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A review of thermochromic liquid crystal with spectrum analysis

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Abstract
At the first an introductory concept to the thermochromic liquid crystal (TLC) and the liquid crystal thermography has been explained. Based on the our experiences in application of the TLC for the heat transfer measurements, the liquid crystal thermography calibration procedures have been briefly described, and the parameters, which can influence the TLC temperature measurement variation, have been analyzed. The analysis shows that the use of an image noise reduction technique, the TLC coating thickness, the lighting angle, and the coating quality can impact the TLC hue calibration and the temperature measurement variation. Later on examples of the applications of the steady and transient liquid crystal thermography techniques to the heat transfer having turbulence measurements have been given.

Keywords: thermochromic liquid crystal, thermography, liquid crystal calibration, spectrum, band width

Introduction
The cholesteric materials form a similar structure; however, under different temperatures the orientations of adjacent liquid crystal molecule planes are different with certain angles, which results in the reflection of different wavelengths of the visible spectrum of light when illuminated with white light and then show different colors [1-3]. Such optical characteristics of the TLC depend on its temperature and can be repeated and reversible. The accurate functionalship between the TLC colors and temperatures can be built through careful calibration experiments, which then can be used for precise temperature measurements of any surface. Currently, the TLC can be provided with the operating temperature between 30.C and 150.C. The TLC may have the bandwidth (the active temperature range) of 1.C to 20.C, in which the liquid crystal can be applied for the temperature measurements by changing color smoothly from red to blue.

Liquid Crystal Thermography
- Liquid Crystal Thermography This technique is based on liquid crystals, which exist in solid and liquid phases and thereby exihibit properties of both liquids and solids.

LCT is based on the liquid group, the cholesteric liquid crystals also known as thermochromic liquid crystals (TLCs).They can be applied as temperature sensing element as its surface colour changes as temperature changes. As temperature is increase colour of TLC changes from red to blue and then after orange, yellow and green. When TLC reaches the clearing point it enters the pure liquid state and becomes colorless again. The color of TLC can be linked to a particular temperature by means of calibration process

a) Liquid crystal Calibration
The main purpose is to get an accurate temperature - hue value (colour) curve so we can use. LCT needs calibration process such that it can relate individual color to individual temperature. This process is very important for high accuracy and resolution in temperature measurements. LC color response to individual temperature is function of other factor such as light's degree of incidence or reflection from environment. Thermocouple may be callebrative but it is too hard to fix. So LC is calibrated such that tool required can be set accurately. Some years ago the calibration of liquid crystal was usually done by human visualization. In today's world, CCD camera is used in order to take picture of liquid crystal which is followed by digital processing. In calibration a black box of hood with window in front and having holes in rear side is used which is for exhausting hot air from inside. Plates having LC is put inside the box an heated by a fan In front of window, two fluorescent lamps are vertically mounted for the purpose of illumination. Also CCD camera installed normal to the plate center with adjustable height Now, surface temperature is measured by thermocouple. To set the reference temperature, end point is emerged in ice bath. To read potential difference by thermocouple digital millimeter is employed. Afterwards, the following equation gave the temperature value for each voltage.

$$[°C] = 24{,}467 \cdot U[mV] + 0.2816$$

The power supplied to the heater was adjusted with a variable transformer. It allowed varying the voltage supplied. The event temperature of the LC was reached by supplying 135V to the heater. At this point the red color appeared for the first time.

The calibration was completed within two days. Each day data were gathered from red color to blue, i.e. varying the voltage from 135V to 165V. In total 23 points (Temperature, Hue value) were obtained. The temperature for each point was obtained by averaging the 5 measures captured with the five different thermocouples.

Magnitude of hue was obtained averaging the hue value of each pixel from the images taken with the CCD camera. Mat lab was used to process all this information and data, scripts can be found in the back-up documents. At the beginning of the calibration the power supply was adjusted at 135V where red color started to appear.

The power supplied to the heater was then increased by 2,5V approximately in every run. After waiting for 20 minutes, in each run, the steady state was reached and all the data regarding temperature and color were gathered, i.e. temperatures of thermocouples were read and an image of the plate was taken with the CCD camera.

