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ScienceDirect
International Journal of Heat and Mass Transfer 50 (2007) 3481–3489
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Liquid–vapor structure near heating surface at high heat flux in subcooled pool boiling

Ayako Ono, Hiroto Sakashita *

Division of Energy and Environmental Systems, Graduate School of Engineering, Hokkaido University, North 13 West 8, Kita-ku, Sapporo 060-8628, Japan

Received 2 September 2005; received in revised form 27 March 2006
Available online 26 March 2007

Abstract

Liquid–vapor behavior close to a heating surface was measured using two conductance probes with tip diameters smaller than 5 μm. Measurements were carried out for water boiling on an upward-facing copper surface under subcooling from 0 to 30 K. The probe signals and the void fraction distributions showed that there is little difference in the liquid–vapor structure beneath large vapor masses in saturated and subcooled boiling, that a macrolayer remains on the heating surface, and that in subcooled boiling it does not dry out even at heat fluxes far higher than CHF for saturated boiling. The thickness of the macrolayer forming beneath large vapor masses was determined from the location where the probe signals corresponding to the large vapor masses disappear. It was found that the thicknesses of the macrolayer formed in subcooled boiling are comparable to or thicker than those near the CHF in saturated boiling, and it is considered that this is most likely to be one of the causes why the CHF increases with the increasing subcooling.

Keywords: Pool boiling; Critical heat flux; Subcooled boiling; Conductance probe; Macrolayer

1. Introduction

There are numerous studies of CHF in pool boiling, but the mechanism of this phenomenon has not been fully elucidated. In saturated pool boiling on an upward-facing surface, large vapor masses form and detach periodically from the heating surface above a heat flux of 20–40% of the CHF, and a thin liquid-rich zone, a so-called macrolayer, exists beneath the large vapor masses. It is generally accepted that this macrolayer is closely related to the occurrence of CHF in saturated boiling. Therefore, attempts have been made to determine the liquid–vapor structure under the vapor masses in saturated boiling, using electric conductance probes [1–4] and an optical probe [5] for the measurements because the vapor masses hovering on the heating surface make it impossible to conduct direct observations of the macrolayer from above the heating surface. These measurements have confirmed the presence of the macrolayer under the vapor masses, however, the detailed structure and dynamics of the macrolayer have not been fully described as the macrolayer is very thin making it difficult to determine the structure accurately.

Large vapor masses are also observed in subcooled pool boiling. With 10 mm diameter circular disks, Inada et al. [6], Yokoya et al. [7], and Li et al. [8] confirmed that the large vapor masses are formed and detach or collapse periodically on the heating surface when the subcooling is less than about 50 K and the heat flux is close to the CHF. Despite the similarities in the boiling conditions in saturated and subcooled boiling, it has been established that with increases in subcooling the CHF for subcooled boiling markedly increases above the CHF for saturated boiling. The causes of the increase in CHF with increases in subcooling could be related to the liquid–vapor structure beneath the vapor masses, but no research has been addressed at clarifying the CHF mechanism based on measurements of the liquid–vapor structure. This study aims to examine the mechanism of CHF for saturated and subcooled pool boiling. The liquid–vapor behavior close to the heating

* Corresponding author. Tel./fax: +81 11 706 6664.
E-mail address: saka@eng.hokudai.ac.jp (H. Sakashita).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.01.026

Nomenclature

h	height from heating surface	T_{me}	measurement time
q	heat flux	ΔT_{sub}	subcooling
q_{CHF}	critical heat flux		

surface was measured with highly accurate conductance probes for pool boiling of water on an upward surface in the range of subcooling from 0 to 30 K. Through these measurements, the thickness of the macrolayer that forms beneath the vapor masses at high heat fluxes near the CHF was determined.

