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Heat transfer characteristics based on microlayer structure in nucleate pool boiling for water and ethanol

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ABSTRACT

The objective of the study is to elucidate the contribution of the microlayer evaporation on heat transfer in nucleate pool boiling of an isolated bubble region for water and ethanol on the basis of microlayer thickness measurement. The distribution of microlayer thickness formed under a growing bubble was measured by laser extinction method using a specially devised system with a thin optical fiber fabricated in a thin tube and gas blowing in former report. In this study, the dominant factors that determine the microlayer characteristics, such as thickness distribution, duration and area on the heat transfer surface were expressed by non-dimensional form based on the similarity of bubble growth rate. Furthermore, a numerical simulation was performed based on modeling of the boiling system. The heat transfer characteristics in nucleate boiling were investigated and the contribution of evaporation from the microlayer during nucleate boiling of isolated bubble region is demonstrated using the relations among dominant factors.

1. Introduction

The boiling phenomenon, which involves heat transfer factors, such as high heat transfer coefficient, high critical heat flux, and utilization of both liquid and vapor phases, is widely used in numerous industries. Although a number of studies have examined the boiling phenomena, unknown quantitative factors affect the heat transfer mechanisms of boiling due to complex physicochemical factors, such as bubble nucleation, growth, and fluid motions, and phase changes at the liquid–vapor interface.

The heat transfer mechanisms of nucleate boiling have been classified into two categories of convective heat transfer and latent heat transfer. The convective heat transfer mechanism is based on diffusion of the thermal boundary layer by bubble motion and sensible heat transport, whereas the latent heat transfer mechanism involves sensible heat stored in the superheated liquid layer being converted into bubble growth and vaporization of the microlayer that forms between a growing bubble and the heat transfer surface. Although the heat transfer mechanism of nucleate boiling has been investigated in terms of these proposed mechanisms, there has not been sufficient quantitative investigation. The heat transfer characteristics of microlayer evaporation, in which a large amount of heat transport results from latent heat of evaporation, is especially important. Therefore, clarification of the microlayer structure is fundamental to understanding the boiling process.

Measurement of the microlayer can be classified into two methods. One involves prediction of the microlayer thickness from the unsteady temperature variation of the heat transfer surface. Moore and Mesler [1] first experimentally demonstrated the formation of a microlayer formed under boiling water bubbles. Cooper and Lloyd [2] measured the microlayer for various organic liquids. Yabuki and Nakabeppu [3] performed high precision measurements of water using microelectromechanical system (MEMS) sensors. The other type of method involves measurement of the microlayer thickness using optical interferometry. This technique enables direct measurement of the microlayer thickness. Mercury arc lamps were used as light sources in early studies, such as those reported by Sharp [4] who confirmed the presence of a microlayer and measured its thickness for water, and by Jawurek [5] for ethanol. Furthermore, Voutsinos and Judd [6] measured the microlayer thickness in dichloromethane using a laser light source. Koffman and Plesset [7] measured microlayer thickness distributions for subcooled water and ethanol with high-speed photography. Gao et al. [8] recently adopted a similar interferometric method and measured the microlayer thickness for ethanol.