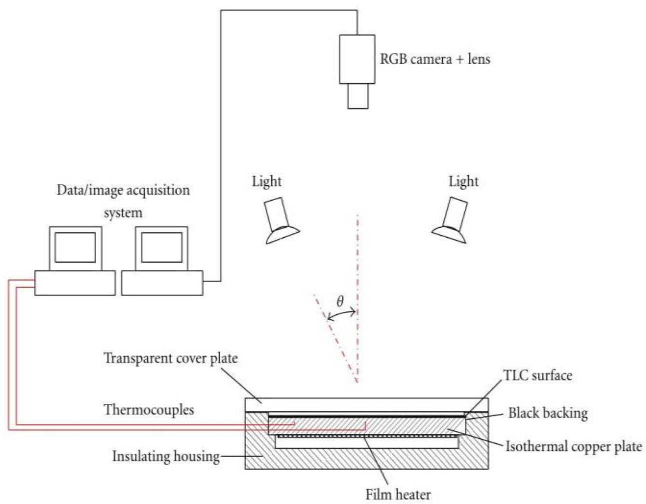

Fig 1: The TLC calibration apparatus Line Diagram

Methodology and Parametric Analysis on the Measurement

a) Factors Influencing TLC

There are many factors that can affect the TLC thermography measurement variation, such as the TLC bandwidth, the color imaging processing techniques, the coating thickness, the quality of the TLC coating, and the lighting angle, and so forth.

In order to study the effects of those parameters on the measurement variation of the TLC, a calibration experimental apparatus was constructed as is shown in Figure 1. The TLC thermography system consists of a Hitachi (HV- D30P) 3CCD RGB camera with a zoom lens, cold lighting source, a data acquisition system, an image acquisition sys- tem, and the related data processing software. The calibration device consists of a transparent Plexiglas cover plate, a copper plate with a film heater, and two type K thermocouples (0.5 mm in diameter) with the measurement variation of ±0.1◦C.

By adjusting the voltage over the film heater, the copper plate's surface temperature can be controlled precisely and rapidly. The surface of the copper base plate was first painted black paint and then a layer of liquid crystal (10–40 μm in thickness). The supplied microencapsulated TLC slurry has an operating temperature range of 40–60°C. The changing color under the varying temperature is recorded by the 3CCD RGB camera. The TLC images are then processed by a self-developed data processing program, and the corresponding TLC hue-temperature relationship can be obtained. With the calibration experimental system, the authors have studied the effects of the influencing parameters on the measurement variation of the TLC

b) Effect of the Bandwidth of TLC on the Measurement Variation

According to the working bandwidth, the TLC can be generally divided into the narrowband TLC and wideband TLC. A narrowband TLC has an active temperature range of 1.C, and a wideband TLC can have an active temperature range of 5.C, 10.C, or 20.C. As the bandwidth of the TLC decreases, the sensitivity of hue to temperature increases, and then the measurement accuracy of the TLC increase. The previous literatures showed that the measurement variation of the narrowband TLCs is about 0.1– 0.3.C [7], and 0.2–0.4.C for the TLCs with the bandwidth of 5.C and 10.C, respectively. The TLC with the bandwidth of 20.C has the measurement variation of about ±0.4–0.5.C [2].

Effect of Image Processing on the Measurement Variation. Figure 2 shows the raw hue and the median filtered. _ Fig 2: The raw hue and the median filtered hue calibrations of the TLC _ Fig 3: The measurement variation in the raw hue and the median filtered hue calibrations hue calibrations of the TLC. The calibration experiment was done with the finely prepared TLC coating with a thickness of 25 μm, and the lighting angle is 27.

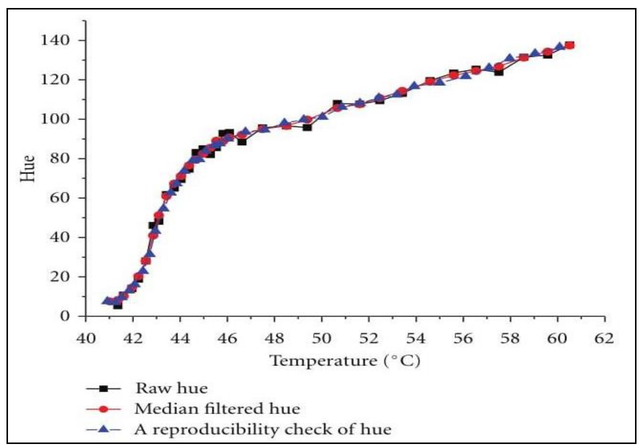

Fig 2: The raw hue and the median filtered hue calibrations of the TLC

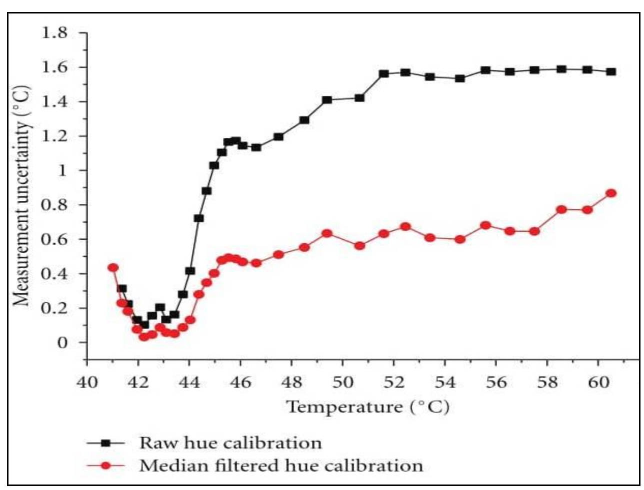

Fig 3: The measurement variation in the raw hue and the median filtered hue calibrations

