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An experimental method to simultaneously measure the dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface

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ABSTRACT

The heat transfer mechanisms of nucleate boiling are associated with how the liquid–vapor phase and the surface temperature are distributed and interact beneath a single bubble on a heated surface. A comparative analysis of the hydrodynamic and thermal behavior of a single bubble may contribute greatly to the understanding of nucleate boiling heat transfer. In this paper, a technique to simultaneously measure the liquid–vapor phase boundary, temperature distribution, and heat transfer distribution at a boiling surface is described. The technique is fully synchronized in time and spatially resolved, and is applied to explore single-bubble nucleate boiling phenomena in a pool of water subcooled by 3 °C under atmospheric pressure. The temperature and heat flux distributions at the boiling surface are quantitatively interpreted in relation to the distribution and dynamics of the dry and wet areas, the triple contact line, and the microlayer underneath the single bubble. The results show that intensive wall heat transfer during single-bubble nucleate boiling exactly corresponds to the extended microlayer region. However, the overall contribution of the microlayer evaporation to the growth of a bubble is relatively small, and amounts to less than 17% of the total heat transport.

1. Introduction

Nucleate boiling is widely used in heat transfer applications due to the significant latent heat of evaporation. Therefore, there have been a number of efforts to improve our understanding of the mechanisms of boiling heat transfer. Heat transfer mechanisms, including micro-convection (or enhanced convection), transient conduction, microlayer evaporation, and contact line heat transfer, have been proposed to describe nucleate boiling, as shown in Fig. 1 [1]. There are three main processes in nucleate boiling of a single bubble: the bubble growth period (see Fig. 1a), when bubble nucleation and the appearance of a microlayer occur, the bubble departure period (see Fig. 1b) when the bubble base shrinks and cold bulk liquid quenches the area of the bubble influence, known as transient conduction, and the wait period from the detachment of the bubble from the surface to the nucleation of next bubble. Intensive evaporation heat transfer occurs at the microlayer and the triple contact line. In addition to natural convection during nucleate boiling, the liquid surrounding the bubble is activated by the growth, departure, and detachment of the bubble, resulting in enhanced convection [1].

Recently, a number of direct numerical simulation studies with interface tracking have been developed to model boiling heat transfer phenomena [2–5]. These require high-quality experimental data to validate the reliability of the model. The increasing need for developing computational multi-phase fluid dynamics simulations has motivated researchers to investigate the fundamental heat transfer mechanisms involved in nucleate boiling using temporally and spatially resolved measurement techniques. The observation of the interaction of the dynamics of the triple contact line, which separates the dry and wet regions on the boiling surface, and the heat transfer in each region is essential to examine the fundamental heat transfer mechanisms of nucleate boiling.

2. Literature review

Visualization of the liquid–vapor phase and heat transfer distributions on the boiling surface and the dynamics of a boiling bubble may contribute greatly to our understanding of the characteristics and mechanisms of nucleate boiling heat transfer. This can be realized through accurate detection of interfacial phenomena on

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Nomenclature

C_p	heat capacity (J kg^{-1} K^{-1})
D	diameter (m)
d	thickness (m)
k	thermal conductivity (W m^{-1} K^{-1})
m	fringe order
n	refractive index
q''_{average}	heater input heat flux (W m^{-2})
q''_m	conduction heat flux through the microlayer (W m^{-2})
R_a	surface roughness (m)
T_i	temperature at the vapor–liquid interface (K)
T_w	wall temperature (K)
ΔT_{sub}	subcooled temperature (K)
t_m	microlayer depletion time (s)
t	time (s)

Greek symbols

δ	thermal penetration length (m)
λ	wavelength (m)
ρ	density (kg m^{-3})
θ	angle of refraction (°)

Subscripts

d	bubble departure
g	bubble growth
inf	wall area of influence
l	liquid
m	microlayer
s	substrate
w	bubble wait

the boiling surface using temporally and spatially resolved measurements of the temperature and liquid–vapor phase distributions. There have been a number of studies on the development of optical techniques to diagnose hydrodynamic and thermal interfacial phenomena at a boiling surface; these are reviewed in this section.

