

MEASUREMENT OF FILM DYNAMICS IN A BOILING LIQUID FILM

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Abstract

Motivated by understanding the micro-hydrodynamics of boiling heat transfer and its critical heat flux (CHF), the present study investigates the boiling phenomenon in a liquid film whose dynamic thickness is recorded by a confocal optical sensor till micrometres, while the bubble dynamics of the boiling in the film is visualized by high-speed photography (10000 fps). This paper is focused on statistical analysis of the thickness signals from the scoping tests from low heat flux till high heat flux (CHF). The dynamic thickness of the liquid film appears peak values, corresponding to the liquid film movements due to nucleation of bubble(s) and its growth and collapse. The maximum thickness decreases rapidly with increasing heat flux, but after 0.625 WM/m^2 it keeps almost constant. It reduces again after 1.09 WM/m^2 and finally reaches $105 \text{ }\mu\text{m}$ prior to the CHF which occurs at 1.563 WM/m^2 for the nano heater made of titanium.

Keywords: boiling, liquid film dynamics, film thickness measurement

1. Introduction

Boiling heat transfer is a preferred method for thermal management in nuclear power plants, such as heat removal in the core of a boiling water reactor (BWR) during normal operation and coolability of corium during a severe accident of a light water reactor (LWR), due to its high efficiency in the nucleate boiling regime. Yet, the capacity of boiling heat transfer limited by its critical heat flux (CHF), above which the surface of the heater (e.g., fuel rod) dries out and temperature rises rapidly, leading to destruction (so-called “burnout”) of the heater. Thus, the critical heat flux of boiling heat transfer is of paramount importance to the efficiency and safety of light water reactors (LWR). One question fascinating researchers’ minds for decades is why, in the presence of plentiful liquid around, the surface dries out.

Motivated by understanding of the physical mechanism(s) of the burnout and quantification of the critical heat flux, great research efforts have been made experimentally and theoretically, though the physical mechanism(s) determining the CHF is still unclear. Based on the hypothesis of physical theory, the primary models for prediction of the CHF can be divided into two groups: one is far field models represented by the Zuber’s model [1] based on hydrodynamic instability theory, which only considers the stability of vapour escape flow while ignores the near-wall fluid behaviour; the other is near-wall models based on macrolayer dryout theory, first proposed by Haramura and Katto [2]. The latter has the possibility to take into account the effects of the heater properties (surface wettability, surface conditions, thermal properties of the substrate, etc.) on the CHF [3-4]. Sadasivan et al. [5] critically analyzed the possible mechanisms of macrolayer formation through a comprehensive review on the experimental investigations on the macrolayer whose thickness is estimated to vary from $11 \text{ }\mu\text{m}$ to $460 \text{ }\mu\text{m}$ in the vicinity of the CHF. Further

quantification of the macrolayer thickness and its dynamics calls for better measurements of the flow patterns close to the heater surface. This is a challenge in the traditional experimental setups (e.g. pool boiling with heater block), due to the chaotic nature of boiling process which impedes direct measurement and close observation on the macrolayer, especially under high heat fluxes.

Inspired by the “scales-separation phenomenon” [6-7] which says that the CHF of pool boiling is governed by micro-hydrodynamics of a near-wall liquid film while the bulk hydrodynamics is irrelevant to the CHF, the boiling experiment is performed on a thin film to facilitate the direct observation on the micro-hydrodynamics of the film without losing the key physics of boiling. The follow-up work [8] further addresses the micro-hydrodynamics of a boiling liquid film based on high-speed photography synchronized with the high-speed IR imaging.

The present study applies the same experimental method, i.e., to perform investigation on boiling in a liquid film, by adding a confocal optical sensor which can record the instantaneous thickness of the liquid film under various thermal-hydraulic conditions [9-11]. The focus is placed on the dynamics of the liquid film under intensive boiling.

2. Experimental method

2.1 Test facility

The test facility, as shown in Figure 1, is designed and developed to achieve high stability and high accuracy for liquid film thickness measurement at micro meter level. It consists of an optical table, liquid supply and temperature control system, power supply and heating system, high-speed visual system, confocal optical sensor system, one-dimensional linear manipulator, three-dimensional micro-manipulator and its control system, lighting system, and a test section for boiling on a titanium film heater coated on a piece of glass sheet. The optical table provides the required vibration isolation for both the test section and the instrumentation mounted on the platform. Water is pre-heated in a stainless steel water tank by two band heaters to a desired temperature which is maintained with a temperature controller; the hot water is then supplied to the test section through a micro pump capable of accurate flow control.

