Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Feasibility Study of Wall Temperature Measurement Method using Temperature-Sensitive Fluorescent Material for Application to High-Pressure Flow Boiling Experiment

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1. Introduction

The design and safety evaluation of a nuclear power plant cooling system and major accident response facilities entails the analysis of subcooling boiling heat transfer phenomena. Recently enhancement of computing power and numerical analysis, analysis of thermo-hydraulic phenomena using computational fluid dynamics (CFD) has been actively attempted, breaking away from system codes (MARS, RELAP, etc.) based on the lumped model. In CFD analysis, a wall boiling model based on a mechanistic model such as the RPI model of Kurul and Podowski [1] is most used.

The wall boiling model based on mechanistic correlation calculates total heat transfer by deriving the bubble-related physical factors (bubble diameter, departure frequency, waiting time, etc.) as auxiliary equations for the wall temperature. Auxiliary equations for calculating each factor are developed through experimental research that visualizes the bubble behavior while measuring the wall temperature.

However, under high temperature and high pressure (15 MPa ~300°C) conditions of PWR, the size of the boiling bubble is reduced to ~10 μm. The infrared (IR) thermal imaging technique currently used for wall temperature measurement has been judged to have technical difficulties in applying to high-pressure boiling experiments due to the following two limitations: absence of high-magnification optical equipment in the infrared region and signal attenuation due to thick high-pressure visible window.

To overcome the limitations of this IR thermal imaging technique for high-pressure boiling experiment application, this study intended to utilize a temperature-sensitive fluorescent material that emits the wavelength of the visible light region. In this study, the wall temperature was measured using a temperature-sensitive fluorescent material and the feasibility test was performed through the droplet-wall collision boiling experiment. Finally, we intend to confirm the possibility of using it for surface temperature measurement in flow boiling experiments under high temperature and high pressure conditions.

2. Theory and Experiment

2.1. Fluorescence Intensity Ratio

When the fluorescent material is irradiated with ultra-violet (UV) wavelength light, the electron of the material is excited and emits fluorescence for the stabilization. Fluorescent materials have many temperature-dependent characteristics, among which FIR technology was chosen for fast optical imaging and accurate measurement regardless of disturbances.

Two wavelengths used for FIR technique are characteristic wavelengths that change according to each material. When UV is irradiated to the fluorescent material, it is excited and emits fluorescence to be ground state. Suitable materials for FIR technique have two or more characteristic wavelengths that respond sensitively to temperature. The ratio of two characteristic wavelength intensities has the following relationship with temperature shown in Eq. (1),

$$\mathrm{FIR} = \frac{I_A}{I_B} \propto e^{-\frac{\Delta E}{\kappa T}} \qquad (1)$$

$$\ln(\mathrm{FIR}) = \left(\frac{\Delta E}{\kappa}\right)\left(-\frac{1}{T}\right) \qquad (2)$$

where ΔE is the difference of instinct energy level value and k is Boltzmann' constant. Both values are independent to temperature. Therefore, Eq. (2) represents the linear relationship between FIR value and absolute temperature.

As described above, if the intensity of the two characteristic wavelengths from temperature-sensitive fluorescent material generated with UV laser is extracted, the temperature of the substrate can be calculated through the above relations. Fig. 1 shows the fluorescence intensity tendency of material according to temperature [2].

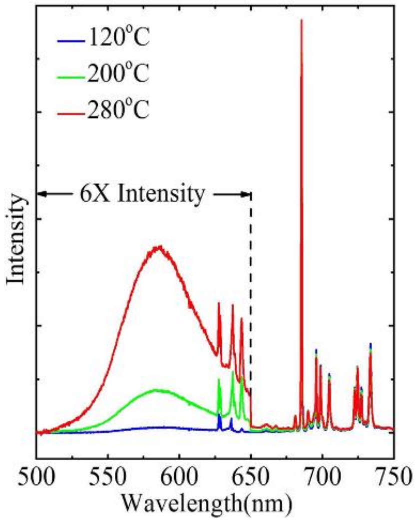

Fig. 1. Spectroscopy result according to temperature of $SrB_4O_7{:}Sm^{2+}$ [2]

MATLAB was used to analyze the fluorescent images. Since the RGB does not stands out for intensity, preferentially the color information was converted from RGB system to HSV system, which presents hue, saturation, value. After converting the system, the image processing was performed by specifying the interested region.

