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Visualization of Thermal Field around Boiling Bubble using Rainbow Schlieren Deflectometry: Preliminary Test

Jihoon Han [a], Hyungdae Kim [a*]
[a]*Department of Nuclear Engineering, Kyung Hee University, Republic of Korea*
[*]*Corresponding author: hdkims@khu.ac.kr*

1. Introduction

Nucleate boiling on a heated wall is a complex physical phenomenon involving intense heat transfer with various mechanisms and thus an important thermal-hydraulic phenomenon for safety assessment of a pressurized water reactor. The advanced mechanistic models of boiling heat transfer have been developed for application to computational fluid dynamics (CFD) simulation codes. The use of high-fidelity CFD simulation such as direct numerical simulation (DNS) using interface tracking method is increasing with recent remarkable advances in high performance computing. Hence, to verify the models applied in the codes, high-resolution experimental data of nucleate boiling phenomena is needed for physically accurate prediction.

Temperature field of liquid around a nucleation site or boiling bubble is important information for boiling simulation using a high-fidelity CFD code. Nucleation, dynamics of the boiling bubble even after departure and associated heat transfer processes depend sensitively on the temperature field. Rainbow Schlieren Deflectometry (RSD) is a refractive index-based measurement technique of temperature field in a fluid, which could be appropriate for this application. The research group in India [1-5] first attempted to utilize the RSD technique for the visualization of thermal field in liquid around a boiling bubble. They calculated the temperature field from the RSD images using Abel inversion and also calculated thermal parameters such as liquid-vapor interfacial heat transfer coefficient and contributions of different heat transfer mechanisms.

This research group at Kyung Hee University (KHU) has been investigating theories of the RSD technique and optimizing the experimental setup for application of nucleate boiling heat transfer studies. A basic test of the RSD method was performed in the previous work [6]. In the study, a color filter for RSD and a required optical setup was prepared and applied to a single-phase forced convection heat transfer example as an exercise. The thermal gradient field in liquid on a heated wall were successfully visualized, and the thermal boundary layer profile was detected.

In this work, we modify and optimize the existing optical setup of RSD at KHU for single bubble nucleate boiling in a pool. A dedicated boiling chamber and a heater specimen were designed and fabricated to apply RSD to the single bubble boiling phenomena. The preliminary results of temperature gradient field around a boiling bubble were obtained for a lifecycle and the associated thermal behavior in liquid were discussed.

2. Experiment

2.1 Test rig

Fig. 1 shows a schematic of the experimental setup for RSD. The body of the chamber was made of PEEK for thermal insulation. Two immersion cartridge heaters were installed for bulk heating. At the cap of the chamber, a T-type thermocouple to measure the bulk temperature of the water and a reflux condenser cooled by an isothermal circulation bath to maintain the level of the water were installed. The rectangular sapphire substrate with a thin indium-tin-oxide (ITO) film as a heater on the top was mounted at the bottom part of the chamber. The ITO film was electrically heated via Joule heating.

2.2 Optical setup

Degree of light refraction needs to be precisely quantified for RSD. Thus, it is desired to minimize undesired refractions which distort information in the resulting image. The optical setup needs to be carefully optimized. For example, it is desired to reduce the optical path length in the boiling chamber and maintain flatness of the optical windows less than λ/4.

A white light source with continuous spectrum in visible range was used. The diverging light from the point source was collimated using an achromatic lens and the collimated parallel beam passed the chamber through the optical windows. Then, it was de-collimated using another achromatic lens. A dedicated circular color filter was located at the focal plane of the lens. The center of the filter has a color of zero (red) hue value. The hue value increases with radius and has 2π at the outermost of the filter. In this manner, the degree of the refraction at each location of the resulting image can be quantified by the hue value. That is, when a light without refraction near the heater surface (where the vertical position is zero) passes through the center of the filter, the default red color is observed, while magenta-type color appears when refraction is severe.

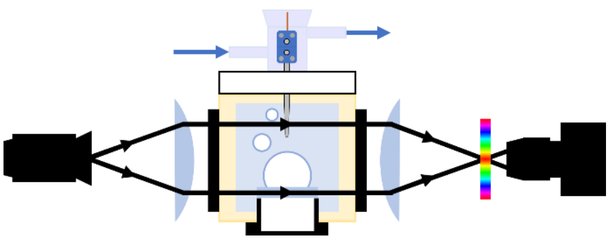

Fig. 1. Schematic of the experimental setup for RSD

The refractive index of water is a function of temperature. Thus, the color distribution in terms of hue value includes information of local temperature gradient field. When there is no gradient, no refraction of the light occurs and an obtained image should be all red (hue value of zero).

2.3 Experimental conditions and uncertainties

Experimental conditions and uncertainties of each values are tabulated in the table I.

