Errors in thermochromic liquid crystal thermometry

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This article experimentally investigates and assesses the errors that may be incurred in the hue-based thermochromic liquid crystal thermochromic liquid crystal (TLC) method, and their causes. The errors include response time, hysteresis, aging, surrounding illumination disturbance, direct illumination and viewing angle, amount of light into the camera, TLC thickness, digital resolution of the image conversion system, and measurement noise. Some of the main conclusions are that: (1) The 3×8 bits digital representation of the red green and blue TLC color values produces a temperature measurement error of typically 1% of the TLC effective temperature range, (2) an eight-fold variation of the light intensity into the camera produced variations, which were not discernable from the digital resolution error, (3) this temperature depends on the TLC film thickness, and (4) thicker films are less susceptible to aging and thickness nonuniformities. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1777406]

I. INTRODUCTION

A. Thermochromic liquid crystal method

In our ongoing work to adapt and develop the thermochromic liquid crystal (TLC) method for measuring surface heat transfer coefficient fields in complex high-speed turbulent flows with separation (application to gas quenching),[1] we have used a hue-based technique. Hue of the light reflected from a TLC varies with the color, and increases typically with the TLC temperature. In this article, we analyze and measure the major sources of error in TLC thermometry in general, and recommend ways for their reduction.

Surface temperature fields are of course often measured by applying thermocouple, thin-film (or other shape) resistance (including thermistor), solid state, and other temperature sensors to the surface, but that method has important disadvantages: The temperatures are measured only at the locations where the sensor is placed, many sensors are needed to cover the entire area of interest, electrical connections need to be made to each sensor, and the presence of the sensors and their electrical connections may in most cases disturb the intended measurements. Noncontact, typically optical, methods which allow simultaneous temperature measurement of the entire surface with minimal effect on the surface temperature, and at reasonable cost, are therefore significantly preferable. Such noncontact methods include the TLC method studied in this work, infrared radiometry (IR), thermographic phosphor, and other fluorescent coatings, including a related technique of fiber-optic luminescent thermometry.[2–4]

The principle of IR is that the intensity of infrared emission from surfaces is increasing, and the spectral distribution changes, with their temperatures, and appropriate detectors are used to measure these intensities. Commercial IR digital video cameras can measure temperatures from below 0 °C to a few thousand °C. No coating of the surface is needed, but its emittance must be known. Disadvantages of IR thermometry are: (1) a direct view, or a view through special IR transmitting glass, of the object is needed; (2) the measurements are sensitive to radiation from the surroundings; and (3) a good IR camera may cost at least $\$50,000$.[2,5–7]

Thermographic phosphors are crystals that radiate light in the visible spectrum when excited, and the intensity of the emission and its decay time are temperature dependent. The excitation is usually provided with ultraviolet light or pulsed lasers. They are applied as a thin-film coating on the investigated surface, but the measurement is sensitive to surface roughness and impurities. While some phosphors are sensitive at cryogenic temperatures, others are sensitive at elevated temperatures, with the possibility to measure temperatures up to about 2000 °C.[8]

Temperature sensitive paints (TSP) contain luminescent molecules in paint within a polymeric binding matrix.[9–11] In a TSP, a fluorescent compound absorbs light, typically supplied by UV lamps, lasers or light-emitting-diode arrays, and emits it at a slightly higher wavelength. The luminescent intensity of the paint emission is related to the temperature in a way that the colder molecules have a higher emission intensity. After appropriate calibration, photography of surfaces painted with TSP shows the temperature field, and it is important to separate, by proper optical filtering, the incident light used for excitation, from the emitted light. The operating temperature is limited to about 100 °C, and accuracies that reach 1 °C were reported.[9]