The hue value can be calculated by the following algorithms. If R= Max If G= Max If B= Max R, G, and Bare, respectively, red, green, and blue components of the liquid crystal image pixel. It can be seen that the hue curve becomes much smoother than the unfiltered curve. The noise in the hue curves has been effectively removed.

Heating is conducted second time to investigate duplicability of curve having hue variation. To observe the measurement variation of the TLC, the method described in was used. A series of constant temperature TLC color images (100 × 100 pixels) of calibration were examined.

If R= Max $$Hue = \frac{G-B}{6(R-\min(R,G,B))}$$

If G= Max $$Hue = \frac{2+B-R}{6(G-\min(R,G,B))}$$

If B= Max $$Hue = \frac{4+R-G}{6(B-\min(R,G,B))}$$

The constructed polynomial function 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 variation for each discrete temperature/image was estimated as twice the standard deviation value. Figure 3 shows the changes in temperature measurement versus the actual temperature measurement. The measurement variation based on the raw hue calibration ranges from 0.1 to 1.6.C with a mean of 0.98.C, and the measurement variation based on the median filtered hue ranges from 0.04 to 0.87.C having mean of 0.42.C. Therefore, a median filtering technique can significantly improve the measurement accuracy of the TLC. It is also noteworthy that the TLC shows a region-wise measurement variation distribution. Over the temperature range of 41–45.C, due to a higher sensitivity of hue to temperature, the TLC has a higher measurement accuracy, and the median filtered hue calibration has a mean measurement variation of 0.17.C

c) Effect of Lighting Angle on the Measurement Variation

According to the working bandwidth, the TLC can be generally divided into the narrowband TLC and wideband TLC. A narrowband TLC has an active temperature range of 1.C, and a wideband TLC can have an active temperature range of 5.C, 10.C, or 20.C. As the bandwidth of the TLC decreases, the sensitivity of hue to temperature increases, and then the measurement accuracy of the TLC increases. The previous literatures showed that the measurement variation of the narrowband TLCs is about 0.1.C [12], 0.1– 0.3.C [7], and 0.2–0.4.C [8] for the TLCs with the bandwidth of 5.C and 10.C, respectively. The TLC with the bandwidth of 20.C has the measurement variation of about ±0.4–0.5.C [2].

Effect of Image Processing on the Measurement Variation. Figure 2 shows the raw hue and the median filtered. Fig 2: The raw hue and the median filtered hue calibrations of the TLC Fig 3: The measurement variation in the raw hue and the median filtered hue calibrations hue calibrations of the TLC. The calibration experiment was done with the finely prepared TLC coating with a thickness of 25 µm, and the lighting angle is 27. The hue value can be calculated by the following algorithms. If R= Max If G= Max If B= Max R, G, and Bare, respectively, red, green, and blue components of the liquid crystal image pixel. It can be seen that the hue curve becomes much smoother than the unfiltered curve. The noise in the hue curves has been effectively removed. Heating is conducted second time to investigate duplicability of curve having hue variation. To observe the measurement variation of the TLC, the method described in [8] was used. A series of constant temperature TLC color images (100 × 100 pixels) of calibration were examined. The constructed polynomial function 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 variation for each discrete temperature/image was estimated as twice the standard deviation value.

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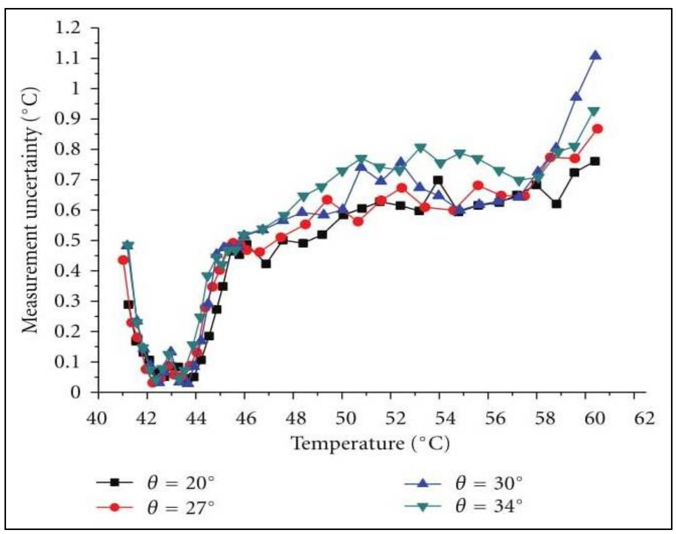

