Pretest of Rainbow Schlieren Deflectometry for Measurement of Thermal Boundary Layer Thickness

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1. Introduction

Boiling heat transfer is important physical phenomenon for thermal hydraulic safety design and analysis of PWR. Therefore, various experimental researches have been performed to improve or verify the models applied in codes for improve accuracy of thermal hydraulic safety analysis. In recent, based on fast development of computer engineering techniques, the use of CFD codes that perform analysis by simulating the actual shape of bubbles directly using the surface tracking technique is increasing, thereby emphasizing the need for high-precision experimental results to verify the analysis results.

In interpreting wall boiling heat transfer using high-precision CFD code, the temperature field information of the liquid around the heating surface is a key factor that greatly affects the heat transfer analysis related to the entire process of boiling air bubbles, and various studies have been attempted to measure the results of code analysis to verify the results of the code analysis.

Rainbow Schlieren Deflectometry (RSD) is one of the refractive index-based optical fluid temperature field measurement techniques that have been widely used mainly for flame or gas jets since its emergence in NASA's technical documents in the 1980s, and it is quite recent to be used in analysis of heat transfer in boiling or natural convection situations and calculation of temperature fields. RSD provides non-intrusive real-time target, especially RSD is specialized in visualizing the gradient of the physical property, enabling more intuitive observation of the distribution of physical property. In addition to qualitative observation, quantitative analysis of color distribution allows investigation of heat transfer phenomenon related to various boiling phenomenon as well as temperature field calculations. For example, Srivastava et al. [1-5] applied RSD to pool, flow boiling situations and studied single bubble boiling heat transfer phenomena for various variables such as superheating, subcooling, and flow rate. Applying RSD, they calculated temperature field and local heat transfer coefficients and divided heat transfer process in various sub-processes such as evaporative heating of microlayer, superheat layer around bubble and natural convection of rest of heater substrate.

Dividing heat flux, so-called heat flux partitioning or RPI modeling is one of most common and popular approach for wall boiling modeling. Local temperature of whole measurement field including away from the heating wall, especially, is also very important as well as that of near wall. Accurate away wall temperature information contributes to behavior of departured bubble in bulk region and to improvement of accuracy of CFD codes. RSD can offer this information in non-intrusive way and this is most advantage of it.

In this study, feasibility test of RSD was performed in simple situations before applying this methodology to various boiling phenomenon. To perform this, an image of schlieren was taken, varying the applied heat flux under the conditions of low flow rate and upward boiling. The color distribution of the image was analyzed to specify the thickness of the thermal boundary layer.

2. Apparatus and Instrumentation

In this section, optical setup for RSD, flow loop and test section are described. Mechanism of RSD method and data reduction are also explained.

2.1 Optical system

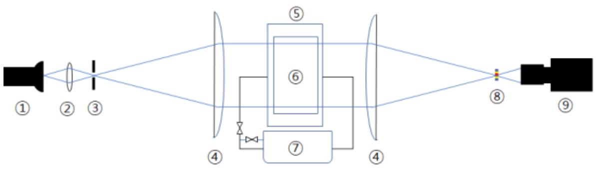


Fig. 1. Schematic of experiment setup for RSD

In Fig. 1, ① is white light source which has continuous spectrum in visible region. The light is focused on ③ pinhole of diameter of 500 μm by ② condensing lens. The light diverging after pinhole is collimated by ④ Plano-convex lens. The parallelized light passes ⑤ test section through ⑥ optical windows. Another plano-convex lens de-collimates the light and the light passes the center (red) of ⑧ color filter which locates exact focal plane of the de-collimating lens. Finally, the light which has only red enters to the camera.

2.2 Test section and Flow loop

The test section has optical windows of glass and 35 mm x 10 mm x 500 µm silicon wafer as the heater material. 25 mm of 35 mm is actual heating length. In order to fully develop the flow, sufficient length of entrance channel was installed. Bulk temperature and flow rate were adjusted to 20 ℃ and 0.5 LPM through ⑦ isothermal circulation water bath and bypass line of outlet of the bath.

2.3 Principles of RSD

Since the refractive index of water is a function of temperature, a refractive index gradient occurs when there is a temperature gradient. The light passing through these gradients field is refracted and consequently passes not the center of the color filter but the other point (not red). Through quantitative design of color filter, the functional relationship between the color variation and temperature gradient can be made. In this respect, color of the filter changes continuously in order of red (0°), yellow (60°), green (120°), blue (240°), and purple (300°) according to H(color) value in HSV color space which is the color quantifying system by hue, saturation and value.