The TLC technique presented below allows the measure-

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ment of spatially resolved steady or transient surface temperatures, using relatively simple equipment and procedures, at a relatively low cost. One of the many advantages of the technique is that the reflected light is within the visible spectrum, allowing viewing and photography of an object through fluids and solids which are transparent in the visible spectrum, and spatially resolved temperatures can be obtained from a single surface photograph. A commercial halogen lamp can be used as the light source, the photos of the TLC can be taken using commercial digital color cameras, and the images can be analyzed using a standard personal computer. The temperature range for TLC is typically limited: The red start temperature can be manufactured to be in the interval −30 to 120 °C, and the interval between the red start and the blue start can be 0.5 to 30 °C.[12]

TLCs show temperature-dependent colors by selectively reflecting incident white light, and the best color play performance appear when they are applied as a thin film on a light-absorbing black background. The reflected wavelength is typically decreasing with rising temperatures. At temperatures lower than its starting point, the TLC is colorless, and with rising temperatures it turns red, orange, yellow, green, blue and finally violet, sequentially, before turning colorless again. The color changes are in principle reversible, and upon cooling the color change sequence is reversed.

The reflected light from a film of TLC is circularly polarized, because of the twisted structure of the molecule layers. Crossed polarizers in front of the light source and in front of the camera objective can therefore reduce the direct reflected nonpolarized light from time TLCs, Fergason, 1968.[13]

In this study, the TLC colors are obviously affected by many parameters beside temperature, such as illumination, viewing incidence angles, TLC film thickness, and by the measurement and image processing method. The TLCs used here are microencapsulated in thin protective spherical shells in sizes down to a few μm. Together with a binder and mixed with water, the microspheres forum a stabilized aqueous slurry. Techniques on how to apply time TLC as a sprayed film and on how to achieve uniform films are described.[14] Premanufactured plastic sheets coated with black primary color and TLC are also available.

A monochrome camera and 18 optical band-pass filters active within different wavelengths, were used in one study for TLC temperature measurement.[15] A charge coupled device (CCD) digital camera, such as the one used here, typically uses only three band pass filters (or other selective devices), which transmit red (R) green (G), and blue (B) light to time sensors. Each pixel in an image then contains time information about time R, G, and B intensities. It is noteworthy though that despite this reduced information about the light, combinations of R, G, and B can form any visible color.

The quantity hue H can be calculated using the R, G, and B magnitudes, and it increases when the dominant color transits from R, to G and then to B. This property of hue and its independence of the light intensity levels, makes it suitable for temperature measurements using TLC. Three somewhat different versions of the definition of hue were investigated and one of these produced lower errors in the temperature reading.[16] The recommended version of hue was found similar to the MATLAB™ function *rgb2hsv*.[17] MATLAB version 5.2.1 (Ref. 18) for Macintosh that calculates hue using Eqs. (1)–(4), was used in our study,

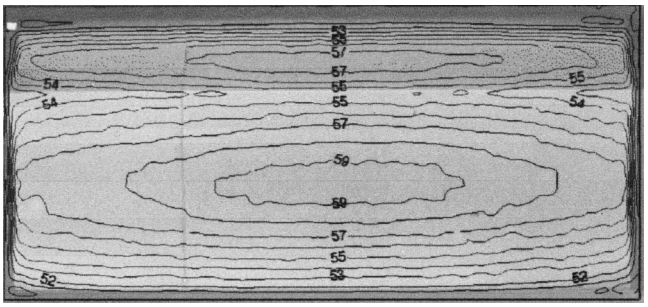

FIG. 1. Example of measured temperature, (°C), using the TLC technique, on a heated quadratic prism of metal cooled by a cross flow of air.

for $R=\max(R,G,B)$ and $G<B$,

$$H=\frac{1}{6}\left(\frac{G-B}{R-\min(RGB)}\right)+1, \tag{1}$$

for $R=\max(R,G,B)$ and $G>B$,

$$H=\frac{1}{6}\left(\frac{G-B}{R-\min(RGB)}\right), \tag{2}$$

for $G=\max(R,G,B)$,

$$H=\frac{1}{6}\left(2+\frac{B-R}{G-\min(RGB)}\right), \tag{3}$$

$B=\max(R,G,B)$,

$$H=\frac{1}{6}\left(4+\frac{R-G}{B-\min(RGB)}\right). \tag{4}$$

An example of a temperature measurement using the present TLC technique is shown in Fig. 1. Isotherms, from which the temperatures were evaluated, were plotted on the original color image. The measured object is an internally heated quadratic metal prism in air cross flow.

