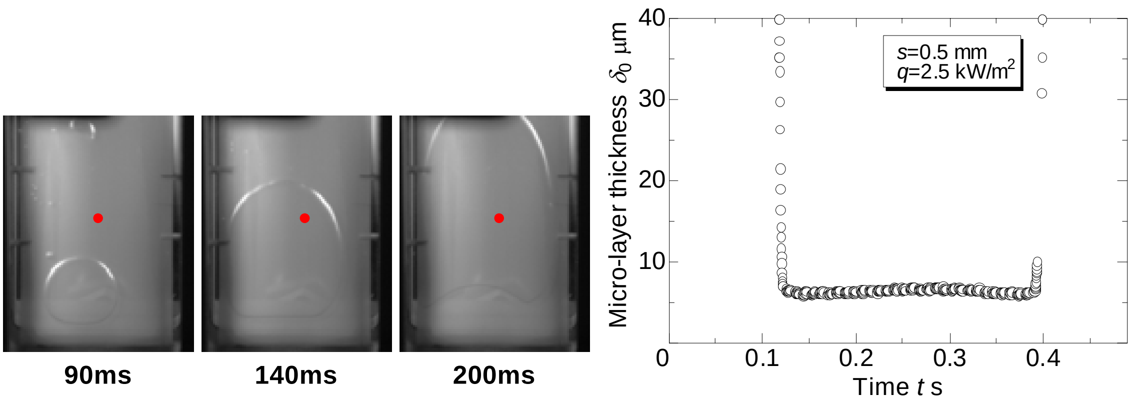
3.1. Bubble behavior and variation of micro-layer thickness

Figures (5(a)) and (b) show the typical aspect of bubble growth and variation of the micro-layer thickness for two different heat fluxes. In both cases it is observed that the bubbles spread rapidly in turn in the lateral direction over the heating surface. In the case of a relatively low heat flux of 2.5 kW/m^2, the advancing bubble forefront maintains a smooth shape as shown in Fig. (5(a)). However, with an increase in heat flux to 6.7 kW/m^2, the shape of the bubble forefront is uneven as shown in Fig. (5(b)). After the bubble spreads over almost the entire heating surface, it slowly moves upward. The residence time of a bubble at the measuring point was independent of heat flux and was between 300 and 500 ms for all the cases.

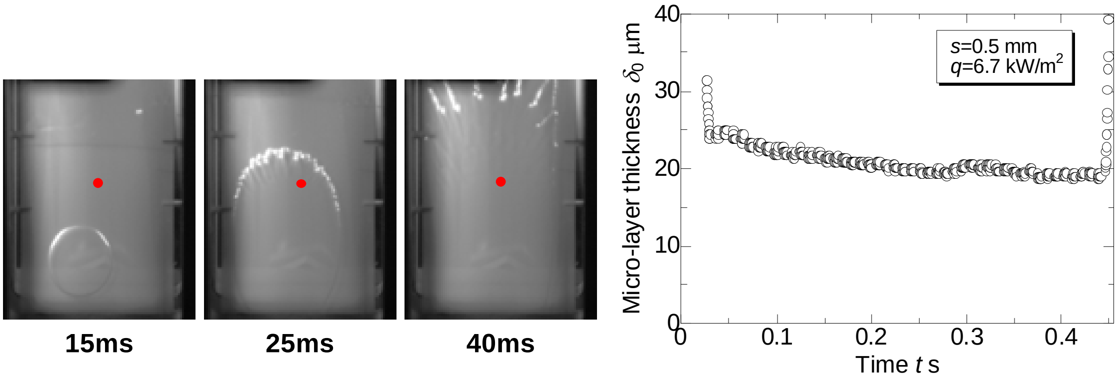
On the other hand, as seen in Fig. (5(a)) and (b), the thickness of the micro-layer formed after the bubble forefront passes tends to decrease with time. Subsequently, it rapidly increases following complete passage of the bubble. The rate of decrease of the micro-layer thickness increased with increasing heat flux, which is attributed to the effect of the rate of evaporation.