2.2. Test apparatus

Experimental apparatus for fluorescence characteristics and droplet-wall collision boiling experiments of temperature-sensitive fluorescent materials is as shown in Fig. 2. The experimental apparatus is divided into 3 parts: fluorescent materials & samples, excitation part, and fluorescence measuring part.

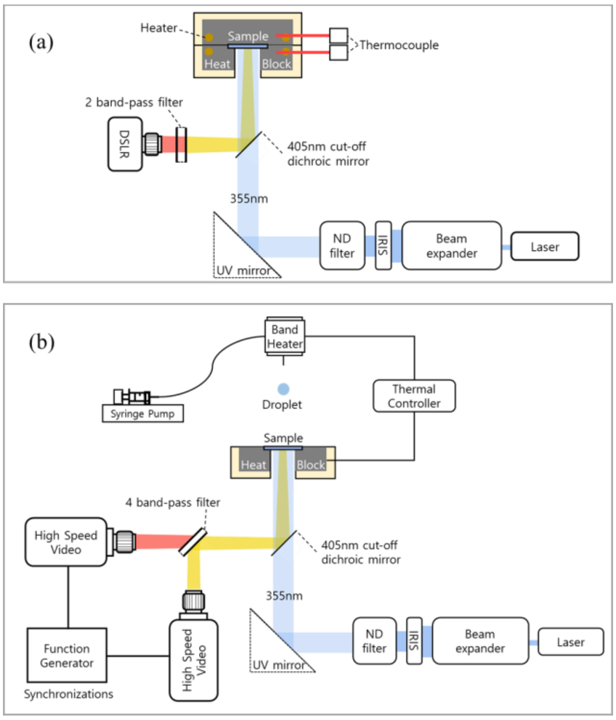

Fig. 2. Schematic of experimental setup (a) Fluorescence measurement experiments according to the temperature of the fluorescent material, (b) Droplet-wall collision boiling experiment

2.2.1. Fluorescence material & sample

The fluorescent material was selected as a candidate material for YAG:Dy [3], Y_2O_2S:Sm [4], ZnO:Ga [5], $La_2O_2O_2S$:Eu, SrB_4O_7:Sm^{2+} [6], YVO_4:Eu $^{3+}$ and finally selected as SrB_4O_7:Sm^{2+} considering the temperature range, characteristic wavelength, sensitivity, and fabrication. The selected fluorescent material was deposited by electrophoretic deposition (EPD) on the soda-lime glass on which the ITO was deposited. The experiment was performed with four substrates according to the deposition time. The types of substrates are shown in table I. below.

The heating of the substrate was in-direct heating by inserting four cartridge heaters into the heating block made of SUS, and one thermocouple (TC) was inserted to measure the temperature.

Table I: Sample deposition conditions

Sample name	EPD-1	EPD-2	EPD-3	EPD-4
Deposition time (sec)	120	60	30	120
Restoration	X	X	X	O

2.2.2. Excitation part

For the excitation of fluorescent materials, Canlas' CP460 pulse UV laser was used. The beam, injected at 1,000 Hz and 2.5 W, increased the area and reduced power density through the Beam expander. The substrate was then irradiated with the desired beam intensity by passing through the iris to create the desired beam area and then passing through the appropriate ND filter.

2.2.3. Fluorescence measuring part

Two measurement methods were used for fluorescence measurement of characteristic wavelengths emitted from the substrate. Fig. 2(a) assumed that the sample's temperature was in a steady state and then fluorescence was captured with a Long & Short pass filter set suitable for each characteristic wavelength and Nikon's D5100 DSLR, SIGMA EX lens. Fig. 2(b) shows the addition of a droplet-dropping device, and dynamic wall temperatures were imaged by separating the fluorescence with a dichroic mirror with a cut-off wavelength of 605 nm, and then shot each with two synchronized high-speed videos (HSV).

3. Results

3.1. Characterization of temperature-sensitive fluorescence material

Fluorescence measurement experiments according to the temperature of the fluorescent material were performed in the range of 300°C to 400°C to simulate a boiling situation of high pressure (15 MPa) as shown in Fig. 2(a). The exposure time of the measurement HSV was maintained at 100 ms, and the fluorescence intensity of the acquired image was taken on a spatial average and then to ratio. Fig. 3 is the result of FIR sensitivity analysis of thin film deposition time. The sensitivity increases as the thin film deposition time increase. Among them, EPD-1 showed the highest temperature sensitivity.

