マイクロ管内スラグ流強制対流沸騰における薄膜厚さ
Liquid Film Thickness in Micro Tube Slug Flow with Phase Change

伝学　*韓　栄培　（東大院）　伝正　鹿園　直毅　（東大工）

Youngbae HAN and Naoki SHIKAZONO
Dept. of Mech. Eng., The Univ. of Tokyo, 3-1, Hongo 7, Bunkyo-ku, Tokyo 113-8656

Liquid film evaporation is one of the main heat transfer mechanisms in micro channels and liquid film thickness is a very important parameter to determine heat transfer coefficient. In the present study, liquid film thickness is measured under flow boiling condition and the relationship between liquid film thickness and heat transfer coefficient is investigated. Pyrex glass tube with inner diameter of D = 0.5 mm is used as a test tube. Laser focus displacement meter is used to measure the liquid film thickness. Under flow boiling condition, liquid film profile 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 the measured liquid film thickness show good accordance with heat transfer coefficients obtained directly from wall temperature measurements.

Key Words: Flow boiling, micro tube, liquid film, evaporation

1. Introduction

Flow boiling in micro channels is an attractive method to dissipate high heat flux from electric chips. Under flow boiling condition, the bubble velocity is not constant but accelerated due to phase change. It is necessary to consider how flow boiling affects the 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 measured under flow boiling condition and the relationship between liquid film thickness and heat transfer coefficient is investigated.

2. Experimental Setup and Method

Figure 1 shows the schematic diagram of the experimental setup. In Fig. 1, water 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. Figure 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 the 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℃ error. The velocity of the vapor bubble is measured from the images captured by the high-speed camera (Photron SA1.1). 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 [1-2]. In the present experiments, liquid film thickness at the tube side is measured. Output signal was sent to PC through GPIB interface and recorded with LabVIEW.

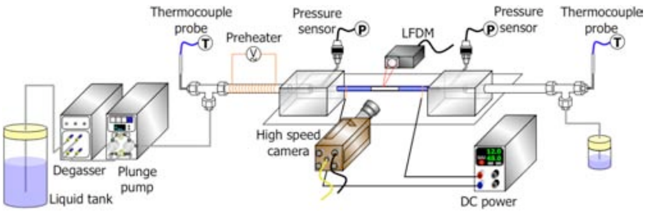

Fig. 1 Schematic diagram of the experimental setup.

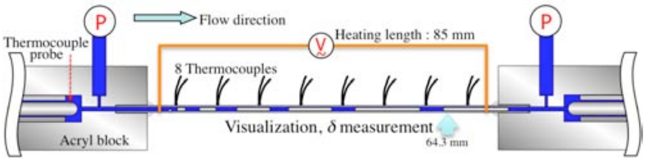

Fig. 2 Schematic diagram of the test section

3. Results and Discussions

3.1 Periodic pattern of liquid film thickness

Figure 3 shows time variation of liquid film thickness with different heat fluxes at z = 64.3 mm, for G = 169 kg/m^{2}s. Liquid film thickness shows periodic pattern. The frequencies of periodic patterns increase as heat flux increases. After liquid film is formed on the wall, liquid film thickness quickly decreases with large fluctuation due to strong evaporation. However, as liquid film gets thinner, fluctuation becomes smaller and liquid film becomes very stable. As heat flux increases above q'' = 187 kW/m^2, flow regime changes from slug flow to annular flow and liquid film becomes more unstable. Even for such cases, time variation of liquid film thickness still shows weak periodic patterns. As heat flux increases above q'' = 261 kW/m^2, dry out region appears.

