Development of Surface Temperature Measuring Method by Thermal Liquid Crystal for Simulated Fuel Rods

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1. Introduction

After the Fukushima nuclear power plant disaster, the thermal behavior of fuel rods with a protective coating for low oxidation and high heat transfer became important, to prevent hydrogen generation leading to a potential nuclear accident.

Information regarding the surface temperatures of fuel rods is important for developing safer, more effective fuel rods and spacer grids. [1-3] Due to the difficulty of an actual fuel rod test, simulated tests are useful for investigating thermal behavior and integrating the data into the design of new fuel rods. The present work was performed to develop a surface temperature measuring technique for fuel rods by using thermal liquid crystal. The color information of the liquid crystal was used to calibrate as a function of temperature and angle from surface normal. The heat transfer from simulated fuel rods was tested, and the measured thermal characteristics analyzed and discussed.

2. Experiment

2.1 Experimental Apparatus

The concept of the present experiment was to develop a non-contact temperature measuring method by recording visual images, under lights, of thermal liquid crystal on a simulated fuel rod. The 2.5-times scaled-up model of the 3 x 3 fuel rods and space grid was made and tested in the air instead of the water. Fig. 1 shows a schematic diagram (cross section) of the fuel rod tested in the present work. The rod pitch to diameter ratio (P/D) was 1.35, and it was installed in a bundle of rods in a transparent acrylic channel. The test rod in the center had a 25 mm outer diameter and a 2.5 mm thick wall of stainless steel 316. A cartridge heater was fitted into the tube; the heater's specifications were 16 mm diameter, 250 mm length and 70 ohms. Liquid crystal whose color play started at 20°C and ended at 30°C (Hallcrest, SPN100, R20C5W) and black paint were uniformly painted on the rod exterior. Six K-type thermocouples were embedded along its peripheral and longitudinal directions in order to calibrate the liquid crystal. Eight neighbor rods made of Pyrex glass and having the same dimensions as the center rod were installed to give periodic hydraulic boundary conditions.

The test rod and channel were installed in a wind tunnel so that the air would flow parallel to the rod length. The inlet air velocity was in the range of 6.2-13.1 m/s (Re=27,900-56,900) and the heat flux was changed at 303-614 W/m^2. An inlet heat exchanger was used to control the incoming air temperature; it was connected to a constant-temperature water bath. Two digital cameras (Samsung, NX 20) were set up at 0 and 22.5 degrees, with two white lights (10W), as shown in Fig. 1.

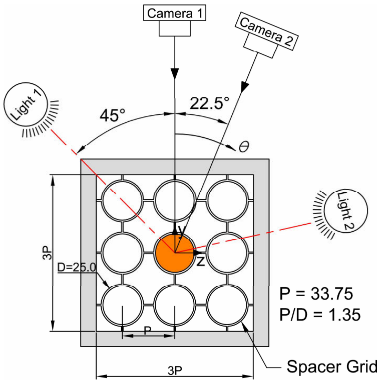


Fig. 1. Schematic diagram (cross section) of simulated fuel rod tested in the present work.

2.2 In-Situ Calibration

The present work conducted an in-situ calibration of the thermal liquid crystal color to temperature. Air velocity was about 3 m/s, and inlet temperature maintained at a constant value in the bandwidth of the liquid crystal color play by the inlet heat exchanger. It was assumed to be steady state when all wall temperatures stayed within 0.2°C for more than 10 minutes. Digital images from the cameras and the wall temperatures were recorded. The inlet temperature was shifted within the bandwidth of the liquid crystal color play, and images taken and wall temperatures recorded again. This process was conducted numerous times to complete the calibration.

2.3 Experiment

For the heating test, the inlet heat exchanger in the front of the wind tunnel was held constant at about 5°C below the starting temperature of the liquid crystal, and the air velocity was constant as well. The input voltage of the cartridge heater was controlled to show the full color play of the liquid crystal on the test rod. When the color play and wall temperatures reached the steady state, the liquid crystal images from 0 and 22.5 degree angles, inlet velocity and wall temperatures were recorded. The images were converted to hue values and processed to get temperatures and heat transfer coefficients.

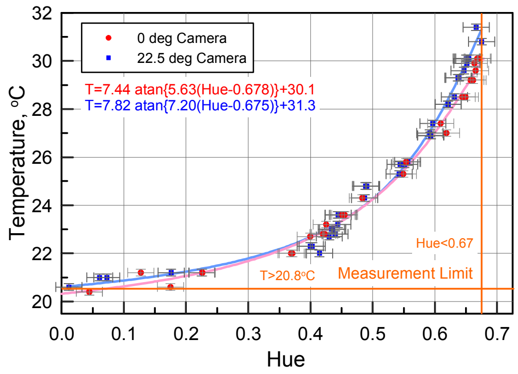
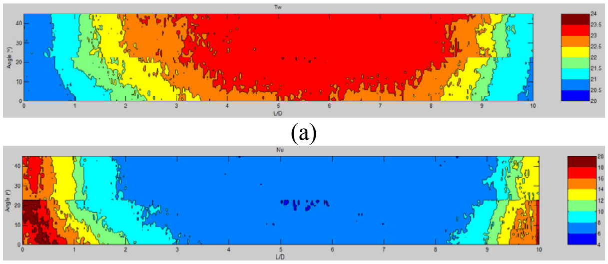


Fig. 2. In-situ calibration curve of the thermal liquid crystal on the simulated fuel rod in the present work.


(a)

(b)

Fig. 3. Distribution of simulated fuel rod (a) surface temperature (b) Nusselt number for air, Re=43,000, u_{in} = 7.76 m/s, T_{in} = 19.3°C, q''=194 W/m^2.

3. Results and Discussion

3.1 Calibration Curve

Fig. 2 shows the calibration curves of cameras 1 and 2 in Fig. 1. The data fit the arc tan function reasonably well: $T=B\tan^{-1}[S(\text{Hue}-H_e)]+T_e$ as proposed by Kang et al. [4]. The coefficients B, S, H_e, and T_e show the bandwidth of color play, sensitivity, high disappearing hue and temperature. The calibration curves of the cameras were affected by the curvature, reflection angle and lighting system. The present calibration function follows the periodic color play nature well and satisfies the measured data statistically as well.

3.2 Surface Temperature

Fig. 3 shows the surface temperature distribution of the fuel rod for u_{in}=7.76 m/s. The horizontal and vertical axes show the flow directional length to the rod diameter (x/D) and the angle (θ) from Fig. 1. The surface temperature of the rod increases along the flow direction from the leading edge up to x/D~5, then decreases. The temperature is low at θ=0°, where the inter-rod distance is minimum, so the local velocity gradient is maximum. The temperature is high at θ=45°, where the bulk velocity is the smallest.

3.2 Heat Transfer Coefficient

Fig. 4 shows the Nusselt number distribution on the center rod surface for Reynolds numbers of 43,000. For constant heat flux conditions, the Nusselt number is the inverse function of the difference between the inlet and wall temperatures. Therefore the Nusselt number on the fuel rod is minimum at x/D~5 and θ=45°. This trend is similar to the measurements of Holloway et al. [1].

4. Conclusions

The present work was performed to develop a surface temperature measuring technique for fuel rods by using thermal liquid crystal. The following conclusions were reached in this study:

An experimental apparatus and method were developed to measure the surface temperatures of a fuel rod in a rod bundle. An in-situ calibration method and calibration function as a form of the arc tan function were proposed, and the calibration function had good results in the present work. The surface temperature of the fuel rod minimum was at x/D~5 and θ=45° in the present test range.

Acknowledgements

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