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Simultaneous investigation of dynamics and heat transfer associated with a single bubble nucleate boiling

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1. Introduction

Nucleate boiling is widely used in practical applications due to its highly thermal efficiency. The thermal performance of Light Water Reactors (LWRs) under normal operation and during transients and accidents is strongly associated with nucleate boiling. Heat transfer mechanisms and characteristics of nucleate boiling are associated with the interaction of liquid-vapor phase and surface temperature distribution underneath a single bubble growing on a heated surface.

The visualization of the liquid-vapor phase and heat transfer distributions on a boiling surface and dynamics of boiling bubble can contribute greatly to the understanding of the characteristics and mechanisms of nucleate boiling heat transfer. It can be realized through the accurate detection of interfacial phenomena on a boiling surface such as time and space resolved measurements of the temperature and liquid-vapor phase distributions on boiling surface.

In this study we develops a unique experimental technique with spatially and temporally synchronized infrared thermometry [1], total reflection [2], and laser interferometry [3] to examine the interactive effects of the temperature and liquid-vapor phase distributions, including microlayer, on a boiling surface.

2. Experimental Technique

2.1 Test Sample

In order to ensure the three different optical techniques, we consider a thin film electric heater on a base plate as the test sample. For visible light, both the film heater and the base plate are transparent to implement total reflection and laser interferometry techniques. For infrared light, the base plate is transparent whereas the film heater is non-transparent, so that the thermal image of the heater surface can be captured from below the base plate. A good example is the combination of an Indium-Tin-Oxide (ITO) thin film heater (transparent to visible and opaque to infrared lights) and a Calcium Fluoride (CaF2) plate (transparent to both visible and infrared lights), which is used for this study.

2.2 Experimental Setup

Figure 1 shows the schematic of the optical setup to measure surface temperature and liquid-vapor phase distributions underneath a bubble growing on heater and visualize dynamics of the boiling bubble from side.

Temperature distribution of the boiling surface is measured using an infrared (IR) camera placed below the base plate. The base plate is transparent enough to acquire thermal radiation from the film heater without considerable loss of accuracy. Simultaneously phase distribution on the boiling surface is detected using the total reflection technique with a high speed video (HSV) camera. The image obtained by the total reflection technique appears dark for liquid phase and bright for vapor phase. It is noted that the prisms for total reflection should not hinder the optical path of the infrared light. The IR and HSV cameras were temporally synchronized using a function generator. The obtained phase and temperature images could be spatially mapped by capturing a non-symmetric image before the boiling test. In addition, another HSV camera and high flux LED were installed to visualize the bubble dynamics from side. The frame rates of HSV and IR cameras were at 13 kHz and 1.3 kHz, respectively.

2.3 Numerical processing for heat flux distribution

Transient heat conduction equation for the heater plate was numerically solved by using the measured time-varying temperature distribution data of the boiling surface as boundary conditions using a commercial computational fluid dynamics program (ANSIS CFX and a user defined code which was added to update the temperature boundary condition on the boiling surface for each time step. Adiabatic and symmetry boundary conditions were applied to the bottom and sides of the heater substrate, respectively.