B. Parameters affecting thermochromic liquid crystal measurements: A brief survey of available information

1. Response time

Cholesteric liquid crystals used for thermal mapping have a response time of about 100 ms, which is time required for the molecules to attain a new configuration after a change in their temperature.[13] The response time for an encapsulated chiral nematic TLC was investigated,[19,20] where a TLC film 10 μm thick was applied to a blackened electrically heated metal foil and illuminated by a white light source, and the reflected light from the TLC was measured using a photodiode detector. The response time was found to be a few ms.

Since the time response of liquid crystals is a function of their molecular adjustment, it can be changed only if other

types of liquid crystals are used, that have a faster response. None have been found in literature. On the other hand, since the thermal response of the TLC film becomes faster as the film is made thinner, a truer representation of the measured surface (film substrate) transient temperature is obtained for thinner films. This is somewhat negated though by the fact, presented below in detail, that thinner films introduce larger temperature measurement errors.

2. Hysteresis

The color response of TLC is known to be different on cooling and heating, the differences can be significantly reduced if the heating and cooling are kept below the upper temperature limit (clearing point) of the specific TLC. Furthermore, the TLC is found to reset when it is cooled below the start temperature for the color play.[17,21] On the other hand, it was found that a TLC (24.5–30 °C) was permanently altered after the temperature was increased to 42 °C, causing a change of 13% of the TLC hue bandwidth.[22] Possibly related is the change of the TLC with time (aging), especially at higher temperatures, which is one of the sources of error pursued further in this article.

As discussed further below, the hysteresis is small and is not a limiting measurement error factor if the temperature of the measured surface remains within or below the TLC active range, but it can introduce significant errors if the temperature exceeds the TLC active range even for short periods of time.

3. Light disturbances

Uncontrolled light sources and possible reflections from surfaces in time view field of the TLC measurement target may cause errors in the measured temperatures. The intensity of the light used to illuminate the TLC should obviously be much stronger than the light incident onto the TLC from other noncontrolled surces.

Reflections can be minimized by shielding the primary light to fall on the TLC surface only, and by making all of the surrounding surfaces nonreflective. Experiments have shown that reflections and spurious light sources caused an error of up to 17% of the effective temperature measurement range (a range in which hue is monotonically increasing).[14] Tungsten–halogen lamps were recommended.[23]

If the light disturbances vary during the measurements, they may be a significant source of error. This variation, of course, is to a large extent under the control of the experiment designer. If the disturbances are constant in time, they may be corrected for by using a local calibration procedure, which also will include possible effects of varying illumination and viewing incidence angles, illumination intensity, and TLC film uniformity discussed below.

4. Illumination and viewing incidence angles

The reading of the TLC colors was found to be dependent on the angles between the light source and the TLC surface, and between the camera and the TLC surface. If the illumination and viewing are on the same line (on-axis), the angle effect was minimized, amounting to a measurement error of only a few percent of the effective hue range for angles 0 to 70°, while off-axis light and viewing can result in much higher errors.[24,14,23,25,26]

5. Illumination intensity

The light intensity entering a CCD camera may have an influence on the colors and hue, which may be influenced from the "gamma correction" of the camera, which reduces the signal for higher light intensities. Light intensity reduction by 75% was found to produce a 4% change in the hue for an optimal choice of the white balance camera setting.[25,26] (The white balance is usually used to compensate the colors for a nonwhite light source.) This is one of the sources of error pursued further in this article.

