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An investigation on dynamic thickness of a boiling liquid film

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ABSTRACT

Motivated by understanding the micro-hydrodynamics of boiling heat transfer and the mechanism of critical heat flux (CHF) occurrence, the present study is to investigate the boiling phenomenon in a liquid film whose dynamic thickness is recorded by a confocal optical sensor with the measurement accuracy of micrometres, while the bubble dynamics of the boiling in the film is visualized by a high-speed photography. This paper is focused on a statistical analysis of the measured thickness signals for the boiling condition ranging from low heat flux to high heat flux (near or at CHF). The dynamic thickness of liquid film appears oscillating with peak values, resulting from the liquid film movements due to nucleation of bubble(s) and its growth and rupture. The statistical analysis in a certain period indicates there emerge three distinct liquid film thickness ranges: 0–50 μm, 50–500 μm and 500–2500 μm, seemingly corresponding to the microlayer, macrolayer and bulk layer. With increasing heat flux to a specific extent, the bulk layer disappears, and then the macrolayer gradually decreases to ~105 μm, beyond which the liquid film may lose its integrity and CHF occurs at 1.563 MW/m^2.

1. Introduction

Critical heat flux (CHF) as a limitation of boiling heat transfer is involved in the design of a lot of industrial applications, such as nuclear power plants, fossil power plants, aerospace field, electronics cooling, etc. [1–5]. The occurrence of CHF leads to a severe increase in wall temperature for heat-flux-controlled systems and a violent decrease of heat transfer for temperature-controlled systems. In other words, the CHF is a key parameter which affects the integrity, safety and economy of the corresponding components and systems. Thus, the fundamental research on high-heat-flux boiling and CHF becomes very important to develop prediction models and enhancement strategies of the CHF.

Motivated by understanding the physical mechanisms of CHF and quantifying its value, great research efforts have been performed both experimentally and theoretically. Based on the hypothesis of physical theory, the primary models for predicting CHF can be divided into two groups: one is 'far field' models [6–8] based on hydrodynamic instability theory, which only considers the stability of vapor escape flow while ignores the near-wall fluid behavior; the other is 'near-wall field' models based on the dryout theory of microlayer and macrolayer, first proposed by Haramura and Katto [9]. 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 [10,11]. Currently, it is well accepted that the physical mechanism of the CHF occurrence should be more related with the characteristics of boiling surface (nano or/and micro structured surface) and the micro-hydrodynamics of thin liquid layer (microlayer with the thickness of some micrometers and macrolayer with the thickness of hundreds micrometers) adjacent to the heated wall surface. Dong et al. [12] experimentally investigated the surface structure effects on the boiling and boiling crisis with various fabricated micro/nano-structures on silicon chips (e.g., micro-pillars, micro-cavities, nanowires, nano-cavities) and concluded that the effect of capillary wicking in nanostructures helps to improve the bubble departure frequency and prevent the formation of vapor film by delaying bubbles to merge which leads to the CHF enhancement. Based on Kandlikar's CHF model [13] which includes the contact angle effect and the surface orientation effect on CHF for smooth heater surface, Quan et al. [14] further developed a CHF model considering the effects of both capillary wicking force and the modification of critical wavelength due to the micro/nano structures. In addition, investigations on detection and quantification of the microlayer and macrolayer were executed. Due to the natural chaos of boiling process especially under high heat flux conditions, the measurements for microlayer thickness were performed under low heat flux so as to facilitate tracing a single bubble as the measurement object. Yabuki and Nakabeppu [15] used MEMS sensors to measure the local wall temperature and evaluate the initial microlayer thickness. Utaka et al. [16] measured the microlayer in mini/micro

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channels through non-contact laser extinction method. Kim and Buongiorno [17] applied a high-speed infrared thermometry to detect and quantify the microlayer structure under a single bubble. Gao et al. [18] used a laser interferometric method to measure the microlayer thickness.

Correspondingly, the experimental investigations on macrolayer had also been performed. Bhat [19] used an electrical resistance probe to detect vapor frequency at various height positions from the boiling surface for the pool boiling of water and take the height value with maximum vapor frequency as the macrolayer thickness. With the same technique, Rajvanshi et al. [20] obtained the macrolayer thickness for various liquids (water, methanol, ethanol and methyl ethyl ketone) while Ono and Sakashita [21–23] detected the macrolayer and evaluate its values under various heat fluxes, subcooling conditions and pressures. Similarly, Auracher and Marquardt [24] used a micro optical probe measured the void fraction at various distances from heated surface and deduced the macrolayer thickness. In a summary, the experimental methods for macrolayer thickness measurement were mainly relying on various probe techniques. Such techniques have the disadvantage that it is an invasive way which affects the measured object and leads to poor accuracy. In addition, it could not reflect the dynamic characteristics of macrolayer evolution. Sadasivan et al. [25] 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 μm to 460 μm 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.

Based on the BETA experiment which measured the flow pattern in pool boiling by a X-ray and the thermal pattern on a thin titanium film heater by an infrared camera, Theofanous et al. [26,27] illustrated the "scales-separation phenomenon" and subsequently proposed that the CHF of pool boiling is governed by micro-hydrodynamics of the near-wall liquid film while the bulk hydrodynamics is irrelevant to the CHF. As a result, the boiling experiment could be performed on a thin liquid film to facilitate the direct observation on the micro-hydrodynamics of the film without losing the key physics of boiling. The follow-up work [28] further addresses the micro-hydrodynamics of a boiling liquid film based on high-speed photography synchronized with the high-speed IR imaging.

In order to quantify the dynamic microlayer and macrolayer thickness, a noninvasive confocal optical technique had been developed in our previous work [29–31]. In addition, with the similar experimental strategy (boiling in a thin liquid film) as the BETA experiment, the characteristics of bubble dynamics and CHF at different liquid film thicknesses had been obtained [32]. Through the comparison of the boiling CHF in the thin liquid film with that in a pool, the "scales-separation" hypothesis was further proven. The present study applies the same experimental method, i.e., to perform boiling tests 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. 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 Fig. 1, was 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 Fig. 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. The static contact angle of water forming on the titanium film heater surface is measured to be 51°. 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. The liquid supply should be sufficient to maintain the film integrity, meanwhile, the flowrate also should be as smaller as possible to avoid the influence of the flowrate on simulating pool boiling. 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 14.2 mm^3/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.

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 [29,30]. The confocal optical sensor is provided by the Micro-Epsilon Company in Germany. As illustrated in Fig. 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