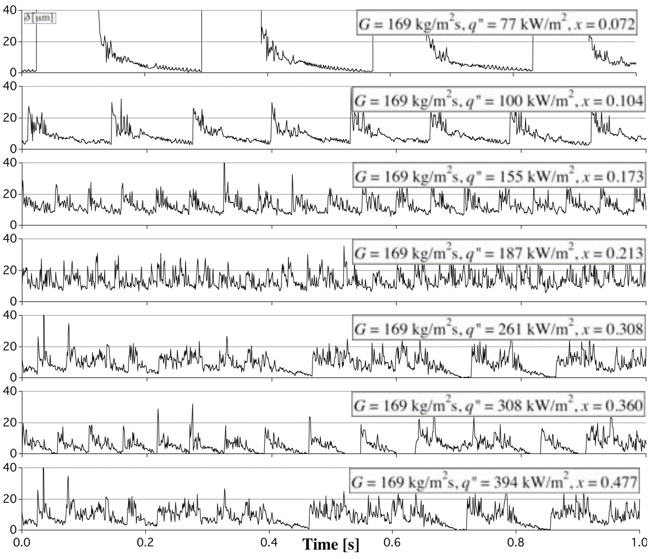

Fig. 3 Time variation of liquid film thickness with different heat fluxes at z = 64.3 mm for G = 169 kg/m^{2}s.

3.2 Heat transfer coefficient

Local heat transfer coefficient can be obtained with the measured outer wall temperatures. Figure 4 shows local heat transfer coefficient versus quality at G = 169 kg/m^{2}s. Obtained heat transfer coefficients show typical trend of flow boiling heat transfer in micro tubes reported in the review paper [3]. At quality around x = 0.1, heat transfer coefficient takes a maximum value. As quality increases, heat transfer coefficient decreases.

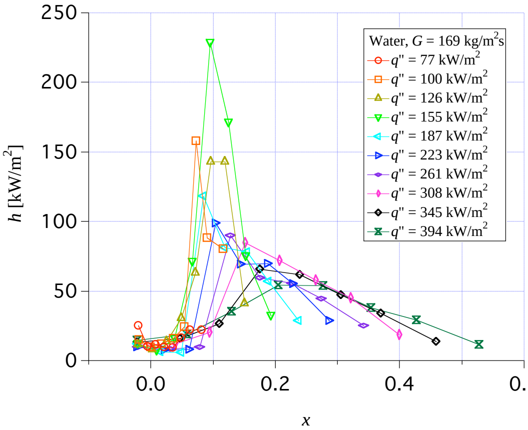

Fig. 4 Local heat transfer coefficient against quality for water and G = 169 kg/m^{2}s.

Time averaged wall temperatures and heat transfer coefficient can be estimated from the measured liquid film thickness. Figure 5 shows the schematic diagram for one dimensional transient heat conduction in the test tube. Local interface temperature is set equal to the saturated temperature which is calculated from lineal interpolation of saturated pressure in the two-phase region. If linear temperature gradient is assumed inside the liquid film, instantaneous heat transfer coefficient h is determined as h = k_L/δ. Figure 6 shows simulated wall temperatures for G = 169 kg/m^{2}s and q'' = 100 kW/m^2. According to the variation of instantaneous heat transfer coefficient, inner and outer wall temperatures also show periodic variation. For the unstable cases, liquid film thicknesses for the period of 2 seconds are used for the simulation. Averaged heat transfer coefficient is obtained as follows:

$$h_{\text{average}} = q''/\left(T_{\text{wall\_in\_average}} - T_{\text{sat}}\right), \qquad (1)$$

where $T_{\text{wall\_in\_average}}$ is the averaged inner wall temperature during one period. Figure 7 shows comparison between the heat transfer coefficients obtained directly from wall temperature measurements and those calcualted from measured liquid film thickness. Liquid film thickness is measured at the position in between the two thermocouple positions. Averaged wall temperature of two positions are used for open symbols. At small quality, heat transfer coefficients estimated from measured liquid film thickness are in good accordance with those obtained directly from wall temperature measurement. This might be attributed to the stable flow at small heat flux. However, as quality increases, flow becomes unstable and estimated heat transfer coefficients from liquid film thickness deviates from those obtained from the wall temperatures. As mass flow rate increases, deviation becomes larger. This might be due to the large pressure fluctuation which affects saturated temperature at the interface.