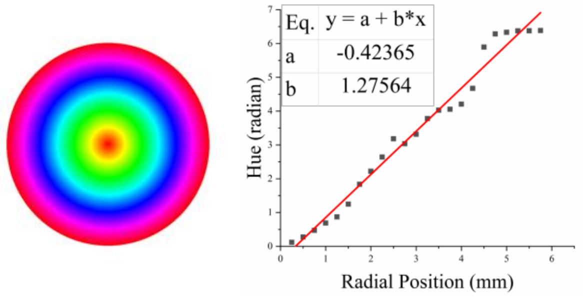


Fig. 2. (a) Design of color filter, (b) Calibration curve of the color filter

In Fig. 2 (a), the circular radial color filter image produced by MATLAB code is presented. Fig. 2(b) shows the calibration curve of the color filter. Calibration was performed by moving the filter from center to radial direction in step of 250 μm and measuring hue values. The quantitative design and manufacture of the color filter was explained in Greenberg et al. [6].

2.4 Resolution and Uncertainty

In the respect of feasibility and reliability of these method and experiment, resolution and uncertainty analysis were performed. Results are tabulated in the table 1.

Table 1. Resolutions and Uncertainties of parameters

Parameter (Units)	Resolution	Uncertainty
Spatial (μm)	18.857	18.857
Bulk temperature (°C)	0.001	0.20908
Volume flow rate (LPM)	10^{-6}	0.028216

3. Results and Interpretation

Fig. 3 represents the obtained schlieren image by heat flux of the heated surface. Each image is 1324 x 570 pixels. Since there is no temperature gradient of bulk area, the light still passes through the center of the filter and shows red hue and the temperature gradient layer was observed in the area presumed to be the thermal boundary layer near the heating surface. Enlarged image of marked part of Fig. 3(b) is presented in Fig. 3(e).

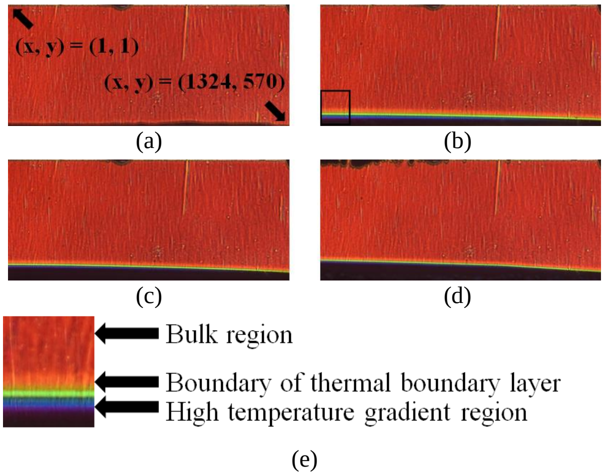
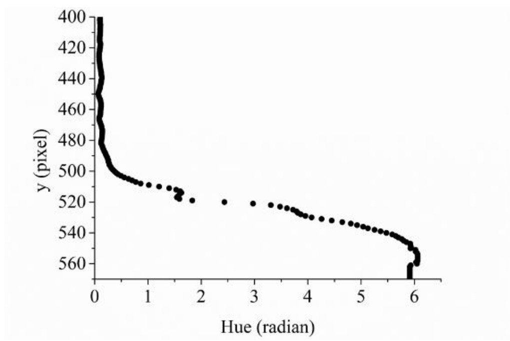
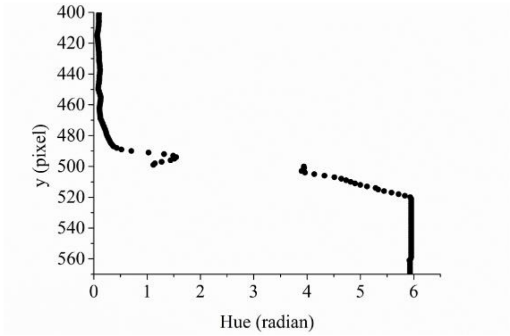


Fig. 3. Rainbow schlieren image at heat flux of (a) 0 kW/m^2, (b) 10 kW/m^2, (c) 50 kW/m^2, (d) 90 kW/m^2 and (e) enlarged image of marked part of (b)

