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Experimental investigation of wall heat flux partitioning during subcooled nucleate boiling on a vertical wall

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1. Introduction

A number of experimental investigations have been conducted for the understanding of the exact mechanisms of subcooled flow boiling and critical heat flux (CHF). Bang et al. [1] conducted a visualization study of CHF and found evidence of a liquid layer beneath the large vapor mushroom. Geradi et al. [2] measured time- and space-resolved temperature distribution on bubble nucleation and boiling heat transfer on an ITO-film-coated glass heater by means of the synchronized high-speed video and IR thermometry. There also have been many numerical simulation studies on flow boiling heat transfer. Yun et al. [3] performed the studies to improve the prediction accuracy of subcooled flow boiling heat transfer. However, our understanding of the physical mechanism is still not enough to accurately model boiling heat transfer phenomena with application to the high-fidelity computational thermal-hydraulic analysis code. As nucleate boiling heat transfer and CHF occur along with complex mutual interactions of two-phase flow and transient wall heat transfer, a promising way to reveal the exact mechanism may be the spatially and temporally synchronized measurements of the two physical phenomena. Such attempt has not been attempted so far.

This study aims to obtain the spatially and temporally synchronized experimental data of liquid-vapor phase and local heat flux distributions on the heated wall during subcooled nucleate boiling, to analyze the data based on the fundamental physical parameters associated with boiling.

2. Heat partitioning model (RPI model)

The most popular model to predict nucleate boiling heat transfer is the heat flux partitioning model proposed by Kurul and Podowski [4]. It has been adopted in many commercial computational analysis codes. In the model, thermal energy in the heater is transferred to the cooling liquid by three mechanisms: the latent heat flux to form bubbles (q''_e), the heat expended in re-formation of thermal boundary layer, so-called quenching heat flux, (q''_q) and the heat transferred to the liquid phase outside the zone of influence of the bubbles by turbulent natural convection (q''_c). The total boiling heat flux (q''_{tot}) is obtained by a sum of the three fluxes as

$$q''_{tot} = q''_e + q''_q + q''_c \qquad (1)$$

3. Experimental setup

Rectangular parallelepiped shape sapphire substrate of 10 mm in thickness was used as a test sample. A 700 nm thickness ITO (Indium Tin Oxide) film heater (8×15 mm^2) was fabricated on the sapphire substrate. Sapphire substrate has IR and visible transparent optical property. On the other hand, an ITO (700 nm) heater has IR opaque and visible transparent optical property [2][5].

Figure 1 shows the schematic of the optical setup to measure the surface temperature and the liquid-vapor phase distributions on the ITO heater. A flow boiling test section with the vertical flat plate geometry and a forced convection flow loop were constructed. A novel experimental technique which simultaneously measures the liquid-vapor phase and temperature distributions on the heated wall with the full synchronization in space and time was developed for the mechanistic modeling of subcooled convective flow boiling. The spatial and temporal resolutions were 80 μm and 1.3 ms, respectively.

A set of basic experimental data for various wall heat fluxes (85-2118 kW/m^2) of fluid flow was obtained by fixing inlet subcooled temperature, 10 ^{o}C.

4. Results and Discussion

Figure 2 shows the spatially and temporally synchronized experimental results. The data for each time step consists of a temperature, liquid-vapor phase, and partitioning heat flux distributions on the heater surface.

The temperature data was calibrated with a reference temperature from the IR image data. The liquid-vapor phase distribution was a good criterion of heat flux partitioning area. Firstly, the surface area was divided into bubble influence area and convective area (A_c). Secondly, the bubble influence area was separated into the evaporation area (A_e) and quenching area (A_q) according to the bubble dynamics. The temperature distribution data on boiling surface were used to numerically calculate the transient conduction problem for the heated surface using Fluent code. The heat flux distribution ($q''_{w,exp}$) was determined from solving the transient heat conduction equation. The divided heat fluxes ($q''_{e,exp}$, $q''_{q,exp}$, $q''_{c,exp}$) are depend on combination of the heat flux and the liquid-vapor phase distributions by each condition.