2. Experiment

2.1. Experimental apparatus

Fig. 1 shows the experimental apparatus. The experiments were conducted using water at atmospheric pressure over a range of subcooling from 0 to 30 K. The boiling vessel is made of Pyrex glass with an inner diameter of 210 mm, filled with deionized water to a depth of 200 mm high. The subcooling of the liquid was achieved with auxiliary heaters and cooling pipes placed in the vessel. The subcooling was defined by the liquid temperature measured at the same height as the heating surface, 20 mm from the center of the surface. The top surface of a conical copper block served as the heating surface making it possible to realize a heat flux up to 10 MW/m^2. The diameter of the heating surface is 8 mm and a vapor mass may cover the whole of the area of the heating surface at high heat fluxes near the CHF at the 30 K subcooling in the present experiment. Three thermocouples of 0.5 mm diameter were embedded in the copper block 5, 13, and 21 mm below the heating surface. The surface temperature and heat flux were calculated with the three thermocouples by considering the conical copper block as approximating a part of a hollow sphere. The heating surface was polished by #1000 emery paper before each experiment.

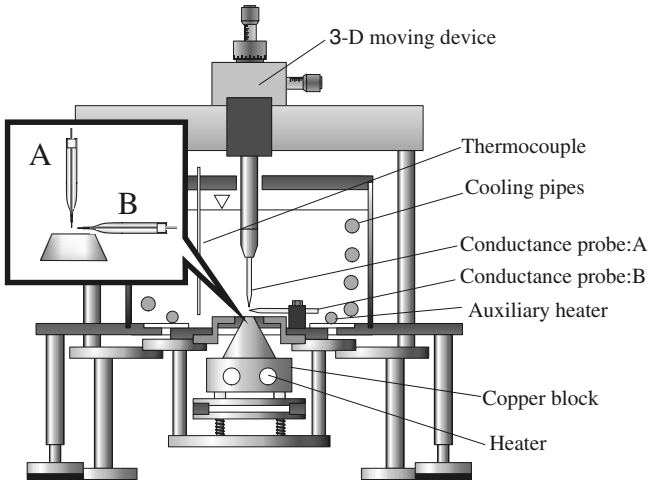

Fig. 1. Experimental apparatus.

A conductance probe method was adopted for the measurements of the liquid–vapor behaviors very close to the heating surface. The sensing element of the conductance probe, which is a 90 μm diameter stainless steel wire, was inserted in a conical capillary quarts tube with very low thermal expansion coefficient. The tip of the stainless steel wire was exposed about 1 mm from the tip of the quarts tube. It is desirable to make the probe tip as thin as possible, to improve the space resolution and to reduce the influence of liquid adhesion at the tip of the probe. In this study, the tip of the stainless steel wire was thinned to less than 5 μm by an electro-polishing technique. This conductance probe was connected to a three-dimensional moving stage with an accuracy of 0.5 μm in the perpendicular direction and 10 μm in the horizontal direction (the moving probe in the followings, A-probe in Fig. 1). A further probe was used to selectively measure the behaviors of vapor masses (fixed probe in the following, B-probe in Fig. 1). The fixed probe was placed near the center of the heating surface 4 mm over the surface. The support rods of the moving prove and of the moving stage were a nickel alloy (super inver) with a thermal expansion coefficient of about 0.5×10^{-6}/K, two orders of magnitude smaller than those of usual metals. During the measurements, potassium chloride was added to increase the electro conductivity of the water, and an AC voltage was imposed between the heating surface and each of the two probes.

2.2. Measurement circuit

Fig. 2 is a schematic diagram of the measurement circuit. To improve the sensitivity of the measurements, the frequency of the AC voltage applied to the probes was adjusted to the resonance frequency of the measurement circuit, the resonance frequency was adjusted to 24 kHz by inserting inductances, and the inverse of this frequency, 42 μs, is the time resolution of the measurements. The position of the moving probe was calibrated by the electrical contact between the probe tip and the heating surface by using a short detection circuit which detects a moment just when the peak voltage and/or the frequency of the probe signals become lower than a given threshold value. The probe position was checked repeatedly during a run under the condition that the heating surface was heated by a set heat flux. The reproducibility of the probe position was