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Microscale wall heat transfer and bubble growth in single bubble subcooled boiling of water

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ABSTRACT

A MEMS measurement technique was used to study the mechanisms of wall heat transfer and bubble growth during subcooled boiling of water in the isolated bubble region. The local wall temperature beneath a single bubble in subcooled boiling was measured at a sampling frequency of 50 kHz using a MEMS sensor. The wall and liquid phase heat transfers were quantitatively evaluated by the analysis with the measured local temperature and bubble size extracted from bubble images. The microlayer evaporation provided a significant contribution to the wall heat transfer and the bubble growth, but the rewetting heat transfer during the bubble departure process was insignificant in the wall heat transfer, as with our previous results for saturated boiling. The subcooling of the bulk liquid was found not to have significant influence to the microlayer evaporation. The condensation heat transfer from vapor bubble to bulk subcooled liquid was comparable to the microlayer evaporation heat transfer, and subcooled boiling single bubbles behaved like a heat pipe on the heated wall. The bubble oscillation on the surface was observed in one case. The evaporation of the microlayer which repeatedly reformed in the oscillation process transferred a high heat flux of around 1 MW/m^2. Evaporation and formation characteristics of the microlayer were additionally examined.

1. Introduction

Nucleate boiling is the most efficient heat transfer mode, and has been utilized in a variety of heat transfer systems, including vapor generation in power plants and cooling of electronic devices. Many heat transfer models have been proposed in past studies on boiling heat transfer mechanisms. The widely supported fundamental heat transfer phenomena governing nucleate boiling are microlayer evaporation beneath the bubble [1], three-phase contact-line heat transfer [2], evaporation of superheated liquid surrounding the bubble [3], forced convection induced by the bubble motion [4–7], transient heat conduction in liquid after a bubble departure [8], and thermal Marangoni convection along the liquid–vapor interface [9]. Better observation and understanding of the fundamental heat transfer phenomena are essential to construct a mechanistic boiling heat transfer model. It has been, however, difficult for commonly-used sensors to precisely measure fundamental heat transfer phenomena at a small spatiotemporal scale, and therefore physical mechanisms of the fundamental phenomena have remained unclear. Recently, high-resolution temperature measurement techniques have been developed and enable the direct measurement of the fundamental heat transfer phenomena of boiling. The boiling mechanisms have been investigated with high resolution measurement techniques including MEMS thermometry [10–14] and high-speed infrared thermometry [15–18]. The details of those studies focusing microscopic aspects of boiling heat transfer are reviewed in our previous paper [13]. The reports providing high-resolution data of the boiling bubble shape and surface temperature or heat flux of the heated wall are valuable for understanding the mechanism of the phenomena. Additionally, highly resolved experimental data is helpful to develop the numerical simulation method usable for the engineering design of the boiling [19–21]. Sato and Niceno [22] numerically simulated our isolated bubble boiling experiments [13], and showed good agreement with our results from the view point of magnitude and rate of local wall temperature variation and behavior and size of bubble.

In a previous paper, the authors [13] investigated the mechanisms of the isolated bubble boiling of pool saturated water with an original MEMS sensor and a high-speed camera. Local temperature and wall heat transfer beneath the bubble were shown by measuring wall surface temperature distribution at a high spatiotemporal resolution and by analyzing transient heat conduction in the wall. Moreover, evaporation heat transfer to the bubble from

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surrounding superheated liquid layer was derived by subtracting the wall heat transfer from latent heat in the bubble. It was demonstrated that the microlayer evaporation on the wall is the dominant mechanism in the wall heat transfer and its contribution to the bubble growth is around 50% for the isolated bubble boiling of saturated water at a wall superheat of 8–15 K. During this experiment, the authors also tried to collect some data for subcooled boiling. But it was difficult under subcooling conditions to generate a boiling bubble ideal for the subsequent analysis. The bubble which is initiated by a trigger pulse, isolated, highly axisymmetric and taken from initiation to departure was favorable to our experimental and analytic procedures. Only three cases of the subcooled boiling under discrete conditions were taken after all. Although comprehensive data could not be obtained, the three cases include important information about the wall temperature, heat flux and bubble shape in subcooled boiling of water. Additionally, some interesting features of formation and evaporation of microlayer and phase-change heat transfer in the liquid side around the bubble were extracted from the data.

2. Experiment and data analysis

Experimental data of the subcooled boiling were collected with the saturated boiling data in the same date and by the same apparatus as in the previous paper [13]. The experimental apparatus, including the MEMS sensor, the measurement system and analysis method are briefly explained here. Details were described in the previous paper [13].

2.1. MEMS sensor

The MEMS sensor has eleven thermocouples (TCs), two resistance temperature detectors (RTDs) and an electrolysis trigger along the center line on a Si substrate. The sensors measure surface temperature with ~0.1 ms temporal resolution at a distance 50–2500 μm from the trigger. The spatial resolutions are $20 \times 40\ \mu m^2$ for TCs and $63 \times 205\ \mu m^2$ for RTDs. A bubble nucleus which is tiny hydrogen bubble can be generated at an intended timing by the electrolysis trigger.