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Nomenclature

f	period of bubble formation cycle (ms)
h_i	interfacial heat transfer coefficient due to interphase mass transfer
k_l	thermal conductivity of liquid (W/(m K))
L	latent heat of vaporization (J/kg)
q	heat flux (W/m^2)
q_1	heat flux at backside of heat transfer plate (W/m^2)
q_2	heat flux at heat transfer surface under bulk liquid phase (W/m^2)
q_3	heat flux at heat transfer surface under microlayer (W/m^2)
Q_{ML}	heat transfer rate through the microlayer to the vapor bubble (J)
r	radial axis (distance from origin at bubble inception site) (mm)
R	gas constant (J/(kg K))
R_{Bmax}	maximum bubble radius of horizontal direction (mm)
R_{dry}	radius of the dryout region (mm)
R_{M}	microlayer radius on heat transfer surface (mm)
R_{Mmax}	maximum microlayer radius (mm)
t	time (ms)
t_{B}	elapsed time from bubble inception (ms)
t_{Bd}	elapsed time from bubble inception to completion of bubble departure (ms)
t_g	time prior to initial microlayer formation at r (s)
t_{Mmax}	time elapsed before maximum radius of microlayer R_{Mmax} (ms)
t_{Md}	time elapsed before commencement of bubble departure (ms)
T	temperature (K)
T_{sat}	saturation temperature (K)
T_w	temperature of heat transfer plate (K)
V_{B}	bubble volume (m^3)
V_{ML}	vapor volume from microlayer evaporation (mm^3)
z	axis perpendicular to heat transfer plate (origin at heat transfer surface) (mm)
α	thermal diffusivity (m^2/s)
δ	microlayer thickness (μm)
δ_0	initial microlayer thickness (μm)
$\delta_{\max}$	initial microlayer thickness at R_{Mmax}(μm)
δ_{T}	thickness of superheated layer (mm)
Δt	time step for calculation (ms)
Δt_{Me}	duration of microlayer presence (ms)
ΔT	superheat of the heat transfer surface (K)
ΔT_{i}	surface superheat temperature at bubble inception (K)
ρ_{v}	vapor density (kg/m^3)
ρ_{l}	liquid density (kg/m^3)
σ	evaporation coefficient (–)

The structure of the microlayer and its effect on heat transfer are understood to a lesser extent, because special measurement devices are often required to investigate the microlayer characteristics for the complex behavior of liquids and vapors during boiling phenomena. Measurements have been mostly performed for only water and several organic liquids; therefore, it is important to systematically investigate the characteristics of the microlayer using various methods, liquids, and conditions.

The previous study of Utaka et al. [9] was advanced to determine the distribution of initial microlayer thickness for water and ethanol using a unique laser extinction method and by developing a method for initial microlayer thickness determination that combines modeling and numerical calculations for a boiling system with analysis of the microlayer behavior recorded with a high-speed camera [10]. The initial microlayer thickness was found to increase linearly with distance from the bubble site and the measurement results were consistent with those reported by different researchers.

The objective of the present study is to elucidate the contribution of evaporation from the microlayer on pool nucleate boiling heat transfer of the isolated bubble region for water and ethanol through derivation of the microlayer characteristics from previously reported measurement results [9] and simultaneous imaging of vapor bubble inception and growth.

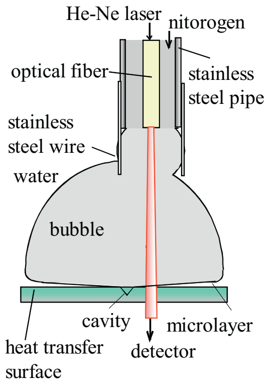

Fig. 1. Schematic diagram of method for measurement of microlayer thickness.

2. Summary of previous study

A previous study by Utaka et al. [10] reported measurements of the microlayer structures for water and ethanol under saturated condition using the laser extinction method with a laser emission apparatus and an optical fiber with a core diameter of 94 μm in a thin metal tube located at the head of the growing bubble in the bulk liquid, as shown in Fig. 1. This special device was employed to obtain measurements without contact by removing the bulk liquid between the optical fiber and the microlayer, where the gas blown from the thin tube coalesced with the growing vapor bubble as it developed. The laser extinction method was combined with the special device, which consists of a boiling system of water and ethanol at atmospheric pressure and a system to measure the transmission ratio of laser light. A 2 mm thick quartz glass heat transfer plate and nitrogen gas as a heating medium were used to realize stable transmission of the laser beam to the detector. Figs. 2 and 3 show the key results of the previous report [10] for water and ethanol, respectively, including the variation in initial microlayer thickness δ_0 (μm) with measurement position r (mm). Here, the initial microlayer thickness δ_0 is defined as the thickness when the bubble forefront reaches r and the microlayer is formed. The extrapolation was applied to determine δ_0 and surface superheat at bubble inception ΔT_{i} simultaneously by iteration until agreement was obtained between the measured and calculated variations in the microlayer thickness because there was short duration without data at the beginning of microlayer formation. Heat flux had little effect on the microlayer thickness within the range of measurement. The results clarified that δ_0 increased with the distance from the bubble inception site. The relation between the distance from the bubble inception site and the microlayer thickness are expressed by Eqs. (1) and (2) for water and ethanol,