3.2. Effect of rate of bubble growth on initial micro-layer thickness

In the process of the bulk liquid being pushed to the sides by the growth of the bubbles, the micro-layer is formed as a result of liquid remaining in the vicinity of the heating surface, indicating the effect of the velocity of bubble movement. As described above, the micro-layer thickness varies either because of movement at the interface between the vapor and the liquid or evaporation from the micro-layer immediately after the bubble forefront passes. Attention



(a) q = 2.5 kW/m^2 and V_L = 0.38 m/s



(b) q = 6.7 kW/m^2 and V_L = 2.8 m/s

Figure 5 Aspect of bubble growth and variation of micro-layer thickness for s = 0.5 mm was focused on the initial micro-layer thickness δ_0 immediately after the passage of the bubble forefront. It is thought that δ_0 is determined by the kinetic interface behavior in the process of bubble growth without being affected by boiling phenomenon. On a high wetting surface, the initial micro-layer thickness may depend on the effect of the displacement of the bulk liquid by the vapor bubbles, the depressing effect by bubble inside pressure and so forth. Therefore, the effect of V_L, local velocities of the bubble forefront at the measuring point, was examined. The initial micro-layer thickness indicates a strong dependence on the velocity of passing bubbles. From the small velocity side, the thickness can be divided into two specific regions. One is a region where the thickness increases linearly with increasing velocity, and the other is region where the thickness is almost constant. The boundary between the two regions was a local velocity of around 2 m/s. Initial micro-layer thickness of between 2 and 30 μm and around 24 μm were measured in the linear increase region and in the constant thickness region, respectively.

3.3. Effect of gap size on initial micro-layer thickness

The variation of the initial micro-layer thickness in relation to the velocity of the bubble forefront for two different micro-channel gap sizes of 0.5 mm and 0.3 mm is shown in Fig. (7). In the case of 0.3 mm, the result show tendency similar to that seen for the gap size of 0.5 mm in Fig. (6(a)). That is, the tendency of the initial micro-layer thickness relative to the velocity of the bubble forefront changed at a bubble forefront velocity of 2.0 m/s for the 0.3 mm gap. Moreover, the initial micro-layer thickness was strongly affected by the gap size and decreased with decreasing gap size. In the constant thickness region, initial micro-layer thickness of 24 and 18 μm were measured for the gap sizes of 0.5 and 0.3 mm, respectively.

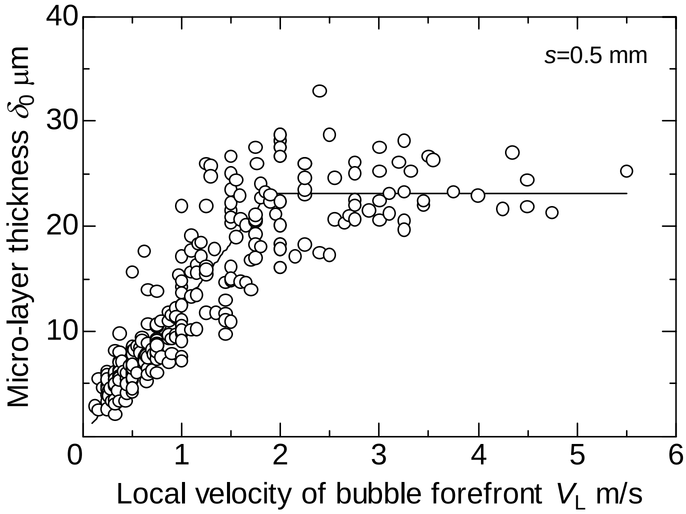


Figure 6 Micro-layer thickness and velocity of bubble forefront for s = 0.5 mm

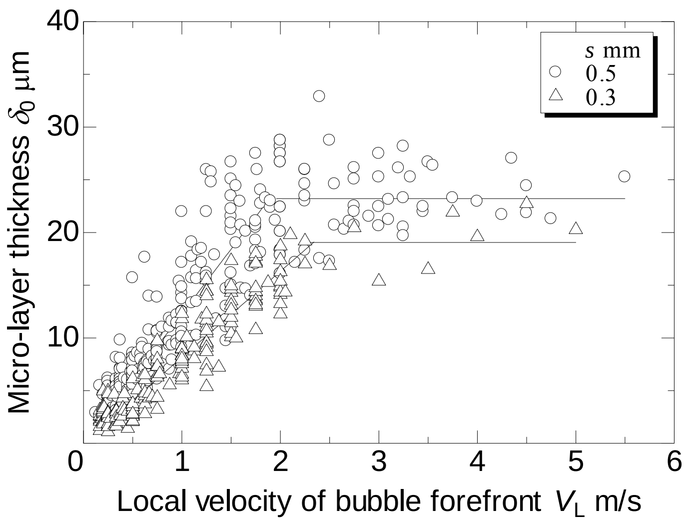


Figure 7 Micro-layer thickness and velocity of bubble forefront for s = 0.3 and 0.5 mm

3.4. Effect of other factors

Heat flux and the distance from the bubble formation site were examined as factors affecting the initial micro-layer thickness. The effects of heat flux on the initial micro-layer thickness for the three gap sizes of 0.5 and 0.3 mm are shown in Figs. (8(a)) and (b), respectively. Measurements were made at four different heat flux levels for each gap size. It is seen from all the figures that the different heat flux levels had a negligible effect on the initial micro-layer thickness, indicating that the formation of the micro-layer is determined by the dynamic behavior of the liquid-vapor interface.