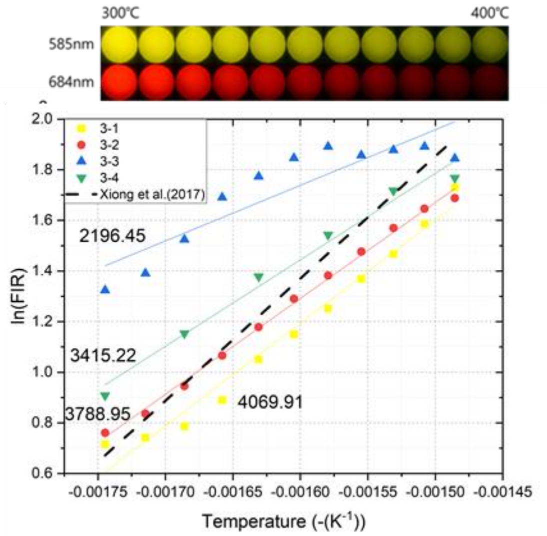

Fig. 3. Spatial average FIR value for each sample

According to the previous study [2], as the temperature increases, the intensity of the short wavelength among the characteristic wavelengths increases, and the intensity of the long wavelength tends to decrease. In this study, as the image was taken by making a narrow wavelength gap through the Short & Long pass filter set, it did not represent the characteristic wavelength and was affected by the strong surrounding long wavelength band, so the results were contrary to the previous research at the short wavelength. As the temperature increased, the brightness of the short-wavelength region tended to darken. But the FIR value showed a linear increase with the temperature as shown in the previous study, reflecting the tendency of the characteristic wavelength.

3.2. Droplet-wall collision heat transfer experiment

Using the temperature sensitivity of fluorescent materials, a droplet-wall collision boiling experiment was performed. The substrate used EPD-1, which had the highest sensitivity. Fig. 4 compared the results of the FIR technique with the IR thermal images previously measured in this research group. Fig. 4 measured the wall temperature at 1000 fps by dropping a droplet of 95℃ on a heating substrate at 245℃.

As in Fig. 4, the temperature tendency of the IR thermal image measurement result and the FIR thermal image measurement result is very similar. Since the two experiments were not designed and performed simultaneously, there was no control over the size of the droplet, and the specific heat of the substrate. In addition, adhesion problems in the EPD thin film caused the phosphor to be placed on the opposite side of the droplet impact surface. Although the two experiments were not performed under perfectly identical conditions, it is determined that the FIR technique can measure the dynamic wall temperature change because the measurement results of the two droplet-wall impact heat transfers show the same temperature behavior.

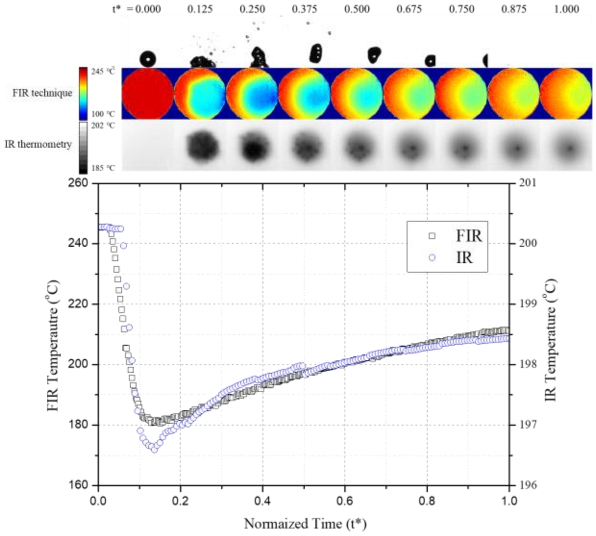

Fig. 4. Comparison of IR thermal imaging method and FIR technique of droplet-wall collision boiling experiment

4. Conclusion

In this study, the FIR technique for measuring surface temperature was performed by considering high-pressure boiling conditions. The result of the feasibility test indicates a linear change of FIR value according to the temperature. The dynamic temperature change of the surface could be measured with high-speed shooting at 1000fps. Through this study, it confirmed that the FIR technique may be used to measure the boiling surface temperature. After improving the durability of thin film, further research will be carried out by applying it to actual flow boiling experiments.

ACKNOWLEDGMENTS

This work was supported by a grant from the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT: Ministry of Science and ICT) (2019M2D2A1A0205936412).

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