Figure 3 shows how we divided the heater areas corresponding to thee heat transfer mechanisms in the RPI model of nucleate boiling. In the experimental data, the total heat flux was partitioned to the three mechanism by 24 % for q''_e, 39 % for q''_q and 37 % for q''_c, respectively. On the other hand, we examined the correlations for the heat partitioning model in Fluent [6] and CUPID [7] to calculate the three heat fluxes. Interestingly, the analyses with Fluent and CUPID presented that the quenching heat transfer is the dominant heat transfer mechanism of subcooled nucleate boiling (~95%). Further studies need to be conducted to clearly understand the reason of the difference.

5. Conclusion

In this paper, the infrared thermometry and the total reflection techniques were spatially and temporally synchronized in during subcooled vertical plate boiling. The three fundamental heat transfer mechanisms in RPI model of nucleate boiling, evaporation, quenching and convection, were separately detected and calculated from the obtained high-resolution experimental data. The contribution of each heat removal mechanism was found to be 24 %, 39 % and 37 %, respectively, while the only quenching heat flux was dominant (~95%) in the analyses using heat partitioning correlation of the commercial and developing computational analysis codes, including Fluent and CUPID.

Acknowledgments

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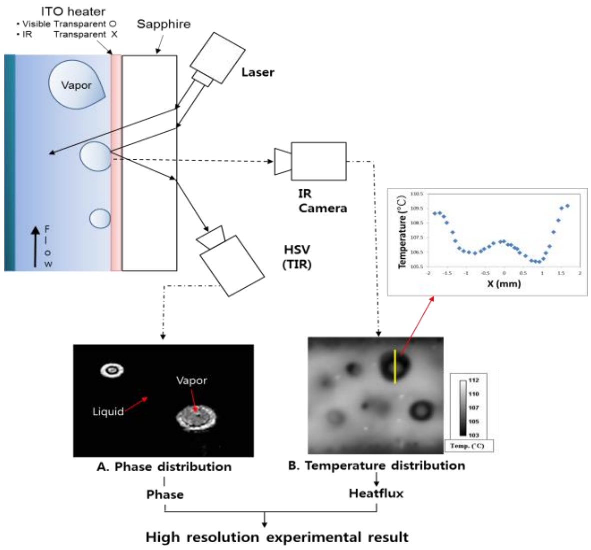

Fig. 1 Schematic of the optical setup for synchronization of total reflection and infrared thermometry.

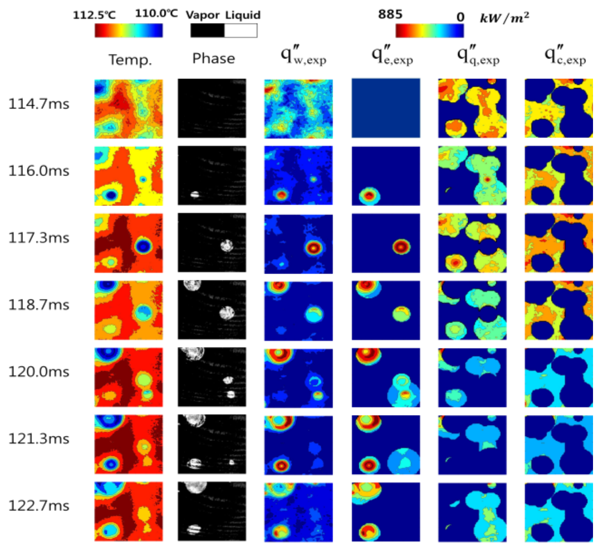

Fig 2. Heat flux partitioning for nucleate boiling in a vertical ($q''_{w,exp}$ = 283 kW/m^2)

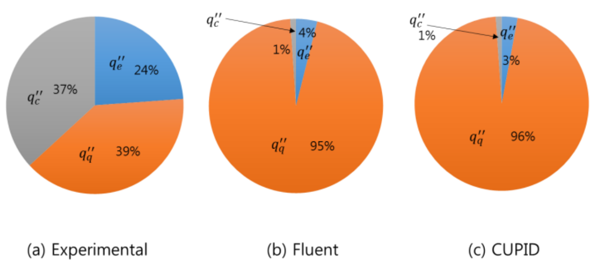

Fig 3. Comparison of heat flux partitioning results (a) measured in the experiment, (b) calculated with the correlations in Fluent, and (c) calculated with the correlation in CUPID ($q''_{w,exp}$ = 283 kW/m^2)