The effects of the distance from the bubble formation site on the initial micro-layer thickness for each gap size are shown in Figs. (9(a)) and (b) for six different bubble forefront velocities as the parameter. The figures also show dotted lines drawn with the least squares method in fitting the data for each condition. It is observed that the initial micro-layer thickness was weakly dependent on the distance from the incipient site. Therefore, it is concluded that the main factors determining the initial micro-layer thickness are the gap size and the rate of bubble growth.

A comparison between Eq. (2) used by Cooper and Lloyd, as a representative example of an investigation of pool boiling, and the present results for the micro-layer thickness is shown in Fig. (10).

$$\delta_0 = 0.8\sqrt{\nu t_g} = 0.8\sqrt{\nu \frac{D}{V_M}} \tag{2}$$

where t_g, ν and V_M are the time until a bubble reaches the position at a distance of D from the incipient site, the

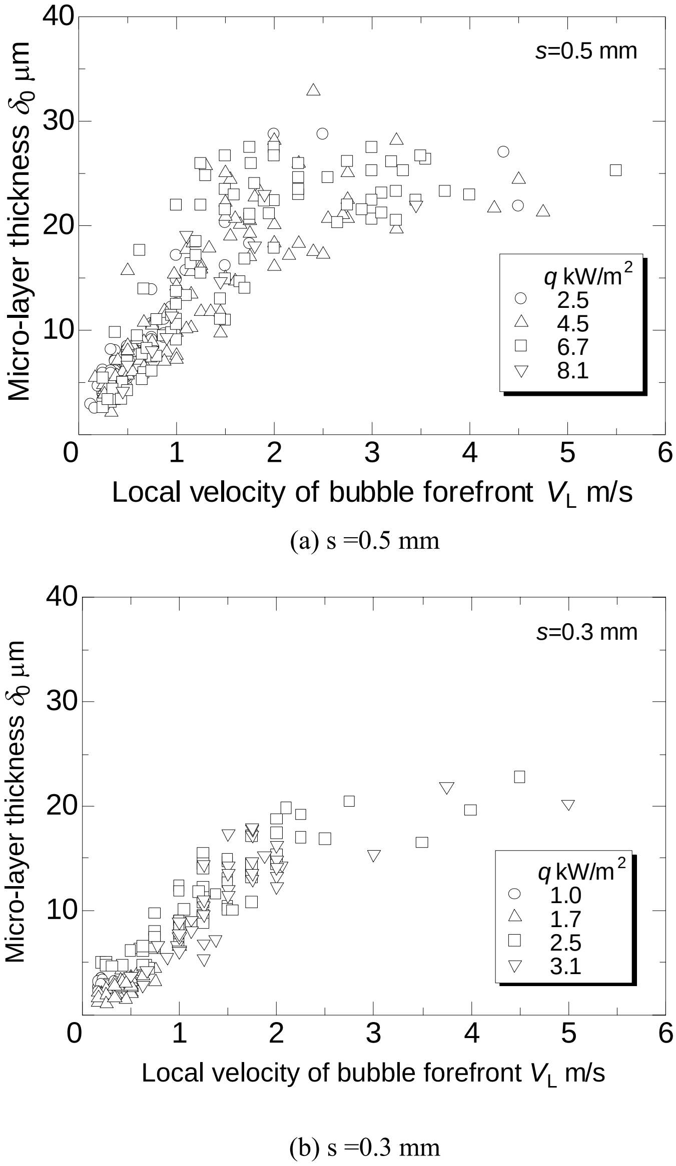
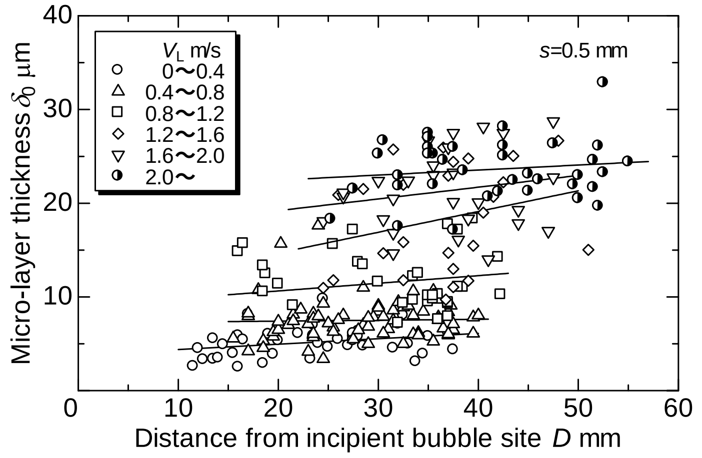
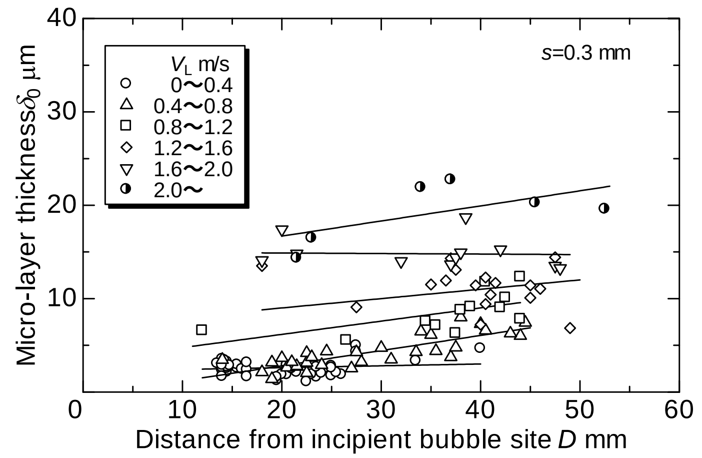


