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A new method of temperature measurement using thermochromic liquid crystals (extension of measurable range based on spectral intensity in the narrow-band wavelength)

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ABSTRACT

This paper describes the extension of the measurable range of temperature measurement using thermochromic liquid crystals (TLCs). In the proposed method, the temperature is uniquely determined by measuring only a single optical parameter: the spectrum intensity of the scattered light at a specific wavelength. In the first stage of the study, the relationship between the spectrum intensity of the scattered light at the TLC and temperature of the heat transfer surface was investigated. It was found that a white LED had more favorable features than a halogen lamp, and thus was suitable as a light source for the proposed method. Using the white LED, the range of the measurable temperature achieved by the proposed method, 27–60 °C, was approximately three times as broad as that by conventional methods that use mapping of the color change of TLCs, 32–42 °C. In the second stage, the proposed method was applied to measurement of the two-dimensional temperature distribution over a planar heat-transfer solid surface. The range of the measurable temperature with a temperature resolution of 0.1 °C was found to be 28–46 °C, which is approximately twice as broad as that by conventional methods using TLCs, 32–42 °C.

1. Introduction

Accurate and instantaneous measurement of temperature distribution over heat transfer surfaces is necessary in evaluating the thermal performance of heat exchangers as well as in the development of devices with high heat-exchange performance. Thermochromic liquid crystals (TLCs) are increasingly being used as an accurate and convenient means of measuring surface temperature and heat-transfer coefficient because their optical properties are dependent on temperature in a predictable and repeatable manner [1–6]. TLCs, whose molecular structure changes with temperature, selectively reflect light at a wavelength characteristic of the local surface temperature. The reflected light is within the visible color spectrum. Namely, TLCs change their color with temperature, and this change is the basis for their application in heat transfer research. In the general application of TLCs for temperature measurement, a heat transfer solid surface is coated with a water-based slurry of TLCs, or is covered with commercially available TLC sheets [7]. To measure the temperature in a liquid, microencapsulated TLCs are mixed into a volume of a solvent to form a suspension and visualize the color distribution.

One of the most important aspects of using TLCs is the color-temperature interpretation. Akino et al. [8] proposed a method to determine an isothermal map on a heat transfer surface coated with a cholesteric liquid–crystal layer that changes color according to temperature. The scattered color on TLCs at a certain temperature is composed of three colors: red, green and blue (RGB). Akino and colleagues focused on the intensity (brightness) of the RGB, and expressed temperature as a function of this intensity; they then developed a regression equation based on this relation between intensity and temperature. Using their method, the range of the measurable temperature was found to be about 6–7 °C. Dabiri et al. [9] focused not on intensity, but hue. In their method, the hue value increased with temperature when the color of TLCs was mapped from the RGB color space to the HSI color space (H: hue; S: saturation; and I: intensity). Errors generated by the color mapping were greatly minimized by applying spline functions for

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Nomenclature

F_0	geometric factor	ε	absolute reflectance
I_0	intensity of the light source [W/m^2]	λ	wavelength
I	spectrum intensity of the scattered light		
L	optical factor	*Subscript*	
R	relative reflectance	i	uniform temperature
S	sensitivity of the camera	w	white calibration plate
T	temperature [°C]	λ	wavelength
T_s	exposure time of the camera [s]		
x, y	coordinates of the image		
α	correction factor		

interpolation. In this method, the range of measureable temperature was found to be ~4 °C. Fujisawa et al. [10,11] applied all of the optical parameters, H, S and I, to more accurately extrapolate temperature from a visualized image. The values of H, S and I were expressed as functions of the measured temperature, and thus temperature could be estimated numerically by solving the set of equations of H, S and I.