Table I: Experimental conditions

	Value	Uncertainty
Spatial resolution (μm)	28.8	0.29
Bulk temperature (°C)	99.7	0.28
Applied heat flux (kW/m^2)	85	0.58
Frame rate (fps)	5000	-

The spatial resolution was calculated by counting the number of pixels along a reference object. The bulk temperature of the water was maintained as the saturated condition and monitored using a thermocouple and a data acquisition system. Uncertainty of the applied heat flux was estimated using the specifications of the used electric power supply.

3. Results and Discussion

Fig. 2 shows the obtained schlieren images. The actual size of the images is 7.6 mm × 9.1 mm. The bottom of the image is the ITO heater surface.

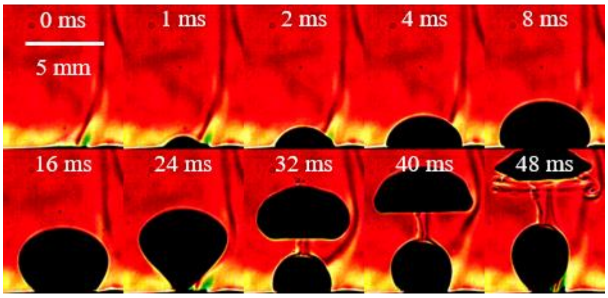

Fig. 2. Color contour images obtained using RSD

There is a dark plum in all time steps rising from near the nucleation site, and some dark regions are also observed in the bulk region. Using the color images in Fig, 2, it is hard to judge whether they are signals or noises. In principle, the RSD contains meaningful signal only as the hue value in the HSV (Hue, Saturation, Value) color system. Therefore, for more appropriate qualitative interpretation of the images, only the hue value was extracted from the color contour images in Fig. 2 (see Fig. 3). The hue value of 0.2 in Fig. 3 was highlighted with black solid lines, which seems to be the borderline of thermal boundary layer of superheated liquid on a heated wall.

The bubble nucleates, grows rapidly inside the superheated liquid and the growth rate decreases when the bubble becomes larger than the layer thickness. The departed bubble carries some superheated liquid layers at its tail (see the bubble base at 32 ms and 40 ms). This is called scavenging of superheated layer [1-2]. The shape of the departed bubble changed from spherical to a hat shape due to drag [2]. With the change of the shape of the bubble, superheated liquid carried at the tail of the bubble is also disrupted and makes yellow wake flow at 48 ms.

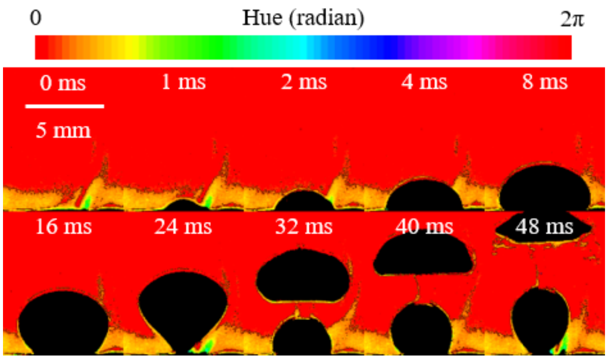

Fig.3. Hue distribution images extracted from the color contour images

To get more insights from the results, the images at 0 ms and 48 ms were drawn in 3D, as shown in Fig. 4. The projected 2D contours corresponding to the images of the Fig. 2 were also presented. As previously interpreted, it is certain that the thermal boundary layer exists near the heater surface where the hue values are relatively high (highlighted in yellow and green) in both time steps. In addition, the superheated liquid layer is observed at the tail of the departed bubble and the peripheral of the next bubble at 48 ms. This may be the scavenging phenomena of the superheated layer due to bubble dynamics.

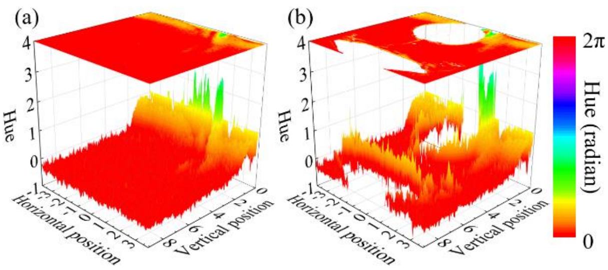

Fig.4. Hue distributions at (a) 0 ms and (b) 48 ms

4. Conclusion and future works

RSD was applied for a nucleate pool boiling at saturated condition. The obtained images were qualitatively interpreted in terms of the thermal behavior of the liquid around boiling bubble. The thermal boundary layer and scavenging of superheated liquid were observed through hue distribution.

Further studies are required to minimize the distortion of the image by optimizing the working distance, focal length of used lens and the radial size of the color filter. In addition, a study to extract temperature field from the obtained schlieren images using Abel inversion is needed.

ACKNOLEDGEMENT

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