6. Thermochromic liquid crystal film thickness

The thickness of a TLC film is known to have an influence on the reflected colors, and film thickness nonuniformity will thus also cause errors in the measured temperatures. In a calculation of the light transmitted through a cholesteric TLC, it was concluded that a film thickness of 20 μm was sufficient.[13] A TLC of type R30C5W was applied in three different film thicknesses, 14, 23, and 30 μm, and the maximal difference found for these films at a constant hue was 2 °C, which was 14% of the used TLC temperature range of 32 to 44 °C. The difference was found to be much smaller between the two thicker films.[26] This is one of the sources of error pursued further in this article.

7. Temperature gradient in the thermochromic liquid crystal film

Since the TLC film is partially transparent, it is obvious that a temperature gradient in the film will present to the observing camera a combination of the different colors exiting along the gradient direction. The consequent read temperature thus represents some type of average, rather than a surface, temperature. For example, for a steady heat flux of 20 kW/m^2, the temperature difference across a 20 μm thick TLC film with the typical heat conductivity of 0.2 W/(K m) is, from Fourier's heat conduction law, 2 °C.[20] Gradients may also arise from transient temperature changes.

While the effect of the temperature gradient error is typically expected to be smaller than other TLC related errors, it could be reduced even further by a correction obtained from an approximate thermal analysis of the heat transfer problem through the TLC film.

8. Electric fields, pressure, and acceleration

No temperature measurement errors were found due to the presence of electric fields up to 150 kV/m.[27] Pressures up to 133 bars were found to have no effect on encapsulated TLCs (Ireland and Jones, 2000[20]) neither had rotation/acceleration up to 1.6×10^4 g.[28]

9. The digital resolution

The digitized *R*, *G*, and *B* values, in combination with the unique color response for a TLC, produce digital values of the hue and of the read temperature. A common representation for digital images is 3×8 bits digitization of the *R*, *G*, and *B*. A test using a sheet of the TLC R25C5W (26 to

43 °C) resulted in a hue resolution of eight bits or higher, except in the dark blue region, where it decreased to about 6 bits.[26] This in one of the sources of error pursued further in this article.

Another digitization error arises from the spatial resolution of the image acquisition. The minimal number of pixels needed per unit length of the TLC surface depends on the magnitude of the temperature gradient: locations with large gradients needing more pixels to achieve a desired accuracy.

10. Measurement noise

Like any measurement, TLC temperature measurement has some noise. Temporal noise is reduced by averaging several images of the same area taken at different times, and averaging over ten images or more was found adequate.[14,26] Local noise is reduced by averaging at several adjacent pixels, done by using a median filter.[17] An average over 5×5 pixels reduced the local noise from 3% to 0.9%, while a combination of time and spatial averaging reduced the noise from 3% to 0.6%.[26]

C. Overall accuracy of thermochromic liquid crystal-measured temperatures

The major source of TLC measurement error and error magnitudes as well as ways to reduce them, reported in literature, were listed in Sec. I B, and the error magnitudes of some of the most important ones are studied in this work and reported below. The overall measurement error is a combination of all applicable errors, and the first step is to try and reduce each one of them individually. Proper calibration, preferably *in situ*, and at sufficiently frequent intervals as dictated by the aging discussed in more detail below, is a critical element in accuracy improvement. The calibration procedure can be either: (1) using a single hue–temperature relation for the entire surface ("global calibration"), or (2) using a unique hue–temperature relation for each pixel in the image ("local calibration"). The latter obviously provides more accuracy, but is more time consuming.

A local *in situ* calibration procedure was tested for which the uncertainty in the read temperature was estimated by using an isothermal test surface. The uncertainty was calculated with a 95% confidence interval, as twice the standard deviation in the read temperature over the surface.[22] The uncertainty over the TLC temperature range was found in the interval from $<1\%$ to 8% (the higher value in the upper blue region) of the effective TLC temperature range from 26 to 36 °C, which is an error from <0.1 °C to 0.8 °C.