2.2 Test section and instrumentation

As shown in Figure 2, the test section is composed of a film heater in an open channel and its supporting structure. The fabrication of the film heater is as follows: on a piece of 1-mm-thick quartz glass (40 mm × 30 mm), first sputtering a 150-nm-thick titanium film to an area of 40 mm × 8 mm, then sputtering two 300-nm-thick gold films (16 mm × 8 mm) over the ends of the titanium film, 8 mm apart. As a result, an 8 mm × 8 mm area of titanium film is formed in the middle of the glass sheet, which is used as the heating zone for boiling. Figure 3 shows the SEM image of the surface of a fresh titanium film heater, which is quite smooth and uniform. Under the heating zone a micro T-type thermocouple is mounted to the downward surface of the quartz glass to measure the wall temperature. A Teflon structure is manufactured to hold the film heater and its electrodes, and then is fixed onto the optical table. The supporting structure can be regulated to reach a horizontal orientation of the film heater surface.

The gold films of the heater are tightly connected to two gold blocks (30 mm × 6 mm × 3 mm) serving as the electrodes to a DC power supply as well as the boundaries of water film formation. The open channel bounding the liquid film between the electrodes is 16 mm wide and 30 mm long, with the heating zone situated at its center. Saturated water is supplied to the channel from one side whose end is sealed by a 3-mm-tall glass dam to direct water flow in only one direction toward the other side where a height-adjustable glass sheet is used to regulate the water layer thickness. When the height of the glass sheet is set to be 1 mm, an adiabatic liquid film above the heating zone in the channel will achieve a balance condition with a relatively flat surface, and its thickness depends on the flowrate of the water supply. To avoid the influence of the flowrate (simulating pool boiling), the flowrate will be kept as close to the evaporation rate of boiling as possible, while the liquid supply is sufficient to maintain the film integrity. The de-ionized water is preheated to desired temperature in the water tank, and delivered to the test section by the micro pump which has accurate step control with the resolution of 0.0142 ml/s. The tube connecting the pump to the test section is heated by coiled electrical-resistance wires so as to maintain water temperature near saturated at the outlet of the tube. The water tank and all tubes are thermally insulated.

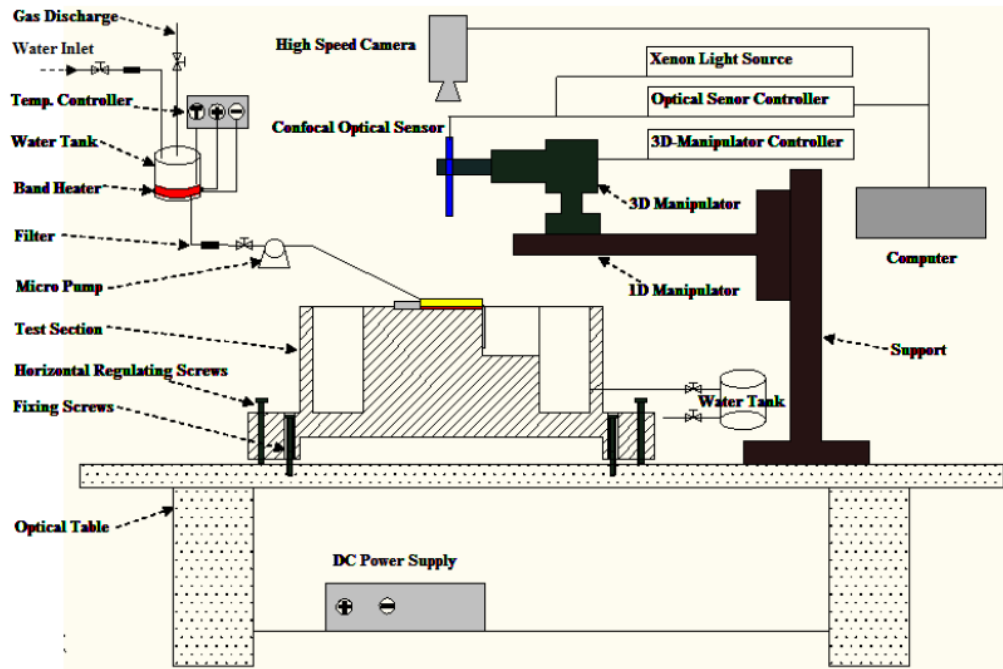


Figure 1 Schematic of a diagram.