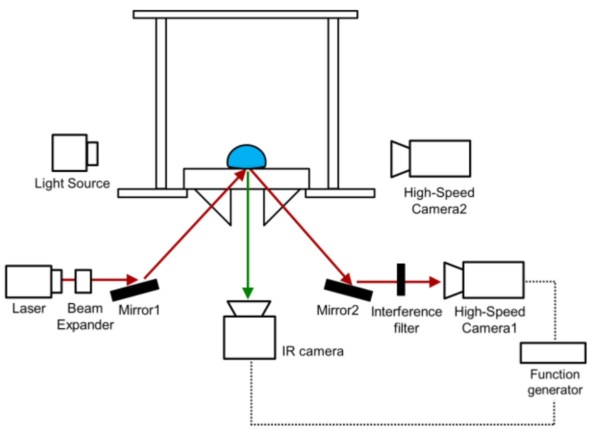

Fig. 1. Schematic of the optical system

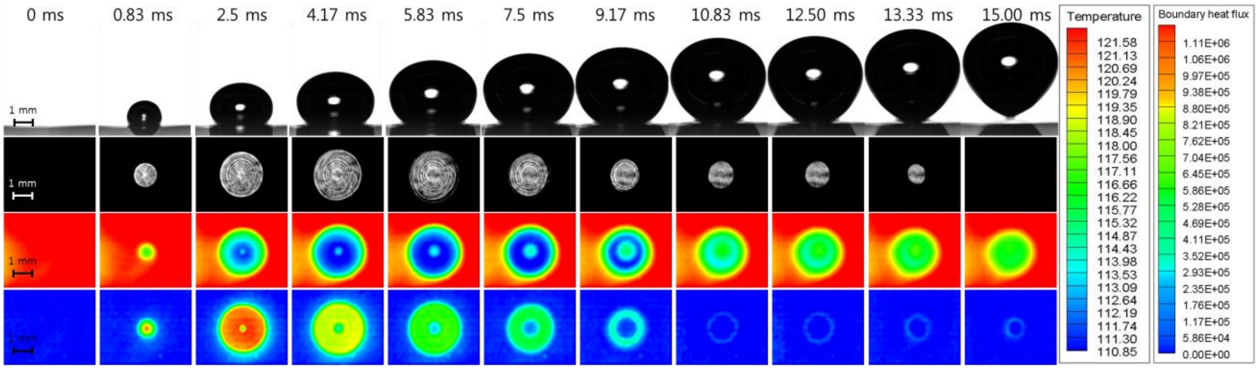

Fig. 2. Visualization results of a boiling bubble and corresponding liquid-vapor phase, temperature, and heat flux distribution on the boiling surface. The images are in the order of the bubble structure, liquid-vapor phase, temperature and heat flux distribution from the top. Units: temperature [℃]; heat flux [W/m^2]. Spatial and time resolution: side view (32 μm, 0.08 ms), phase distribution (17 μm, 0.08 ms), temperature and heat flux (84 μm, 0.8 ms)

3. Results and Discussions

A set of temporally and spatially synchronized measurement data for bubble dynamics, liquid-vapor phase, temperature, and heat flux distributions is presented in Fig. 2. All the data presented in this paper were obtained for single bubble nucleate boiling of water at ΔT_{sub}= 3℃ and q"= 53 kW/m^2 under atmospheric pressure.

Microlayer geometry can be determined from the analysis of the fringe patterns underneath the growing bubbles. Fig.3 shows the microlayer geometries corresponding to the bubbles in Fig.2. In addition, the complete geometry of the boiling bubble at each time step can be determined by combining the macroscopic side view of the bubble.

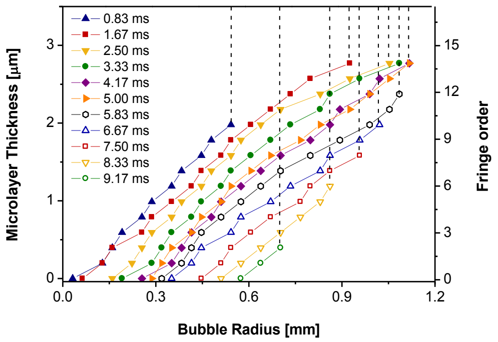

Fig. 3. Geometries of microlayer underneath a growing bubble

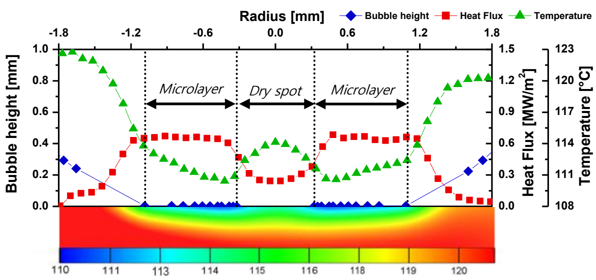

Fig. 4. Boiling bubble shape and phase, temperature, and heat flux distributions on the boiling surface, and temperature distribution in heater plate at 5.83 ms

Figure 4 shows the surface temperature and heat flux distribution spatially mapped with the completed bubble geometry and temperature distribution in the heater plate at 5.83 ms.

It is found that the heat transfer characteristics below the bubble strongly correspond to the regions of the dry spot and microlayer during bubble growth region. In order to assess the contribution of the microlayer evaporation, the total heat flow rate for the bubble growth was estimated from the equivalent bubble radius and the microlayer evaporation heat transfer was calculated by integrating the heat flux values corresponding to the microlayer region. In the present study, the contribution of the microlayer evaporation for the whole growth of a bubble is found to be approximately 17 %.

4. Conclusion

In this paper, the complete geometry of bubbles including dry spot radius, microlayer geometry, and macroscopic bubble shape could be determined by combining the total reflection and laser interferometry

The wall heat transfer distribution underneath a boiling bubble strongly depended on the liquid-vapor phase and microlayer distribution. The wall heat transfer is very intensive on the area where microlayer exists. The contribution of heat transfer through liquid microlayer to the complete growth of a single bubble is estimated to be 17% when neglecting condensation on the upper side of the bubble.

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