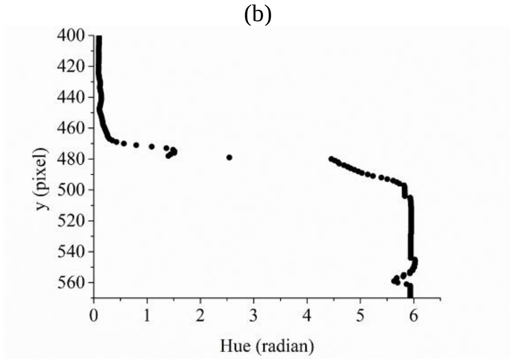
Fig. 4 is an analysis of hue distribution of 10 x 170 pixels from left and bottom side. Plotted hue values are average values of ten x of each y. It can be seen that the hue value in the bulk area is nearly constant to zero and then rapidly increases as the thermal boundary layer begins. We assumed that pixel has hue value over 0.2 is starting point of thermal boundary layer. This analysis provides the number of pixels of thermal boundary layer and multiplying the pixel size results thickness of thermal boundary layer. Those are 82 pixels (1.536475 mm), 95 pixels (1.7800625 mm) and 111 pixels (2.0798625 mm) in order.



(a)



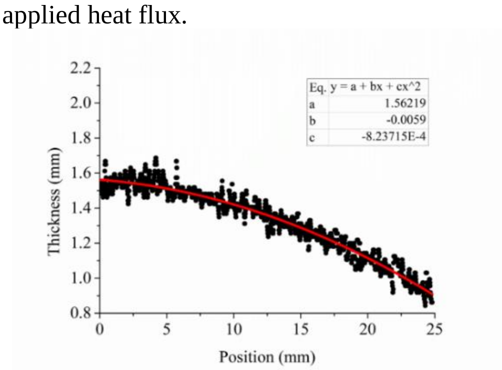
(b)



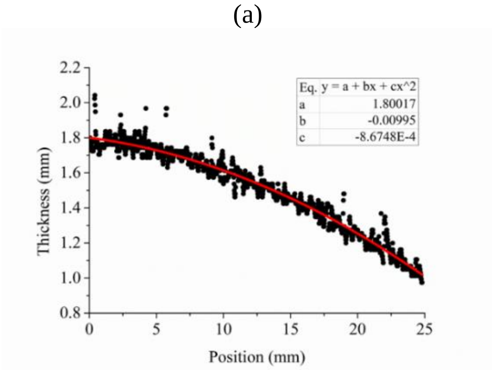
(c)

Fig.4. Hue distribution of the area of analysis of (a) $10\ \mathrm{kW}/m^2$, (b) $50\ \mathrm{kW}/m^2$, (c) $90\ \mathrm{kW}/m^2$

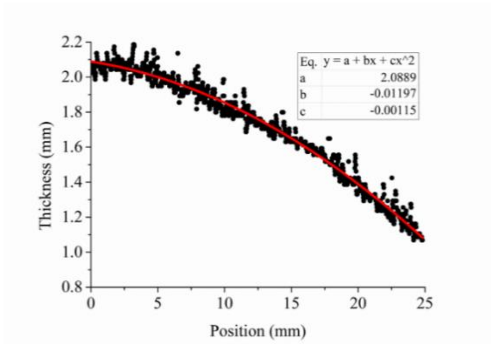
Through applying this analysis to whole columns of images, thickness profiles of thermal boundary layer are obtained in Fig. 5. To remove noise of profile, a pixel that average hue value of five pixels including itself is larger than 0.2 is pointed as a boundary of thermal boundary layer. Fig. 5 shows trends that the thickness of thermal boundary layer increases along flow direction and applied heat flux.



(a)



(b)



(c)

Fig. 5. Thickness profile of thermal boundary layer of (a) $10\ \mathrm{kW}/m^2$, (b) $50\ \mathrm{kW}/m^2$, (c) $90\ \mathrm{kW}/m^2$

4. Conclusions

A set of experimental tests were conducted to examine capabilities of Rainbow Schlieren Deflectometry (RSD) as means of measurement methods for liquid temperature field and thermal boundary layer thickness for single-phase convective flow. The obtained experimental data demonstrated that two-dimensional profiles of thin thermal boundary layer can be reasonably visualized and quantitatively measured using the RSD technique. Further studies are required to reduce geometrical distortion of two-dimensional temperature field images due to light refraction and uncertainty in temperature measurement.

ACKNOLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018M2B2A906584122).

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