The key feature of the present study is to measure the dynamic evolution of the liquid film under boiling condition, by using the confocal optical sensor system developed and qualified in our previous studies [9-11]. The confocal optical sensor is provided by the Micro-Epsilon Company in Germany ([micro-epsilon.com](http://www.micro-epsilon.com)). As illustrated in Figure 1, the sensor is incorporated with a controller and a special Xenon light source. The dedicated controller optoNCDT2431 is communicated with the computer through a software package. The sensor IFS2431-3 is chosen in the present work, which has maximum sampling rate of 30 kHz, measurement range of 3 mm, spatial resolution of 0.12 μm and maximum tilt angle of 22°. The principle and calibration of the confocal optical sensor system was documented in [9],

showing a good agreement with the measured results of a micro conductive probe, and a promising capability to capture liquid film dynamics. In the current experiment, the confocal optical sensor is fixed onto a 3D micro manipulator (with a μm resolution) to precisely position the sensor above the heating zone. In addition to the optical sensor, a high-speed digital camera with a recording rate up to 100,000 fps is used for the visualization of the two-phase flow dynamics from the top. Due to time and space limitations, the visual results will not be presented here in this paper.

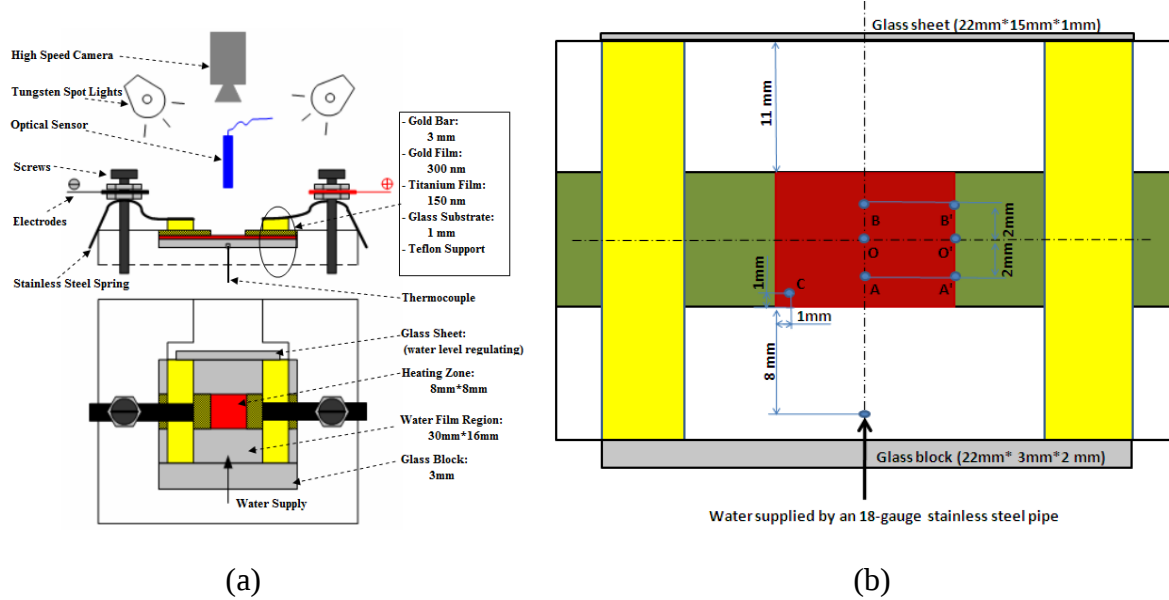


Figure 2 Test section: a) assembly of test section and arrangement of instrumentation; b) thickness measurement positions.

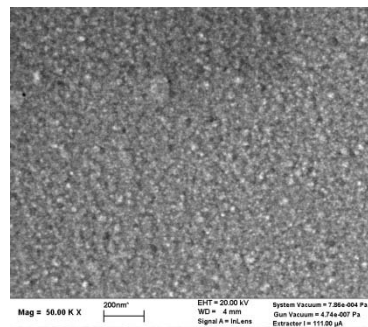


Figure 3 SEM image of the titanium film.