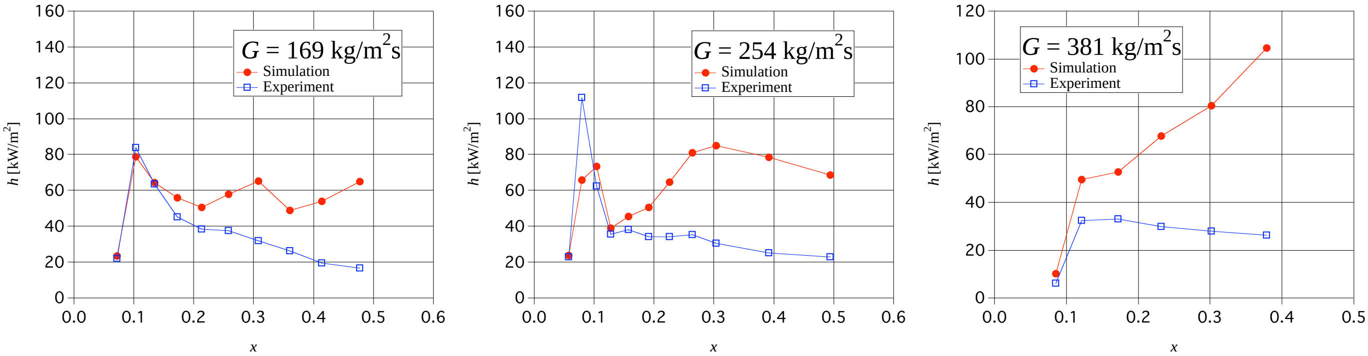

Fig. 7 Comparison of time averaged heat transfer coefficients calculated from measured liquid film thickness and those obtained directly from wall temperature measurements.

Fig. 5 Schematic diagram for 1D transient heat conduction.

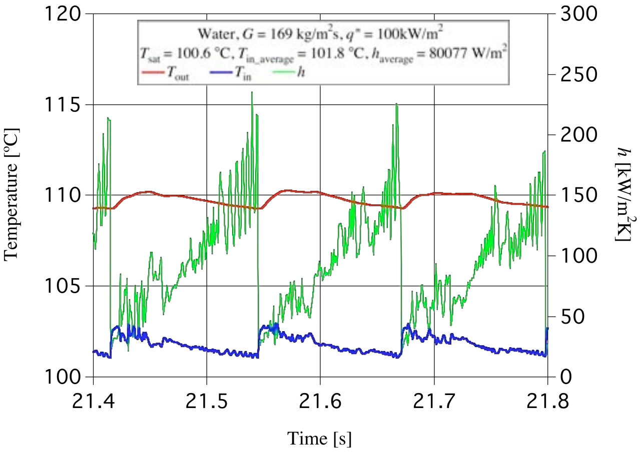

Fig. 6 Time variation of inner wall and outer wall temperatures simulated from the measured liquid film thickness.

4. Conclusion

In the present study, liquid film thicknesses are measured under flow boiling condition. The relationship between liquid film thickness and heat transfer coefficient is also investigated. Liquid film profile shows periodic patterns and fluctuates due to high vapor velocity. Frequency of periodic pattern increases with heat flux. As heat flux further increases, flow becomes unstable and flow regime is changed to annular flow. At small quality, averaged heat transfer coefficients calculated from measured liquid film thickness show good accordance with heat transfer coefficients obtained directly from wall temperature measurements. However, they deviated at higher heat fluxes. Large pressure fluctuation which affects saturated temperature might be one of the causes of this deviation.

Acknowledgement

We would like to thank Prof. Kasagi, Prof. Suzuki and Dr. Hasegawa for the fruitful discussions and suggestions. This work is supported through Grant in Aid for Scientific Research (No. 20560179) by MEXT, Japan and GCOE Mechanical System Innovation program by MEXT, Japan.

References

(1) Han, Y. and Shikazono N., Int. J. Heat Fluid Flow. 35(2009), 896. (2) Han, Y., Shikazono N., Int. J. Multiphase Flow, 30(2009), 842. (3) Thome, J. R., Heat Transfer Engineering, 27(2006), 4.