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An experimental study on the effect of liquid film thickness on bubble dynamics

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HIGHLIGHTS

► Measurement of bubble dynamics using confocal optical sensor, micro-conductive probe and high-speed photography.
► Quantification of liquid film integrity under isolated bubble regime of nucleate boiling.
► Identification of the dry condition at the bubble root using the void signal of the micro-conductive probe.

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ABSTRACT

Experiments were conducted to investigate the boiling phenomenon in various liquid layers on a silicon heater surface with an artificial cavity. Deionized water is employed as working liquid. The emphasis is placed on how the liquid layer thickness affects bubble behaviour and liquid layer integrity for nucleate boiling under the isolated bubble regime. The experimental results show that for boiling in a liquid layer of ~7.5 mm, the bubble dynamics reproduce the typical pool boiling characteristics with the averaged maximum diameter of 3.2 mm for the isolated bubbles growing on the cavity. As the water layer thickness decreases to the level comparable with the bubble departure diameter, the bubble is found to remain on the heater surface for an extended period, with a dry spot forming under the bubble but rewetted after the bubble rupture occurs. Further reducing the liquid layer thickness, an irreversible dry spot appears, suggesting a minimum rewettable thickness ranging from 1.2 mm to 1.9 mm corresponding to heat flux of 26 kW/m^2 to 52 kW/m^2. The void measured in the cavity confirms that it is dry inside the artificial cavity at high heat flux.

1. Introduction

Boiling is a common phenomenon encountered in our daily lives and many engineering applications due to its high heat transfer efficiency. So, a lot of boiling heat transfer enhancement technologies are investigated and developed, such as applications of nanoparticles [1,2], surfactants and polymeric additives [3,4], and various micro-structured surfaces [5,6]. Yet, the physical mechanisms of boiling are still not well understood due to the chaotic/random characteristics of bubble dynamics [7]. Although it has been agreed that the near-wall thin liquid layer behaviour and bubble dynamics are of paramount importance to boiling heat transfer, the study on near-wall bubble and liquid dynamics is not straightforward, due to difficulty in measurement which is further complicated by the chaotic nature of nucleation. In order to overcome this limitation, artificial cavities were introduced by some researchers [8–12] as fixed nucleation sites to produce bubbles under relatively low heat flux conditions so as to facilitate visualization of bubble dynamics and bubbles coalescence through a side-view of pool boiling.

In another attempt of characterizing macrolayer and dry spot dynamics on a heater surface, indium tin oxide (ITO) coated transparent heaters were developed and employed to enable visualization from the bottom of the heaters [13–17]. Ohta [13] performed both pool boiling and flow boiling tests under microgravity conditions. In pool boiling tests, the tiny bubbles beneath vapour clot were observed by a high-speed camera from bottom and the macrolayer thickness was measured by a thin film sensor. Chung and No [14] used R-113 as the liquid to do the boiling tests and simultaneously observed the dynamics of bubbles and dry spots. Similarly, Nishio et al. [15,16] observed the dry spot distribution and calculated the contact line-length density for subcooled and saturated ethanol boiling on a horizontal flat plate. In addition, Diao et al. [17] obtained the bubble departure diameter, nucleation site density for the boiling of binary mixtures Rll-R113 through observation with a high-speed camera from the bottom of a transparent heater.

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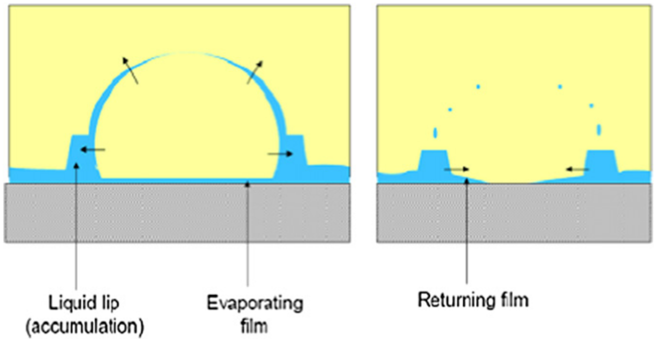

Fig. 1. A conceptual picture of bubble collapse in a liquid film on heater surface [20].

The BETA experiment performed by Theofanous et al. [18,19] provides an innovative design of a nano-film heater to enable direct observation of thermal patterns on the boiling surface from bottom of the heater. Based on the results of the BETA experiment, the "scale separation" hypothesis was proposed, which says that high heat flux pool boiling physics are governed by micro-hydrodynamics of a liquid layer sitting on the heater surface. Accordingly, the studies on boiling mechanisms can be carried out on a thin liquid layer (see Fig. 1), which facilitates the visualization and measurement of boiling from both the top and the bottom [20].