2.3 Test procedure

To minimize the disturbance of water inflow, an 18-gauge stainless steel tube is used to deliver water so as to reduce the initial velocity of water arriving at the liquid film on the heater surface. Moreover, the outlet of the tube locates 8 mm away from the heating zone as shown in Figure 2b. Prior to water supply to the test section, the film heater surface is regulated to be horizontal by using the displacement mode of the confocal optical sensor [9]. For adiabatic tests, water at room

temperature (21 ± 1 °C) is supplied to the test section through the micro pump whose revolution speed indicates the flowrate accurately. When the flow becomes stable at a given flow rate, the confocal optical sensor is used to measure the liquid film thickness profiles along the directions of AA', OO' and BB' (as in Figure 2b), perpendicular to the channel. The line of OO' is at the center of the heating zone, while the lines of AA' and BB' are situated 2 mm away from the centreline at two sides, respectively.

For boiling tests, de-ionized water is heated by the band heaters to saturated temperature more than half an hour, and then opens the gas discharge valve for degassing purpose. Water is then pumped to the test section. After the channel is flooded, turn on the DC power supply, and gradually regulate the water supply flow rate as well as the heating power to desired values. The water supply is controlled by the micro-pump. The flow rates are selected in such a way that they are comparable to evaporating rates at boiling condition while sustaining the liquid film surface to be flat and stable on the heating zone. This way the extra water flowing out the channel is minimized while a stable water film is formed on the heater surface. In other words, the shear force due to film flow should be negligible.

Following is the establishment of steady-state boiling in the liquid film, the high-speed camera and the confocal optical sensor are brought into operation subsequently. At a given heat flux, the high-speed camera is used to observe and record the boiling phenomena at first, and then the confocal optical sensor is moved into the position at the point C locating at the corner of heating zone, as shown as in Figure 2b to measure the liquid film thickness. The choice of the point C instead of the center of the heating zone for measurement position is to avoid the influence of the splashing droplets on the confocal optical sensor at high heat flux.

3. Results and discussions

3.1 Thickness profile of adiabatic liquid film

In order to choose a suitable liquid flowrate to form a uniform and stable thin liquid film above the heating zone, tests with adiabatic liquid film flow is performed as mentioned in section 2.3. Figure 4 shows the time-averaged liquid film thickness profiles along the OO' direction under various water supply rates from 71 mm³/s to 184.6 mm³/s, where the coordinate d is the distance from the centerline of the flow channel. It can be seen that the liquid film appears concave shape over the heating zone, and with the increase of flowrate the curvature decreases but the thickness increases. When approaching the side walls of the channel, the curvature of the liquid film is more pronounced due to capillary force. At the flowrate of 71 mm³/s (the line #1 shown in Figure 4), the minimum liquid film thickness is around 285 μm, while it is 1147 μm at the flowrate of 99.4 mm³/s (the line #2 shown in Figure 4). The maximum thickness difference over the heating zone is less than 150 μm. When further increasing the flowrate, the liquid film thickness slightly increases while the liquid surface profile keeps similar with that of the line #2. Apparently, the variations of the liquid film thickness are not proportional to the changes in flowrate.

The profile of the liquid film thickness along the flow direction is quite uniform, as reflected in Figure 5a where the three lines are almost identical with the maximum deviation of 80 μm (the red bars). Figure 5b shows the dynamic evolution of the liquid film thicknesses at 4 points along

the OO' direction under the flowrate of $99.4 \text{ mm}^3/\text{s}$. The waving characteristics of the liquid film surfaces at different locations above the heating zone are quite similar and the amplitudes of the waves are among $20 \sim 40 \text{ }\mu\text{m}$. Since a stable and relatively uniform liquid film forms above the heating zone at the flowrate of $99.4 \text{ mm}^3/\text{s}$, thereafter it is chosen in boiling tests performed in the present work.

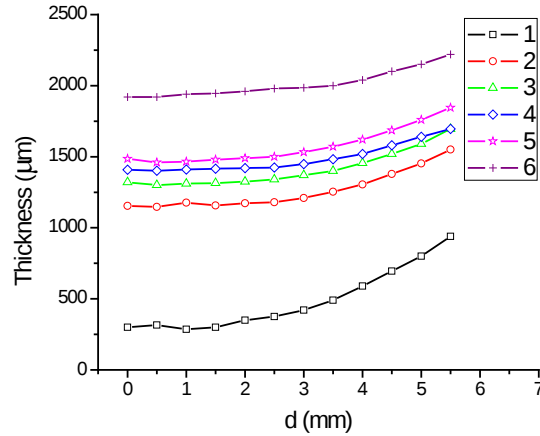


Figure 4 Averaged liquid film thickness profile along the OO' direction vs. water flow rate: 1 – $71.0 \text{ mm}^3/\text{s}$; 2 – $99.4 \text{ mm}^3/\text{s}$; 3 – $113.6 \text{ mm}^3/\text{s}$; 4 – $127.8 \text{ mm}^3/\text{s}$; 5 – $156.2 \text{ mm}^3/\text{s}$; 6 – $184.6 \text{ mm}^3/\text{s}$.

