Effect of coating thickness on the calibration and measurement uncertainty of a wide-band liquid crystal thermography

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The liquid crystal thermography is a high-resolution and non-intrusive optical technique for full-field temperature measurement. We present detailed calibration data for a wide-bandwidth thermochromic liquid crystal (TLC) to investigate the effect of the coating thickness on the hue-temperature characteristics and the measurement uncertainty of the TLC. It is found that the coating thickness has appreciable effect on the TLC hue-temperature curve. For TLC coatings with the thickness over 20 μm, a thicker TLC coating shows a relatively smaller measurement uncertainty, but the effect of the coating thickness is non-distinctive on the measurement uncertainty.

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Thermochromic liquid crystals (TLCs) are optically-active mixtures of organic chemicals. When illuminated by white light, they can react to temperature changes by varying the color: smoothly from red at the low temperature to blue at the high end of the active range. This behavior is repeatable and reversible (on cooling) and allows the TLC color to be calibrated as a function of temperature directly. A wide-band TLC normally has a bandwidth of 5 – 20 °C, and a working temperature range of –30 – 150 °C can be selected[1].

The TLC thermography as a powerful tool for temperature measurement has been used for gas turbine heat transfer and cooling research and complex turbulent flow heat transfer research[1−2]. However, the measurement accuracy of the TLC thermography strongly depends on the TLC calibration.

In the past, many studies have been conducted on the calibration for wide-band TLCs by using the color-based image processing, which produced reasonable suggestions for the application of TLCs. Those studies indicate that some parameters can significantly affect the TLC hue-temperature relation, which include the lighting and viewing angles[3−6], and TLC coating thickness[5,7], etc. Behle *et al.* examined the effect of coating thickness on the relation of hue versus temperature[5,7]. Their study showed that for TLC coatings with the thickness over 23 μm, the hue versus temperature relation exhibited reasonably similar characteristics. However, for a thinner TLC coating, it reflects less bright color, which may cause a bigger measurement error. It is noted that most of the previous research only indicated that the coating thickness could influence the hue-temperature relation of the TLC, however the report on how it influences the measurement uncertainty for the TLC coating is still quite limited.

In this letter, a calibration for the TLC with a wide bandwidth of 20 °C is done with true color processing by using an isothermal calibrator. The effect of the coating thickness is investigated on the calibration and measurement uncertainty of the TLC.

To calibrate the TLC fast and reliably, a calibration experimental system was constructed (Fig. 1). The calibration experimental system consists of an isothermal calibrator, a direct current (DC) power supply with a precise and controllable power output, a data acquisition system, and an image acquisition system. To determine the lighting angle θ, it needs to measure the horizontal distance between the light and the axis of the charge-coupled divice (CCD) camera, and the perpendicular distance between the light and the surface of calibrator. A more detailed description of the calibrator design was presented in our previous paper[8].

A Hitachi (HV-D30P) 3CCD RGB camera with a zoom lens and a Matrox Meteor II-Multichannel image acquisition board were used to capture the color images of the TLC. The 3CCD color camera was mounted perpendicularly to the calibrator. The TLC images were saved in BMP format with a resolution of 768 × 576, and were subsequently processed by Matlab.

To improve the RGB image quality in Ref. [9], the black and white reference settings for the R, G, and B channels of the Meteor II frame grabber are adjusted. In addition, by using the gray card the camera's R and B gains are adjusted so that the R, G, and B values of the gray image are close to each other.

The supplied microencapsulated TLC slurry (Hallcrest

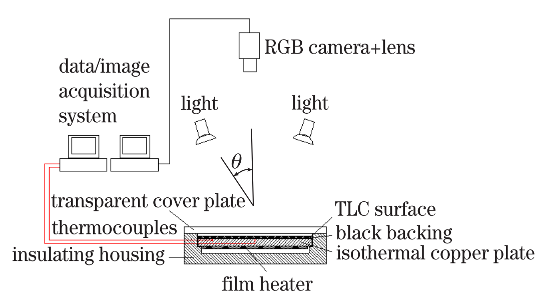

Fig. 1. TLC calibration experimental setup.