2.2. Methods of experiment and analysis

The thin-film TCs and RTDs signals were measured at a sampling frequency of 50 kHz, and the high-speed video of the bubble was taken at a framing rate 6000 fps. Distilled and degassed water was used as the boiling liquid. The degree of subcooling was monitored using a thermocouple located 6 mm above the MEMS sensor. After the liquid temperature reached a steady state via a heater wound around the test chamber, the heating by the backside heater of the MEMS sensor was started. The measurement of local wall temperatures under the nucleated bubble and the recording of the bubble video were synchronized by the trigger signal. The temperature distribution in the wall was calculated by the two-dimensional transient heat conduction simulation using the measured wall temperature as a boundary condition. Because an axisymmetric cylindrical coordinate system was used for the simulation, only the axisymmetric boiling bubbles were selected for accurate analysis. Then, the local heat flux from the wall surface to the bubble and liquid was derived from the temperature gradient in the thickness direction at the surface.

From the obtained local heat flux distribution and bubble size extracted from the taken images, the heat transfer mechanisms related to the single bubble growth, as shown in Fig. 1, are qualitatively evaluated. The boiling bubble is grown by the evaporation of the microlayer and the superheated liquid layer developed on the heating wall and surrounding the bubble. In subcooled boiling, the condensation of vapor to the subcooled liquid causes the shrinkage of the bubble, and the bubble growth rate $\dot{Q}_b$ is determined as a result of a competition between the total rates of the evaporation $\dot{Q}_{ml} + \dot{Q}_{sl}$ and the condensation $\dot{Q}_c$ as shown in Fig. 1.

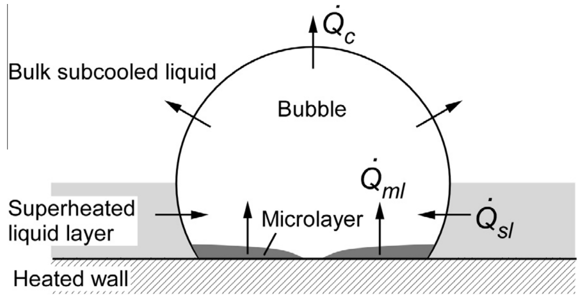

Fig. 1. Heat transfers related to single bubble growth in the subcooled water.

$$\dot{Q}_b = \dot{Q}_{ml} + \dot{Q}_l = \dot{Q}_{ml} + \dot{Q}_{sl} - \dot{Q}_c \tag{1}$$

The heat flow caused by microlayer evaporation, called microlayer heat flow $\dot{Q}_{ml}$, was calculated by integrating the resultant local heat flux within the apparent contact area. The microlayer heat flow $\dot{Q}_{ml}$ can be temporally integrated to obtain the amount of heat transferred by microlayer evaporation, which is called microlayer heat, Q_{ml}. Further, the instantaneous latent heat accumulated in the bubble Q_b was calculated by reading the bubble shape from the high speed images, and the bubble growth rate $\dot{Q}_b$ was calculated by temporal differentiation of Q_b. Evaporation or condensation heat transfer from/to the surrounding liquid $\dot{Q}_l$ was derived by the subtraction of the microlayer heat flow $\dot{Q}_{ml}$ from the bubble growth rate $\dot{Q}_b$.

2.3. Measurement uncertainties

The uncertainties in this experiment are as follows. The uncertainty in absolute temperature measurement by the RTDs was ±1 °C from the calibration error. The differential temperature measurement by the TCs includes the uncertainty of 2% from the dispersion of the calibration. The resolution of the temperature sensors was evaluated to be 0.05 K from the root mean square of the temperature data. The uncertainty of the local heat flux calculated by the transient heat conduction analysis includes 2%, and its resolution is $30\ kW/m^2$. The uncertainty in estimation of latent heat in the bubble depends on the bubble size. Supposing a reading error of the liquid–vapor interface position is ±1 pixel (=26.7 μm) and bubble shape is spherical, the uncertainties in the latent heat at bubble diameters of 2 mm and 5 mm are evaluated to be 8% and 3%, respectively. The uncertainties of wall heat transfer and the latent heat in the bubble are less than 10%, thus the heat transfer into and out of the surrounding liquid also can be discussed accurately.

2.4. Experimental conditions

The experimental data were collected at three subcooling levels of ΔT_{sub} = ~10 K, ~20 K and ~30 K. Because the generated bubble did not depart and stayed on the wall at those subcooling levels under the low wall superheat of ΔT_{sat} = 8 K − 15 K, the wall superheat was set higher than that in the previous saturated boiling experiment [13]. As a result, three cases of subcooled boiling were taken. They are also distinctive each other by good fortune: Case 1 is usable to compare the isolated bubble boiling under the