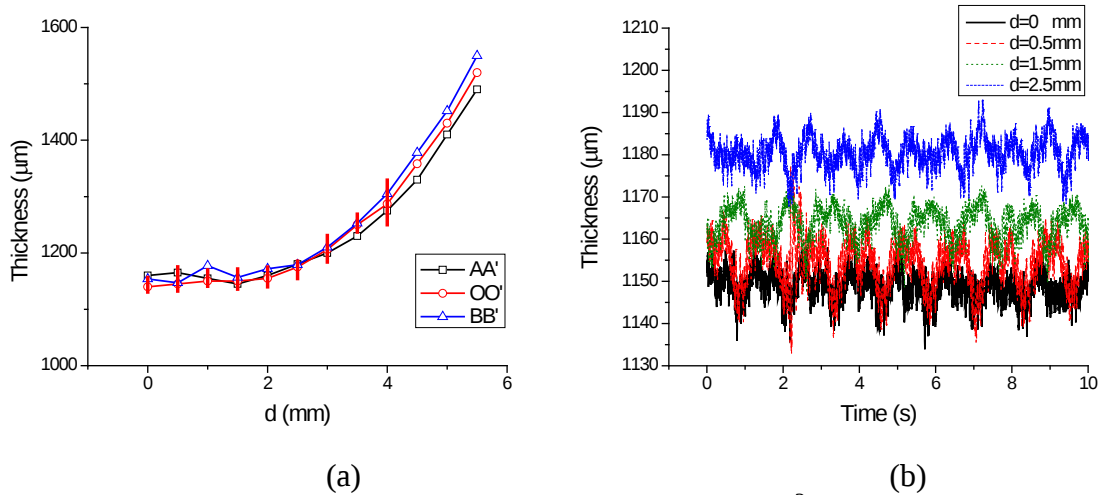


Figure 5 Liquid film thickness at liquid flowrate of $99.4 \text{ mm}^3/\text{s}$ (sampling rate = 1 kHz): a) averaged liquid film thickness profiles in the directions of AA', OO' and BB'; a) instantaneous liquid film thickness at 4 points in the OO' direction.

3.2 Dynamic thickness of liquid film under boiling condition

After a stable liquid film is formed on the heater surface, switch on the heater and increase the heat flux step by step. Special care is taken when boiling is initiated, to avoid early rupture of the film due to formation of a large bubble at low heat flux [11]. At each level heat flux, the dynamic thickness of the liquid film is measured at the position C (as shown in Figure 2b) by the confocal optical sensor. Figure 6a shows the evolution of the measured (local) thickness within a period of 0.5 seconds at heat flux of 0.156 WM/m^2 , while Figure 6b is a “zoom-in” view within a shorter period (~ 0.03 seconds) where more details of the thickness evolution can be scrutinized .

Compared with the non-heating case, one can see that the thickness of the liquid film is varying dramatically under the boiling condition. This is mainly because the nucleation of bubble(s), and its growth and collapse force the liquid film to move forth and back accordingly. Thus, the characteristics of thickness dynamics have an inherent connection with the boiling bubble(s) in the vicinity. In the case of Figure 6a, there roughly appears three dominant levels of the liquid film thickness: i) the high level between 1000~2000 μm , close to bulk liquid film thickness; ii) the medium level between 0~500 μm , well separated from the high level; iii) the low level with null values, representing 2 possible situations: a) instantaneous (local) dryout; b) invalid measured signal due to curvature of liquid surface beyond the sensor measuring range or light being scattered and blocked by splashing droplets.