SPNR40C20W) has a concentration of 10%. The TLC has a nominal red start temperature of 40 °C and a bandwidth of 20 °C. Prior to the preparation of the TLC coating, the surface of the copper base plate was first painted with a thin layer of Hallcrest SPBB black paint. The TLC slurry was first diluted with an equal amount of distilled water, and carefully mixed and fine filtered. Then the TLC slurry was repeatedly sprayed by an airbrush and dried on the black backing on the surface. To investigate the effect of the TLC coating thickness on the hue-temperature relation and the measurement uncertainty, the TLC coatings with various thicknesses of 10, 20, 25, 30, and 40 μm were prepared.

The calibration experiments were carried out between the temperature range of 38 − 60 °C. A rectangular region of interest (ROI) of 100 × 100 pixels with the thermocouple point at the center was chosen in the TLC image for analysis. A 5 × 5 median filter was used in the image processing to reduce the noise in the TLC image. The median filter sets the hue value at each pixel with the median of the hue values of the pixels in its 5 × 5 neighborhood[10].

The matrix of the hue values of the ROI was calculated by using the Matlab's RGB2HSV function[10−12], and all the values were normalized to a scale of 0 − 255 (8-bit resolution). To process the series of TLC images, a program based on Matlab was developed, which could automatically analyze the hue matrix of the TLC images, complete the polynomial fitting of the hue curves versus temperature, and perform the measurement uncertainty calculation. The whole image processing for one calibration experiment normally takes only 1 − 2 min.

To investigate the effect of the coating thickness on the TLC calibration, the TLC coatings with various thicknesses of 10, 20, 25, 30, and 40 μm were tested, and the lighting angle was kept at 27° for each experiment.

Figure 2 shows the comparison of the hue-temperature curves of different TLC coatings. The hue-temperature curves show approximately the same monotonically calibratable temperature range of 41 − 60 °C. The coating thickness has appreciable effect on the TLC hue-temperature curve, and the hue curve shifts upwards as the coating thickness increases.

The hue characteristics of the TLC coatings are region-wise, i.e., in 41 − 45 °C the hue increases dramatically with the temperature and the TLC coatings have a high hue sensitivity (to temperature change) of about 20.7 unit hue/°C, and in 45 − 60 °C the hue increases mildly with the temperature and the TLC coatings have a low hue sensitivity of about 3.5 unit hue/°C. It is also noted that the hue curve of the TLC coating with the thickness of 10 μm shows an unusually rising trend in the temperature range of 45 − 60 °C. This can be explained by the fact that in the temperature range of 45 − 60 °C the hue sensitivity is relatively low, and the TLC coating thickness of 10 μm is very thin, therefore the reflected hue signal from the coating is relatively weak, which makes it susceptible to the background noise. Each of the hue-temperature curves shown in Fig. 2 can be well fitted by a 7-order polynomial separately, which will be used for the conversion of a TLC color image to the temperature field.

Figure 3 shows the standard deviation in hue for the

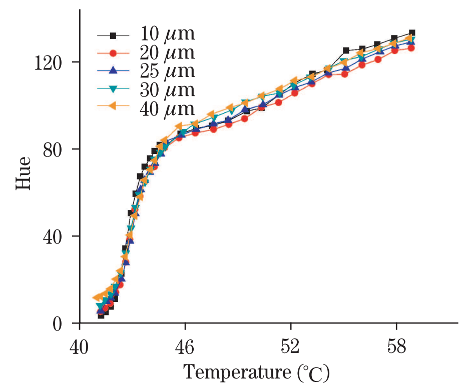

Fig. 2. Effect of the TLC coating thickness on the hue-temperature curves.