To examine the validity of the "scale separation" hypothesis to low heat flux boiling, the present study is carried out to investigate how the liquid film thickness affects the bubble dynamics at relatively low heat flux. An artificial cavity is created on a silicon wafer by MEMS fabrication, serving as a prescribed nucleation site. For comparison, tests are first performed with a thick water layer ($\sim$7.5 mm), and then placed on thin water layers (less than 2 mm). The bubble base regime (dry/wet) as well as the dry spot formation and behaviour are also verified by a micro-conductive probe and high-speed photography.

2. Experimental method

2.1. Test facility

As shown in Fig. 2, the test facility consists of an optical table, liquid supply and temperature control system, power supply and heating system, high-speed and stereo microscope visual system, confocal optical sensor system, micro-conductive probe system, 2 one-dimensional linear manipulators, a three-dimensional micro-manipulator and its control system, lighting system, and a test section for boiling on solid surfaces. The optical table provides the required vibration isolation and serves as an ideal platform for installation of the test section and the instrumentation. Liquid is preheated in a stainless steel tank by a band heater to a saturated temperature and maintained with a temperature controller. The saturated liquid is then supplied to the test section through a micro pump capable of accurate flow rate control.

2.2. Test section

The test section is composed of a leak tight vessel and heater surface. The vessel is made of Teflon and has the cross-sectional area of 90 mm $\times$ 60 mm and the depth of 15 mm. Deionized water is used in the tests, conducted at atmospheric pressure. Cartridge heaters are immersed in the pool to maintain the water to be saturated in the vessel. Water temperature is monitored by T-type thermocouples. In order to facilitate high-speed camera visualization and optical sensor thickness measurement, an ITO coated glass window (30 mm $\times$ 30 mm) is mounted in the centre of the top cover and heated by a DC power to avoid vapour condensation. The glass window has a small hole in the centre for the accommodation of the micro-conductive probe which is used to measure the void. Two other observation windows are arranged on opposite lateral walls. A silicon wafer serving as heater's surface is embedded into a centre-hollowed quartz glass sheet (2 mm thick)

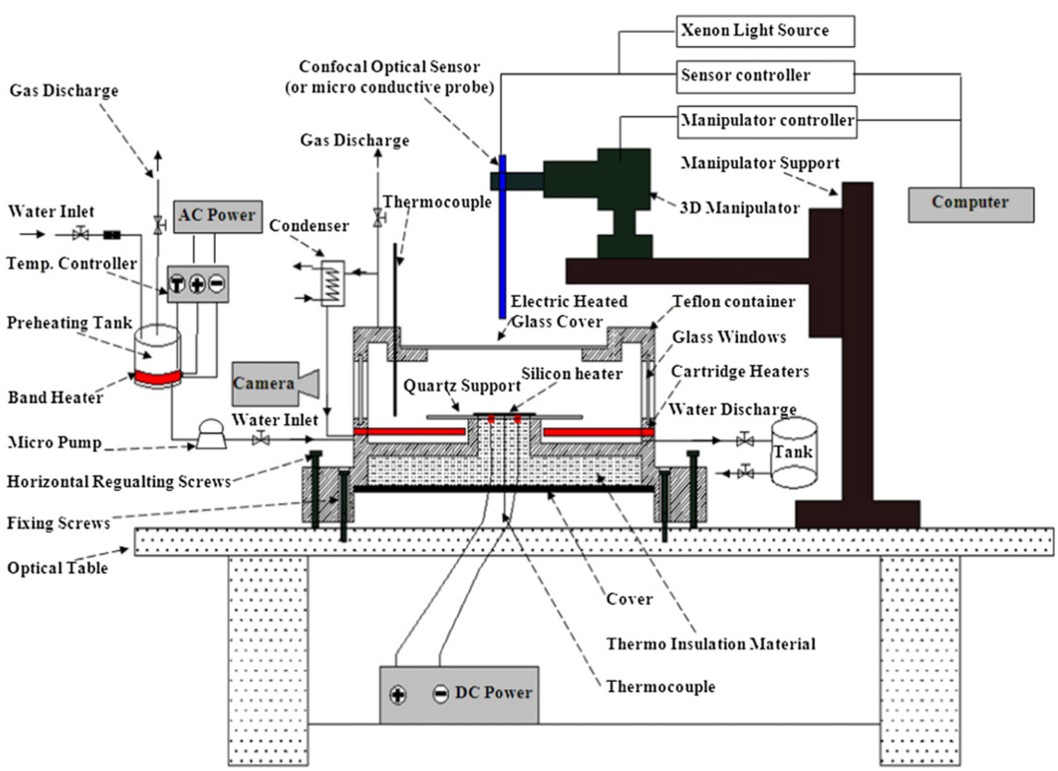

Fig. 2. Schematic of the test facility.