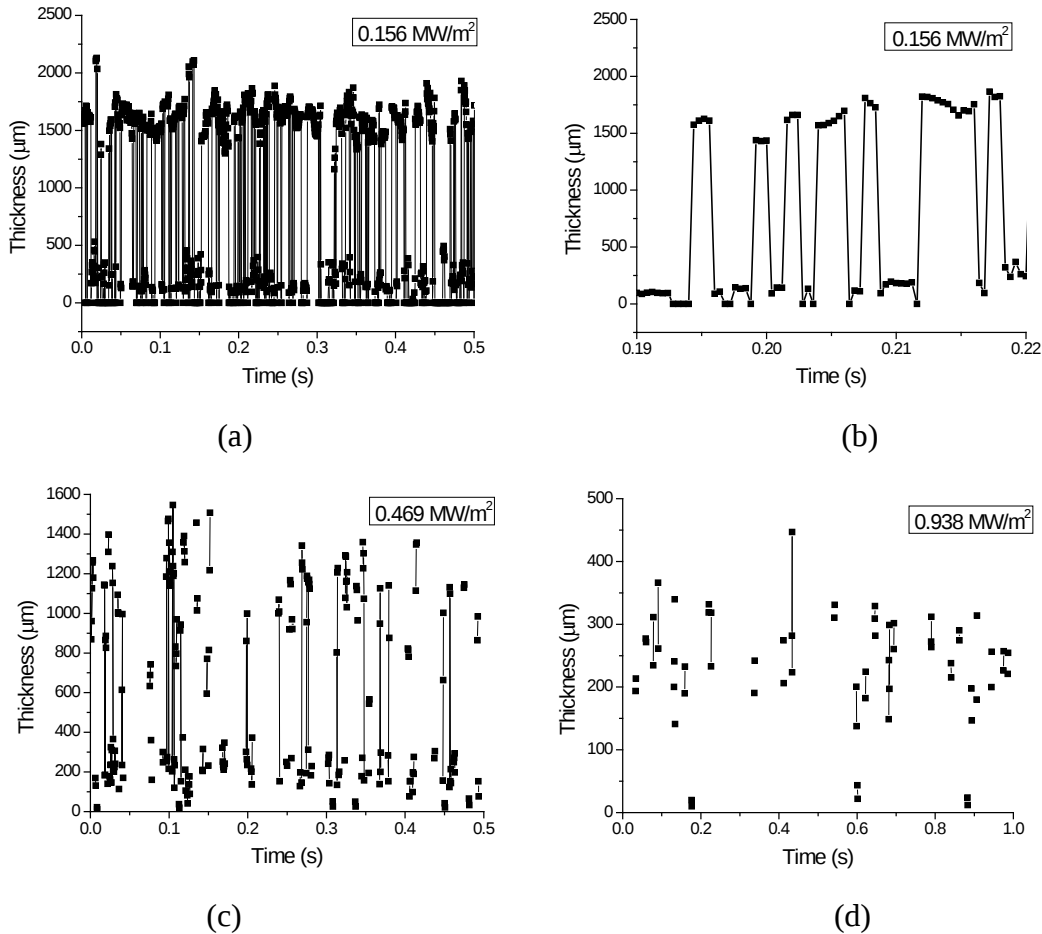


Figure 6 Instantaneous liquid film thickness at various heat flux (sampling rate = 2500Hz).

The number of the effective signals (non-zero thickness) recorded by the confocal optical sensor is getting less when the heat flux is increasing, as illustrated in Figures 6c and 6d where only the non-zero values are drawn. This is mainly because of increased chaotic movements (splashing of droplets and waving of liquid film surface) over the heating zone. Interestingly, when the heat flux increases to a certain level, such as 0.938 WM/m^2 as shown in Figure 6d, the high level liquid thickness 1000~2000 μm disappears, while a new separation with the thickness threshold of 100 μm appears.

To characterize the dynamic liquid film, the occurrence of its different thickness (10 μm apart) is counted within 1 minute. Since the sampling frequency is fixed at 2500 Hz, from the occurrence statistics as shown in Figure 7 one can find the dominant thickness at the measurement point. With increasing heat flux, the occurrence profile appears two peaks at the beginning, and then three peaks at heat flux of 0.469 WM/m^2 , and finally two peaks again after heat flux 0.625 WM/m^2 .

Figure 8 shows the maximum liquid film thickness at the peaks versus heat flux. It can be seen that maximum thickness decreases rapidly with increasing heat flux, but after heat flux of 0.625 WM/m^2 it keeps almost constant with small deviation. It reduces again after 1.09 WM/m^2 and finally reaches $105 \mu\text{m}$ at heat flux of 1.4 WM/m^2 and the CHF occurs at 1.563 WM/m^2 .

