International Journal of Heat and Mass Transfer 108 (2017) 1285–1291

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Detailed structure of microlayer in nucleate pool boiling for water measured by laser interferometric method

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ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form 29 December 2016
Accepted 4 January 2017

Keywords:
Heat transfer
Phase change
Nucleate pool boiling
Microlayer
Laser interferometry

ABSTRACT

During nucleate pooling boiling, a microlayer forms on the heat transfer surface beneath a growing bubble. In previous studies, the existence of a microlayer was confirmed, and its structure was investigated by using several different experimental methods. However, the characteristics and mechanism of the formation of a microlayer have not been thoroughly elucidated to date. In this study, in order to obtain further understanding on the microlayer structure, a laser interferometric method was adopted for a more detailed observation. As a result, it was observed that the special bended shape of the microlayer forms near its outer margin when the microlayer radius is close to its maximum value. By analyzing the variation of the ratio of bubble height to diameter, it can be inferred that the detachment of a bubble causes a decrease of the initial microlayer thickness when the microlayer thickness is close to the maximum radius. This effect explains the formation of the bended shape of initial microlayer.

1. Introduction

As one of the most important heat transfer mechanisms of nucleate boiling, the microlayer formed beneath the bubble has been studied for several decades. Microlayer evaporation, in which a large amount of heat is transported, is especially important since the existence of a microlayer was confirmed and its structure was investigated by adopting several different measuring methods. However, although the existence of microlayer was experimentally confirmed and its thickness distribution was measured, the results studied to date have been limited. Therefore, further investigations on the structure of microlayer are necessary.

To date, the microlayer thickness was investigated by different experimental methods, such as the direct measurement by using optical interferometry [1–6], laser extinction method [7,8], and the indirect measurement by measuring the unsteady temperature variation of the heat transfer surface [9–11]. For optical interferometry, Sharp [1] confirmed the presence of a microlayer and measured its thickness for water by using a mercury arc lamp as the light source. A similar method was adopted by Jawurek [2] and the microlayer thickness for methanol and ethanol was measured. Furthermore, lasers were also adopted as the light source of the interferometric method. For example, Voutsinos and Judd [3] measured for dichloromethane, Koffman and Plesset [4] studied water and ethanol during subcooled boiling. MacGregor and Jawurek [5] measured the microlayer thickness for methanol and analyzed experimental errors of laser interferometry technique, the results showed that errors of laser interferometry technique were lower than 0.5% when measuring the microlayer. Gao et al. [6] adopted a similar method to Koffman and Plesset's [4] and measured the microlayer thickness for ethanol. Using the laser extinction method, Utaka et al. [7,8] was advanced to determine the distribution of initial microlayer thickness for water and ethanol. For the indirect measurement, Moore and Mesler [9] first experimentally demonstrated the formation of a microlayer formed under bubble during nucleate boiling of water. Cooper and Lloyd [10] measured the microlayer for various organic liquids and predicted the thickness based on a simplified hydrodynamic analysis. Yabuki and Nakabeppu [11] performed high precision measurements for water using microelectromechanical systems (MEMS) sensors. The initial microlayer thickness was found to increase almost linearly with the distance from the bubble inception site and the measurement results were consistent with those reported by different researchers. On the basis of the experimentally measured microlayer structure and bubble behaviors using the laser extinction method, Utaka et al. [12] performed a 2-D heat conduction simulation on the heat transfer plate. The contribution of the microlayer evaporation during the nucleate boiling for water and ethanol was investigated by

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.01.003
0017-9310/

Nomenclature

m	order of interferometric fringes (–)
n	refractive index of liquid (–)
q	heat flux (kW/m^2)
r	distance from bubble inception site (mm)
r_{Mmax}	distance from bubble inception site when microlayer initially reached its maximum value (mm)
t	duration of microlayer from bubble inception (ms)
δ	microlayer thickness (μm)
δ_0	initial microlayer thickness (μm)
$\delta_{0\mathrm{max}}$	maximum of initial microlayer thickness (μm)

comparing the calculated microlayer evaporation to the experimentally measured bubble volume. Moreover, Chen and Utaka [13] and Sato and Niceno [14] performed numerical simulation of vapor growth process in nucleate boiling with the microlayer structure measured in [12] and examined the effect of microlayer evaporation for water. However, the knowledge on the microlayer structure and the mechanism of microlayer formation is still quite insufficient since both the experimental conditions and results were limited in the former studies. Further investigations on the microlayer structure should be performed in detail in order to clarify the mechanisms and characteristics of microlayer formation and nucleate boiling.

