A liquid crystal thermography calibration with true color image processing

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Liquid crystal thermography is a high-resolution, non-intrusive optical technique for full-field temperature measurement. We present the detailed calibration data for the thermochromic liquid crystal (TLC) with a useful range of 41−60 °C. The calibration is done with true color image processing by using an isothermal calibrator. The hue-temperature curve of the TLC is obtained, and the measurement uncertainty is analyzed. Combined with the image noise reduction technique of a 5×5 median filter, the measurement accuracy of the liquid crystal thermography can be significantly improved by approximately 57.1%.

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Thermochromatic liquid crystals (TLCs) are optically-active mixtures of organic chemicals, with molecular orientations sensitive to temperature. When illuminated with white light, they can react to the temperature change by changing the color: smoothly from red at the low-temperature end to blue at the high end of the active range. This behavior is repeatable and reversible (on cooling), and it allows the TLC color to be calibrated as a function of temperature directly. A wideband TLC normally has a bandwidth of 5−20 °C, and a working temperature range of −30−150 °C can be selected. For the calibration of wideband TLCs, typically the color components, i.e., red (R), green (G), and blue (B), of each pixel in a TLC image are converted to hue (H), saturation (S), and intensity (I)[1]. The hue represents the displayed color of the TLC and is a monotonic function of temperature. The calibration process is to construct the hue-temperature relation over the useful calibratable temperature range.

The TLC thermography as a powerful tool for temperature measurement has been used for complex turbulent flow heat transfer research[2−5]. It has been showed that the TLC is capable of providing a high-accuracy continuous temperature field measurement, especially for a complex structured heat transfer surface. However, the measurement accuracy of the TLC thermography strongly depends on the TLC calibration, and also the bandwidth of the TLC itself. The TLCs with the bandwidth of 5 and 10 °C were typically used for the calibration[6−12]. For the TLC with a wider bandwidth than 10 °C, the calibration data is still limited[7]. As the bandwidth of the TLC increases, the sensitivity of the hue to temperature decreases, and more noise may arise in the hue curve and TLC image and thereby decreases the measurement accuracy of the TLC. Therefore for the calibration and application of a wideband TLC, a noise reduction technique should be incorporated into the TLC image processing.

In the letter, a calibration for a TLC with a wider bandwidth of 20 °C is conducted. The characteristics of the TLC hue curve versus temperature and their corresponding measurement uncertainty are analyzed. To reduce the noise of the TLC image and improve the measurement accuracy, a 5×5 median filtering technique is used to process the TLC images.

In order to do a fast and reliable calibration of the TLC, a calibration experimental system was constructed, as shown in Fig. 1. The calibration experimental system consists of an isothermal calibrator, a direct current (DC) power supply with precise and controllable power output, a data acquisition system, and an image acquisition system.

The calibrator has a total length of 146 mm, a width of 96 mm, and a thickness of 30 mm. The calibrator consists of a transparent Plexiglas cover plate, a copper base plate, a film heater, and an insulating housing. The copper plate is uniformly heated from the bottom surface by a film heater. Two precisely calibrated type-K 0.5-mm-in-diameter thermocouples were inserted into the copper plate, one at the center and the other on the 40-mm away left side. Both of them were 1 mm below the top surface of the plate to measure the surface temperature, and a good uniformity of the surface temperature was validated to be within ± 0.05 °C. Between the copper plate and the transparent cover plate, there was 2-mm high gap, which made the TLC coating avoid

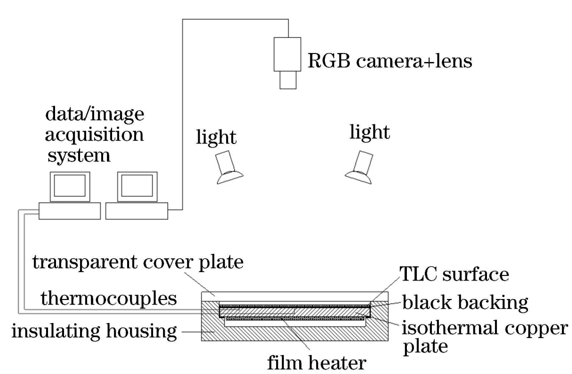

Fig. 1. TLC calibration experimental setup.

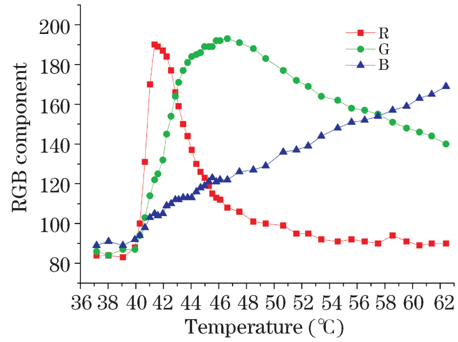

Fig. 2. RGB components of TLC images versus temperature.

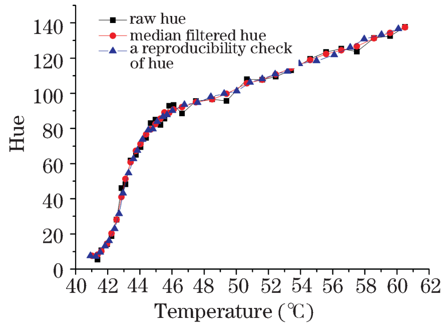

Fig. 3. The raw hue and the median filtered hue calibrations of the TLC.