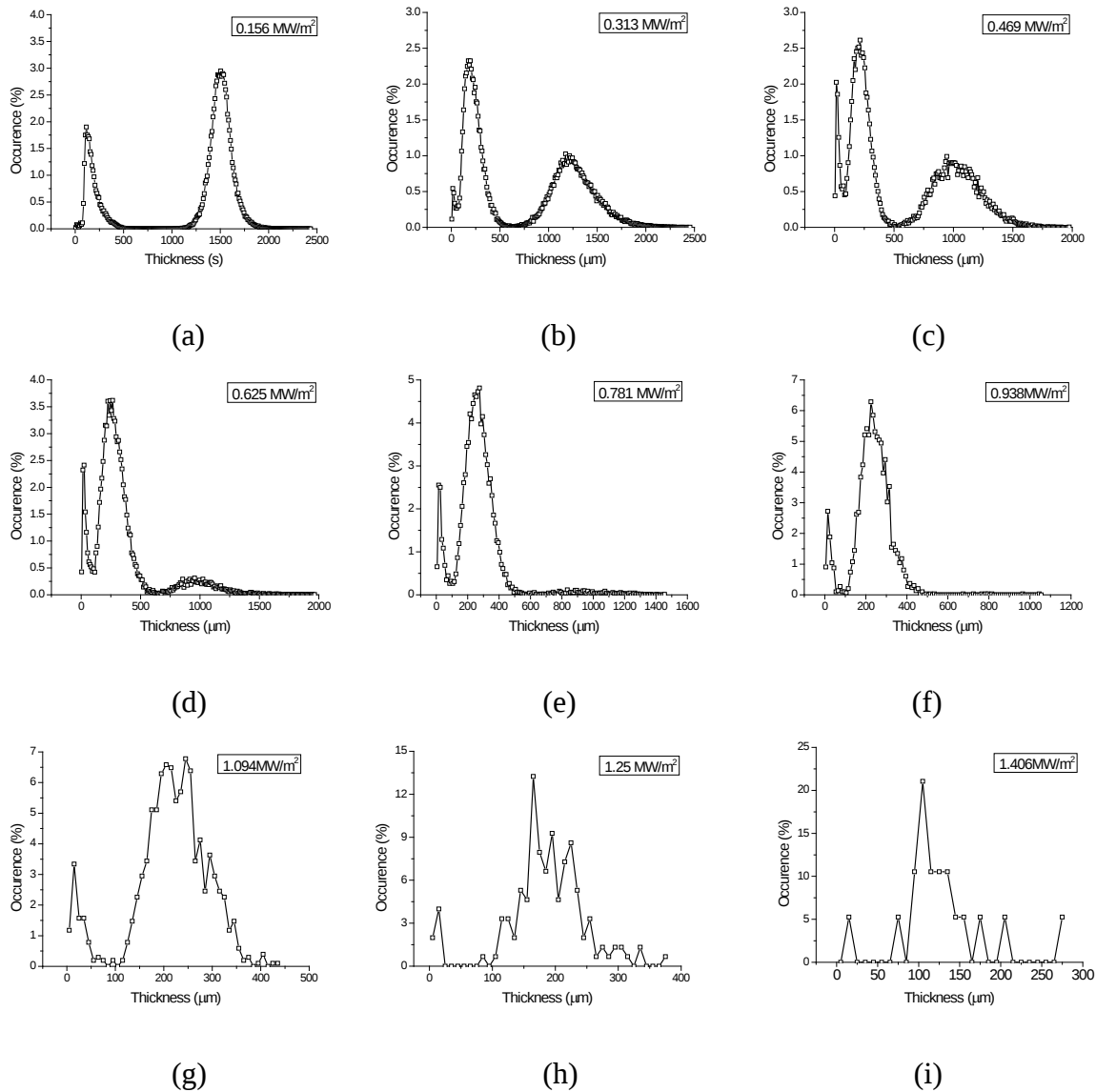


Figure 7 Occurrence of the liquid film thickness during 1 minute.

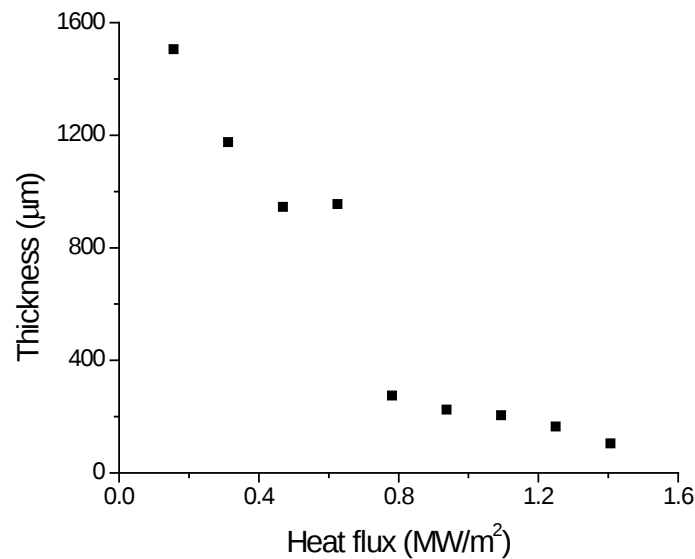


Figure 8 The maximum thickness of the liquid film vs. heat flux.