Figure 8 Effect of heat flux on micro-layer thickness



(a) s =0.5 mm



(b) s =0.3 mm

Figure 9 Micro-layer thickness and distance from incipient site of bubble

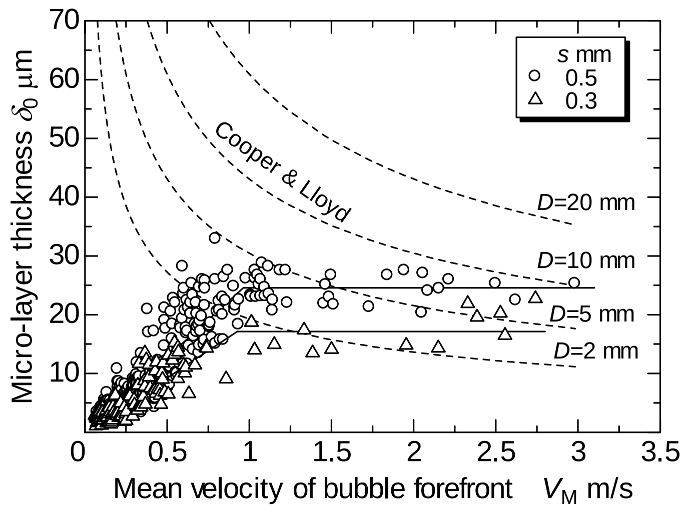


Figure 10 Comparison between Cooper & Lloyd (1969) and present results on micro-layer thickness

dynamic viscosity and mean velocity in relation to *D*, respectively. Although, in the range of *D* between 2 and 10 mm and V_M between 1 and 3 m/s, the initial micro-layer thickness shows similar values, the opposite tendencies against the bubble velocity were seen. Further investigation is required to clarify the difference in trend of bubble growth between the systems of micro-channel and pool boiling.

4. Conclusions

The thickness of the micro-layer that forms between the heating surface and bubbles was measured with the laser extinction method to clarify the heat-transfer characteristics of boiling in a micro-channel vaporizer. The following results were obtained for micro-channel gap sizes of 0.5 and 0.3 mm.

(1) The rate of bubble growth determines the initial micro-layer thickness.

(2) For two gap sizes, the variation of the micro-layer thickness relative to the rate of bubble growth was divided into two regions from the small velocity side a region where the thickness increases linearly with increasing velocity and a region where the thickness is almost constant. The latter region appears at a bubble forefront velocity of 2 m/s.

(3) The initial micro-layer thickness tended to decrease with decreasing gap size of the micro-channel. The initial micro-layer thickness was about 1~2 μm in the linear increase region. In the constant thickness region, the values were 18~24 μm for a micro-channel gap size in a range of 0.5~0.3 mm.

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