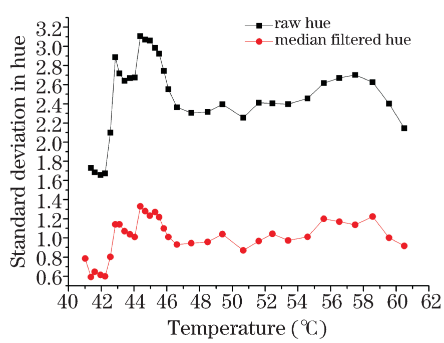

Fig. 4. Standard deviation in the raw hue and the median filtered hue versus temperature.

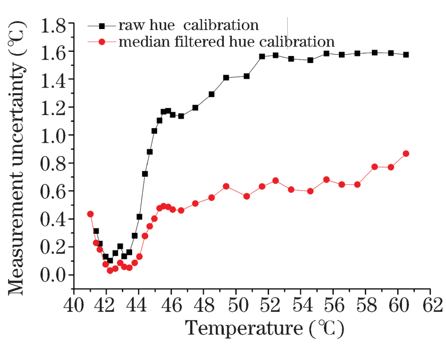

Fig. 5. Measurement uncertainty in the raw hue and the median filtered hue calibrations.

the stress from the cover plate. By regulating the voltage over the film heater, the copper plate temperature can be controlled quickly and precisely. For the illumination of the TLC surface, two 18-W Phillips high-color rendering fluorescent lamps were used, and they were about 300 mm above the calibrator. To minimize the room light and the reflected light, a black drape was placed over the system.

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 directly above the calibrator. The TLC images were saved in BMP format with a resolution of 768×576, and were subsequently processed by Matlab.

The supplied microencapsulated TLC slurry (Hallcrest SPNR40C20W) has a concentration of 10%. The TLC has a nominal red start temperature of 40 °C and a bandwidth of 20 °C. The surface of the copper base plate was first black 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. The prepared coating looked plane and dark. The resulted TLC film had an estimated thickness of 25 μm.

The calibration experiments were carried out between the temperature range of 38−60 °C. A rectangular region of interest (ROI) of 100×100 pixels (totally 10000 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 set the hue value at each pixel with the median of the hue values of the pixels in its 5×5 neighborhood[13−14].

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

Figure 2 shows the R, G, and B components of the TLC images versus temperature. The TLC starts the color play at approximately 40 °C. Data below the temperature shows the background reflection characteristics. Figure 3 shows the monotonically calibratable raw hue curve over a useful temperature range between 41.0−60.0 °C. From 41 to 45 °C, the hue value increases dramatically with the temperature. The TLC has a high hue sensitivity to temperature of 16.5 unit hue/°C, and the noise in hue is shown to be relatively little. Between 45−61 °C, the hue values increase mildly, and the TLC has a lower hue sensitivity of 3.4 unit hue/°C. It is noted that in the temperature range the noise in hue is shown to be distinctive, and there are fluctuations as much as ± 4.0 in the hue values. Figure 3 also shows the hue curve processed by a 5×5 median filter. It can be seen that the hue curve becomes much more smooth than the unfiltered curve. The noise in the hue curves has been effectively removed. And the overall hue range after the processing of the 5×5 median filter is 7.6−137.5, which is about the same as the raw hue range.

To check the reproducibility of the hue curve of the TLC, a second heating process was conducted. Figure 3 shows a good reproducibility of the hue curve of the

TLC. The hue-temperature curves shown in Fig. 3 can be well fitted by a 7-order polynomial, which will be used for the conversion of a TLC color image to the temperature field.

Figure 4 shows the standard deviation in hue, which serves to quantify the noise level of the TLC coating. It can be found that the average standard deviation in the raw hue is approximately 140% higher than that of the median filtered hue. The method described in Ref. [9] is used to estimate the measurement uncertainty of the TLC coating. A series of the constant-temperature TLC color images of calibration are examined. The constructed polynomial fitting of the temperature-hue relation is 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 is estimated as twice the standard deviation value. Figure 5 shows the uncertainty in temperature measurement versus the actual temperature measurement. The measurement uncertainty based on the raw hue calibration ranges from 0.1 to 1.6 °C with a mean of 0.98 °C, and the measurement uncertainty based on the median filtered hue ranges from 0.04 to 0.87 °C with a mean of 0.42 °C. The calibration of the median filtered hue shows a considerably improved measurement accuracy by approximately 57.1% over the raw hue calibration. It is also noteworthy that in the temperature range of 41−45 °C, due to a higher sensitivity of hue to temperature, the TLC has a higher measurement accuracy, and there is a mean measurement uncertainty of 0.17 °C for the median filtered hue calibration.

In conclusion, a calibration for the TLC with a wide bandwidth of 20 °C has been done with true color image processing by using a calibrator. Combined with the image noise reduction technique of a 5×5 median filter, the measurement accuracy of the liquid crystal thermography has been significantly improved. It is also found that the temperature measurement accuracy of the TLC varies with temperature. In the temperature range of 41−45 °C, due to a higher sensitivity of hue to temperature, the TLC has a higher temperature measurement accuracy of 0.17 °C.

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