As shown above, different experimental methods with different characters for microlayer thickness measurements are preferable to obtain more correct information regarding microlayer. There are direct measurements of microlayer thickness such as absolute (laser extinction method) and relative (laser interferometric method) methods, and indirect (from measurement of heat transfer surface temperature) method. In the laser extinction method [7,8,12], it is possible to measure the absolute thickness and the initial microlayer thickness could be measured at the local position of the microlayer for a bubble. For obtaining the initial microlayer thickness at different positions from the bubble inception site (r), many experimental data must be measured from different bubbles. On the contrary, the difference of liquid film thickness between adjacent locations (adjacent fringes) is measured by laser interferometry and the planer thickness distribution could be measured at one time for a bubble. As shown in details later, since the tracking interferometric fringes on the consecutive images enhances the measurement precision concerning the liquid shape measurement, we adopted the interferometry of precise planer measurement used by Koffman and Plesset [4] for acquiring the detailed information on the microlayer structure in this study. Furthermore, the nondimensional correlation was also investigated for examining the dominant factors on the microlayer formation.

2. Experimental apparatus and method

2.1. Experimental apparatus

Fig. 1 shows the schematic diagram of experimental apparatus. The experimental apparatus is comprised of a boiling chamber and a laser interferometry system. A quartz glass of 25 mm in diameter and 2 mm in thickness was attached on the bottom of the boiling chamber as a heat transfer plate for the interferometric measurement. In order to generate bubbles on the heat transfer surface, the heat transfer plate was heated by a jet of hot nitrogen gas from a nozzle (inner diameter: 2 mm) at a position where the laser light was not interrupted. The heat flux was determined using the method introduced in [8] by performing iterative calculations for the overall heat transfer system using the heating-side heat transfer coefficient obtained from the flow rate. The liquid in the boiling chamber was heated by an immersed auxiliary electric heater and the saturation temperature was kept. The boiling chamber was exposed to the atmosphere in order to keep the atmospheric pressure. On the side wall of the boiling chamber, several glass windows were arranged for observation.

A helium-neon laser with a wavelength of 632.8 nm and an output power of 15 mW was adopted as the light source of the interferometric measurement. The laser beam is first directed into a beam collimator after generation in order to obtain a parallel laser beam with large radius. After that, the laser beam is directed normal to the heat transfer surface by a beam splitter that is positioned between the microscope and the bottom of the boiling chamber. The incident laser beam is both reflected by the surfaces of microlayer and the heat transfer plate, the laser beams reflected by different surface interfere with each other and as a result the interferometric fringes form (bright and dark fringes as shown in Fig. 2). As shown in Fig. 2, the movement of interferometric fringes toward the larger radius of microlayer could also be observed by

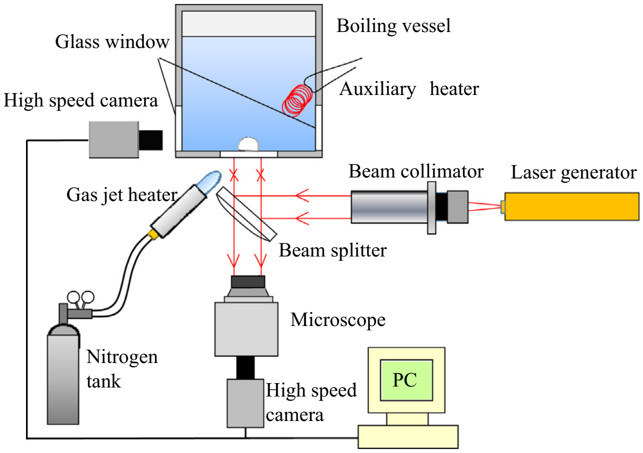

Fig. 1. Schematic diagram of experimental apparatus.

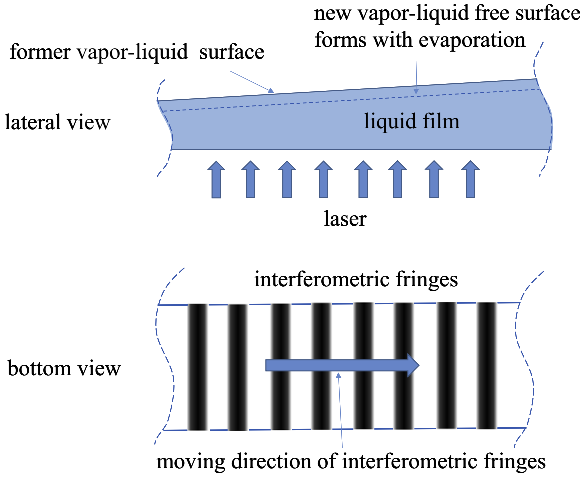

Fig. 2. Schematic diagram of laser interferometry.