2.1. Infrared thermometry to measure temperature distribution

Some studies using high-speed and high-resolution infrared cameras have reported the transient temperature distribution at a boiling surface [6–10]. Theofanous et al. [6,7] used an infrared camera to record the distribution and variation of the surface temperature during boiling of water on a 140-nm-thick titanium film heater deposited on glass, which was powered at a frequency of 1 kHz. Golobic et al. [8,9] measured the transient wall temperature distribution during bubble growth on a thin platinum foil heater with a spatial resolution of 40 μm at intervals of 1 ms. The heat flux distribution was also obtained by analyzing the successive wall temperature distributions on the thin foil heater. Using the local heat flux results, the heat transfer from the heated wall into the bubble was analyzed. Recently, Gerardi et al. [10] observed temporally and spatially resolved bubble nucleation and boiling heat transfer on an indium-tin-oxide (ITO) film heater coated on a glass substrate by means of synchronized high-speed video and infrared thermometry with a spatial resolution of 50 μm and 100 μm, respectively. Quantitative data on the bubble departure diameter and frequency, and the growth and wait times were obtained for nucleate boiling of pure water and nanofluids.

2.2. Total reflection to visualize the liquid–vapor phase distribution

Total reflection has been used to investigate the liquid–vapor phase distribution continuously at a transparent boiling surface [11–14]. Nishio et al. [11] visualized the liquid–solid contact patterns in high heat-flux nucleate boiling on a transparent boiling surface. They proposed a contact-line-length density model of the boiling surface to interpret the high heat-flux nucleate boiling heat transfer phenomena. Chung and No [12] conducted a similar study with a focus on the dynamics of dry spots underneath the boiling bubbles. They proposed a critical heat flux model based on the dry area fraction of the heater surface. Nishio and Tanaka [13] examined the relationship between the liquid–solid contact distribution and two-phase structures under the high heat flux that occurs at saturated and subcooled pool boiling. Chu [14] systemically investigated the formation and dynamics of irreversible dry spots/patches triggering critical heat flux phenomenon. He found that, for a single bubble growing at a low heat flux, not only the dry spot area, but also a microlayer region, can be detected using the total reflection technique.

2.3. Laser interferometry to determine the microlayer geometry

Single-bubble nucleate boiling studies using laser interferometry have been carried out to investigate the geometry and dynamics of the microlayer at the interface between a boiling bubble and the heated surface [15–17]. Koffman and Plesset [15] investigated the microlayer formation and changes in thickness with time. Jawurek [16] obtained the history of the microlayer geometry

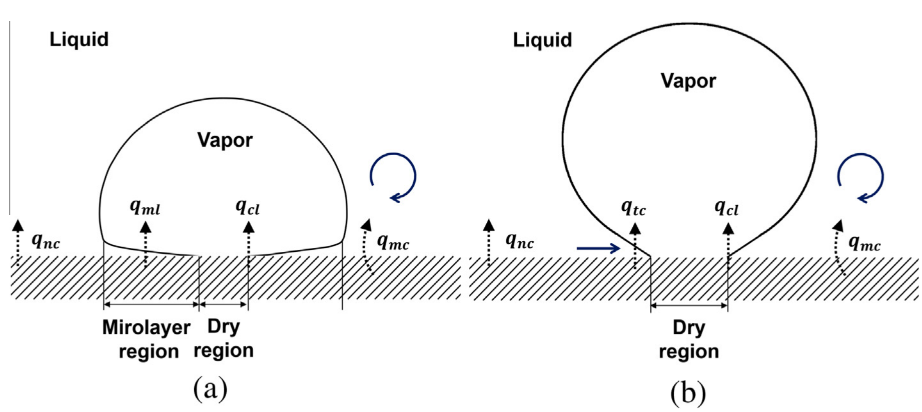

Fig. 1. Physical mechanisms of heat transfer during single-bubble nucleate boiling. (a) Bubble growth period and (b) bubble departure period.