Fig 5: Effect of the lighting angle on the measurement variation

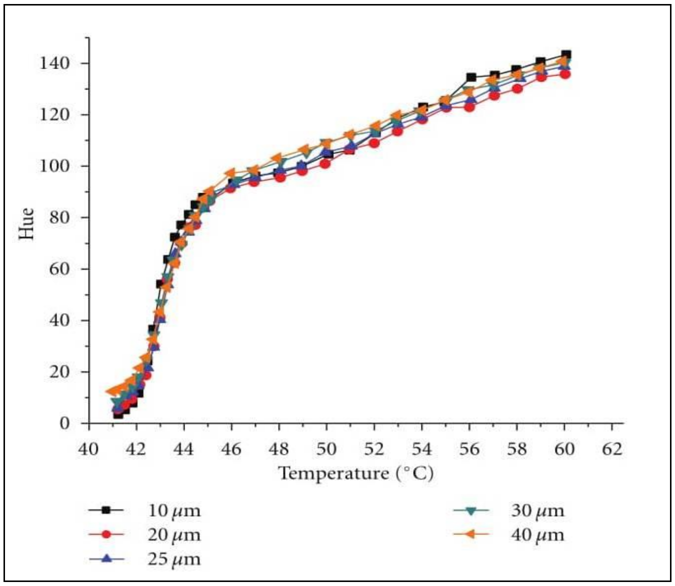

Fig 6: Effect of the TLC coating thickness on the hue curves.

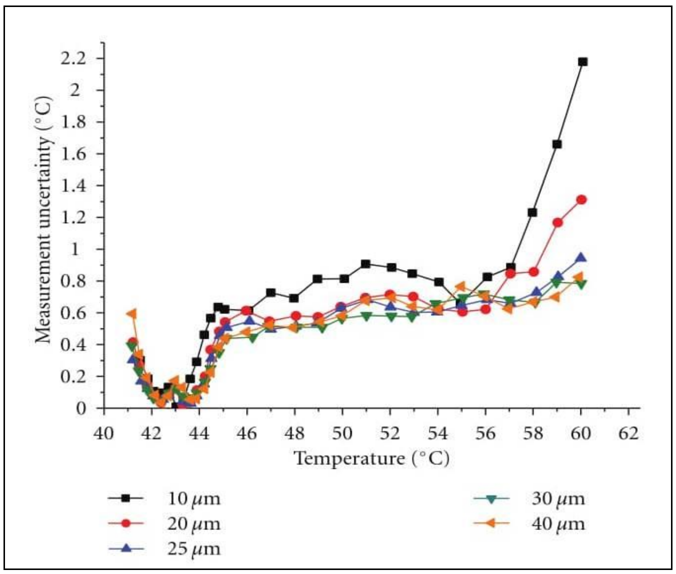

Fig 7: Effect of the TLC coating thickness on the measurement variation.

d) Effect of TLC Coating Thickness on the Measurement Variation

The TLC calibration was conducted at various lighting angles of 20., 27., 30., and 34. with the finely prepared TLC coating based on the calibration experimental system as Figure 1. Figure 4 shows the effect of the lighting angles on the hue calibration. The lighting angle has a notable effect on the hue-temperature curve, and as the lighting angle increases, the hue curve shifts upward. Fig 5: Effect of the lighting angle on the measurement variation _ FIGURE 6: Effect of the TLC coating thickness on the hue curves. _ FIGURE 7: Effect of the TLC coating thickness on the measurement variation. Figure 5 shows the effect of the lighting angles on the variation in temperature measurement versus the actual temperature measurement. It can be found that the mea-surement variation increases with the lighting angle. The average measurement variation with the lighting angle of 34. Is about 25% higher than that the lighting angle of 20.. The reason should be that as the lighting angle decreases, the lighting intensity on the coating of the TLC is stronger, which leads to a stronger reflection of the color signal and thereby a higher measurement accuracy.