In previous methods, temperature has been evaluated by adopting a temperature-color interpretation in which the color change of TLCs was quantified with some means of interpolation. As a result, the range of the measurable temperature is restricted by that of the visible color change of TLCs. Although the rapid development of image-processing techniques has led to inexpensive systems that provide real-time, full-field temperature measurement using TLCs, the range of the measurable temperature is still limited to that of the color change of TLCs even with currently available methods using TLCs [12]. In this paper, we attempted to extend the range of the measurable temperature as much as possible by adopting the spectrum intensity of scattered light at TLCs, instead of the color appearance of TLCs, as the measure of the temperature evaluation. Specifically, the spectrum intensity of short wavelength light scattered at the TLC, which has been mostly overlooked in heat transfer research in the past, was employed as the primary tool of the temperature identification. The results using the TLC with the range of color change 32–42 °C showed that the range of the measurable temperature achieved by the proposed method (27–60 °C) was approximately three times as broad as that by conventional methods.

2. Experimental apparatus and procedures

The experimental apparatus shown in Fig. 1 was used to test the proposed temperature-measurement method using the spectrum intensity of scattered light. The apparatus consisted of an optical receiver, a halogen lamp with an infrared cut-off filter and a water jacket. A choresteric-type TLC sheet (Japan Capsule Products Co., Ltd.) and type T thermocouples were set on the surface of a water jacket that was made from a 20 mm thickness aluminum plate. The surface temperature of the water jacket was kept constant by circulating the temperature-controlled water through a thermo-chiller. The optical receiver was set in the vertical direction with respect to the plane of the TLC sheet and placed right above the measuring point. The halogen lamp was placed above the TLC sheet with its lighting direction tilted 45° against the surface normal of the TLC sheet. The infrared cut-off filter was set in front of the halogen lamp to prevent infrared heating of the TLC sheet by the illumination light. The spectrum intensity of the scattered light was measured by a multi-channel-type spectroscope (Soma Kogaku Co., Ltd.; S-2431). The experimental apparatus was placed in a dark enclosure to shield it from external illumination disturbances. The experiment was carried out by varying the temperature of the TLC sheet from 20 °C to 60 °C in increments of 1 °C. The temperature range of 20–60 °C was broader than that of the color change of the TLC sheet (32–42 °C). The measurement was repeated 100 times for each temperature to minimize uncertainties, and the average values were used for analysis.

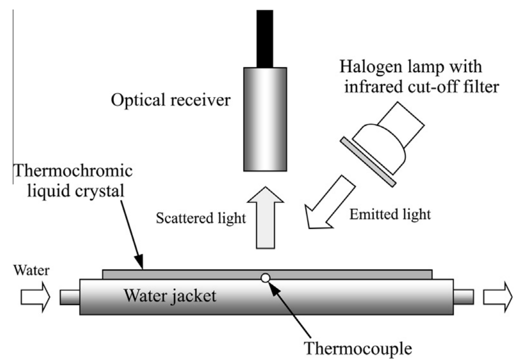

Fig. 1. Schematic of the experimental apparatus.

3. Results and discussion

3.1. Relationship between spectral intensity and wavelength

Fig. 2 shows the relationship between the spectrum intensity of scattered light at the surface of the TLC sheet and the wavelength of the scattered light at various temperatures. The spectrum intensity is in arbitrary units. As a common feature of the profile of the spectrum intensity that varied with temperature, a peak appeared at a certain wavelength regardless of the level of temperature. The value of the wavelength where the spectrum intensity took the maximum value became smaller with the increase in temperature – that is, the color of the TLC changed from red to blue with the increase in temperature. Looking at the spectrum intensity profiles in Fig. 2, we note that the spectrum intensity varied monotonically with temperature within the range $\lambda < 450$ nm. This implies that temperature can be uniquely identified by measuring only a single optical parameter, the spectrum intensity at $\lambda < 450$ nm, instead of simultaneously measuring multiple optical parameters such as the RGB of color, etc. as reported in numerous previous studies.

In order to quantitatively examine this situation in detail, the relationship between the spectrum intensity and temperature at wavelengths from 410 nm to 450 nm at 10 nm intervals is shown in Fig. 3. The area bounded by two vertical lines at the temperatures of 32 °C and 42 °C in the figure indicates the range of the color change of the TLC, namely, the temperature range between the red starting point and the clearing point temperature of the