4. Conclusions

Toward understanding of the micro-hydrodynamics of boiling at high heat flux, an experimental study is carried out to investigate the boiling phenomenon in a liquid film on a titanium nano heater, with the intention of direct measurement and visualization on bubble and film dynamics. The liquid film dynamics is measured by a confocal optical sensor.

This paper is focused on statistical analysis of the thickness signals from the scoping tests from low heat flux till high heat flux (CHF). The dynamic thickness of the liquid film appears peak values, corresponding to the liquid film movements due to nucleation of bubble(s) and its growth and collapse. The maximum thickness of the liquid film decreases rapidly with increasing heat flux, but after 0.625 WM/m^2 it keeps almost constant. It reduces again after 1.09 WM/m^2 and finally reaches 105 μm before the CHF which is 1.563 WM/m^2 at the water supply rate of $99.4 \text{ mm}^3/\text{s}$.

It should be noted that the tests presented here are of scoping nature, with the primary objective to demonstrate the measurement systems, especially the confocal optical sensor for application to boiling condition. More tests are needed to increase the readable signals for the cases of high heat flux (intensive boiling) by extra measures, such as removal of the splashing droplets. More stringently, a complete picture of liquid film and bubble dynamics calls for the synchronization of the thickness signal with high-speed photography.

References

- [1] N. Zuber, "Hydrodynamic aspects of boiling heat transfer", Report AECU-4439, U.S. Atomic Energy Commission, 1959.
- [2] Y. Haramura and Y. Katto, "A new hydrodynamic model of critical heat flux applicable widely to both pool and forced convection boiling on submerged bodies in saturated liquids", Int. J. Heat Mass Transfer, Vol. 26, 1983, pp. 389-399.

- [3] C. Pan and T. L. Lin, "A model for surface wettability effect on transition boiling heat transfer", Proc. 9th Int. Heat Transfer Conf., 1990, pp. 147-152.
- [4] C. Pan and T. L. Lin, "Predictions of parametric effect on transition boiling under pool boiling conditions", Int. J. Heat Mass Transfer, Vol.34, 1991, pp. 1355-1370.
- [5] P. Sadasivan, P.R. Chappidi, C. Unal and R.A. Nelson, "Possible mechanisms of macrolayer formation", International Communications in Heat and Mass Transfer, Vol. 19 (6), 1992, pp. 801-815.
- [6] T. G. Theofanous, J. P. Tu, A. T. Dinh and T. N. Dinh, "The boiling crisis phenomenon: Part I: nucleation and nucleate boiling heat transfer", Experimental Thermal and Fluid Science, Vol.26 (6-7), 2002, pp.775-792.
- [7] T.G. Theofanous , T.N. Dinh, J.P. Tu and A.T. Dinh, "The boiling crisis phenomenon, Part II: dryout dynamics and burnout", Experimental Thermal and Fluid Science, Vol. 26 (6-7), 2002, pp.793-810.
- [8] T.N. Dinh, J.P. Tu, "The micro-hydrodynamics that govern critical heat flux in pool boiling", International Conference on Multiphase Flow, ICMF 2007, Leipzig, Germany.
- [9] S. Gong, W. Ma, T.N. Dinh, "Diagnostic techniques for dynamics of a thin liquid film under forced flow and evaporating conditions", Microfluid and Nanofluid, Vol. 9, 2010, pp. 1077-1089.
- [10] S. Gong, W. Ma and T.N. Dinh, "An experimental study of rupture dynamics of evaporating liquid films on different heater surfaces", Int. J. Heat and Mass Transfer (2010), doi:10.1016/j.ijheatmasstransfer.2010. 11.036.
- [11] S. Gong, W. Ma, "An experimental study on micro hydrodynamics in a boiling liquid film", the seventh International Conference on Multiphase Flow, ICMF 2010, Tampa, FL USA, May 30 -June 4, 2010.