The effect of the lighting angle on the measurement variation is more distinctive in the temperature range of 45–60.C, which corresponds to the region of low TLC hue sensitivity. Therefore, in order to get a higher measurement accuracy, the lighting angle should be kept as small as possible providing the experimental space and arrangements allow. Behle *et al*. [7] studied the effect of lighting angle within the range of 0–70. on the temperature measurement variation of the TLC.

They have shown that the measurement variation increases with the lighting angle, and the average measurement variation with the lighting angle of 35. is about 20% higher than that with the lighting angle of 20., which agrees with the experimental results in the present paper.

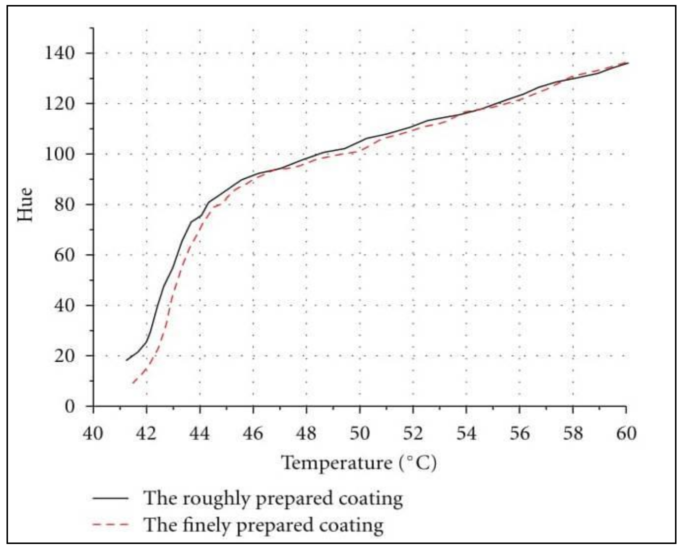

Fig 8: The hue curves comparison between the rough and fine TLC coatings

e) Effect of Coating Quality on the Measurement Variation

The coating thickness is also an important fac-tor affecting the TLC measurement variation. Figure 6 shows the hue curves of the TLC coatings with different thickness of 10 µm, 20 µm, 25 µm, 30 µm, and 40 µm. The lighting angle is 27.. It can be found that the coating thickness has a notable effect on the hue-temperature curve, and as the coating thickness increases, the hue curve shifts upward. Figure 7 shows the effect of coating thickness on the measurement variation. It can be found that, except for the TLC coating thickness of 10 µm, the measurement uncertainties of the other TLC coatings show similar values with a mean of about 0.45.Cover the calibratable temperature range of 41–60.C, and a thicker TLC coating shows a relatively smaller measurement variation. Figure 7 also indicates that the effect of the TLC coating thickness over 20 µm is no distinctive on the measurement variation.

The TLC coating with the thickness of 10 µm shows a distinctively higher measurement variation, which is because that the coating is very thin, leading to a weaker reflection of the color signal and correspondingly a higher noise level in the hue. _ FIGURE 8: The hue curves comparison between the rough and fine TLC coatings Effect of Coating Quality on the Measurement Variation. Due to the congregation of the micro-sized TLC particles in the slurry, the suspended congregated particles can be of relatively larger size of 10–20 µm. The TLC coating on the copper surface can be roughly prepared. The TLC coating can also be finely prepared by the following procedures: 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 and dried on the black backing on the surface (1–5 µm TLC particle diameters). To investigate coating quality effect on the TLC hue curve calibration and the measurement variation, comparative calibration experiments were conducted with a roughly prepared TLC coating and a finely prepared TLC coating wityh same lighting angle(the lighting angle = 27.). Both coatings have the same thickness of 25 µm. Figure 8 shows the comparison of the hue curves of the rough coating and the fine coating. It is found that, the rough TLC coating and the fine TLC coating show different hue curves over the same monotonically calibratable temperature range. The fine TLC coating has a wider hue range, which means that the fine coating has a higher hue sensitivity to temperature and a higher resolution of the measurement. Conclusions Main conclusions are following: At 40 µm, TLC coating thickness measurement uncertainty lowest. At 10 µm, TLC coating thickness measurement uncertainty highest. At lightning angle 200 measurement uncertainty is lowest. At lightning angle 300 measurement uncertainties is highest. At low temperature (up to 450 approx) finely prepared coating has lowest hue quality

Conclusions

Main conclusions are following:

- At 40 µm, TLC coating thickness measurement uncertainty lowest.
- At 10 µm, TLC coating thickness measurement uncertainty highest.
- At lightning angle 20^0 measurement uncertainty is lowest.
- At lightning angle 30^0 measurement uncertainty is highest.
- At low temperature (up to 45^0 approx) finely prepared coating has lowest hue quality.

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