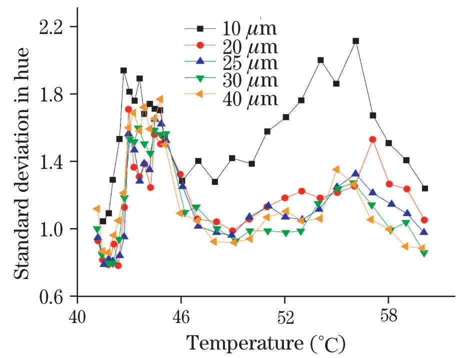

Fig. 3. Effect of the TLC coating thickness on the standard deviation in hue.

TLC coatings with various thicknesses, which serves to quantify the noise level of the TLC coatings. It is seen that the TLC coating with the thickness of 10 μm shows a distinctively higher standard deviation in hue, especially in the range of 45 − 60 °C, mainly because the very thin TLC coating reflects less light, and there is a higher noise level in hue signal. For the TLC coatings with the thickness over 20 μm, it is found that they show a similar distribution of standard deviation in hue, which ranges between about 0.8 and 1.7 over the whole calibratable temperature range, and a thicker TLC coating shows a relatively smaller standard deviation in hue.

To estimate the measurement uncertainty of the TLC coatings, the method described in Ref. [12] was used. A series of the constant-temperature TLC color images of calibration were examined. The constructed polynomial fitting of the temperature-hue relation was employed to convert each sample image to the corresponding temperature field, and the standard deviation in temperature was determined for each image. Using a 95% confidence interval, the uncertainty for each discrete temperature/image was estimated as twice the standard deviation value.

Figure 4 shows the measurement uncertainty of the TLC coatings with various thicknesses. It can be found that, except that, due to a higher noise level in hue, the TLC coating with the thickness of 10 μm shows a distinctively higher measurement uncertainty, the measurement uncertainties of the other TLC coatings show similar values with a mean of about 0.42 − 0.48 °C over the calibratable temperature range of 41 − 60 °C, and a thicker TLC coating shows a relatively

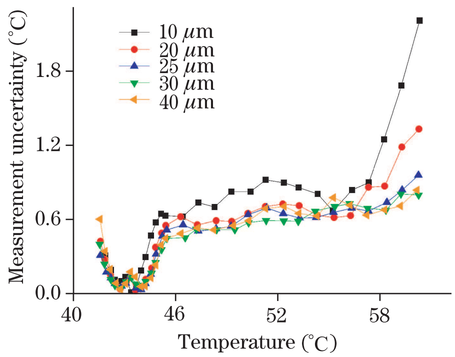

Fig. 4. Effect of the TLC coating thickness on the measurement uncertainty.

smaller measurement uncertainty. Figure 4 also indicates that the effect of the TLC coating thickness over 20 μm is non-distinctive on the measurement uncertainty, which is similar to the report in Ref. [7]. The reason could be that even though a thicker TLC coating could reflect more color signal, which was positive to reduce the measurement error, however, this advantage could be counteracted somewhat by the rougher surface of the thicker coating, which could produce additional noise to the hue signal due to the non-uniformity of the coating thickness.

The measurement uncertainty distribution is typically region-wise, i.e., in range of 41 – 45 °C the measurement uncertainty is relatively lower with a mean of about 0.15 °C, and in range of 45 – 60 °C the measurement uncertainty is higher with a mean of about 0.64 °C. To get higher measurement accuracy, the TLC coating with a thickness of 20 – 30 μm is desired.

In conclusion, the TLC with a wide bandwidth of 20 °C is calibrated by using an isothermal calibrator with the lightings and the camera in an off-axis arrangement. The effects of the coating thickness are investigated both on the calibration and measurement uncertainty of the TLC coating. It is found that the coating thickness has appreciable effect on the TLC hue-temperature curve, and for TLC coatings with the thickness of 20 – 40 μm, a thicker TLC coating shows a relatively smaller measurement uncertainty, but the effect of the coating thickness is non-distinctive on the measurement uncertainty. It is also found that a thin TLC coating with the thickness of 10 μm can cause unusually higher measurement uncertainty due to a higher noise level in hue. For the measurement application, the TLC coating with a thickness of 20 – 30 μm is desired.

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