If a global calibration is used instead, it is recommended to minimize the light disturbances, to ensure uniformity of the TLC film, and to use coaxial illumination and viewing, which together will minimize the errors in the temperature reading.

A way to determine the uniformity of the TLC film, used by the authors but not reported here, is to measure the uniformity of the reflected colors of the surface in an isothermal chamber. The system consisted of: (1) a chamber with thermally insulated walls, which allows for optical access from outside for photographs, and (2) a relatively strong fan to circulate the air in the chamber, increase temperature uniformity in the chamber, and reduce the thermal equilibration time of the measured object in the chamber. The air temperature is regulated by a controller and electric heater, and a temperature level is chosen for which the specific TLC has the highest sensitivity to the TLC film nonuniformities. Measurement of the surface hue field will reveal the temperature measurement errors due to variations in film uniformity.

TABLE I. Number of sprayed TLC-type R45C10 layers and the TLC film thickness, as used in the experiments.

Number of layers:	4	5	7	9	11	13	15	17
Thickness in μm:	9	11	16	20	25	29	34	38

Other calibration techniques have been investigated: A temperature-controlled minicalibrator for use *in situ*, was able to account for the effects of the local light condition and the view angle.[29] These effects could also be corrected by using another technique, in which the optical system was calibrated, using a standard color chart, a mathematical algorithm, and a reference TLC temperature–hue relation.[14]

In another investigation, it was indicated that the characteristics of the temperature–hue relations may be similar for different TLCs, and a dimensionless temperature, which collapsed the temperature–hue relations from three different TLCs (R29C4W, R40C5W, and R40C15W), to a single curve was defined.[30]

II. EXPERIMENTAL SETUP

The calibrations of the TLCs were performed where they were applied on a solid aluminum block ($20\times60\times236$ mm), which was placed inside a closed box, with a lid made of Plexiglas giving optical access from outside. The aluminum block was equipped with a flat electrical heater foil, which was glued to almost the full area of its lower surface, and a reference Pt-100 thermometer was mounted centered iniside the aluminum block with thermal conductive grease.

One of the two larger aluminum surfaces was first spray-painted black, and the paint was allowed to dry before the TLC application. A mixture of two volume parts of TLC mixed with one part of tap water was applied on the painted surface, using an airbrush with a nozzle diameter of 0.35 mm, with 1.8 bar feed air pressure.

A TLC film was created by spraying a number of thin layers, in a simlar manner each, on top of each other, where each layer is allowed to dry before the next one is applied on top of it. This technique gives better control of film thickness magnitude and uniformity than one where a thick film is applied all at once.

The TLC material used was Hallcrest microencapsulated chiral nematic of type BM/R45C10/C17-10 with a measured effective temperature range 47–63 °C which is an interval in which hue is monotonically increasing with the temperature. Eight films of it were applied on the aluminum block side by side, each in a different thickness as shown in Table I, which served to examine the effect of film thickness on performance and errors. The thickest film was made from 17 TLC layers, and the total measured thickness of this film

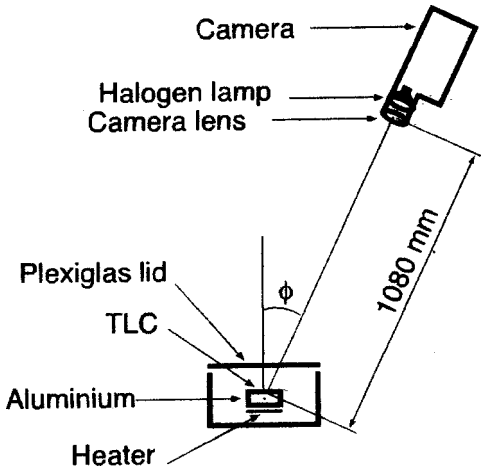

FIG. 2. The experimental setup.

was 38 μm. Each layer was thus approximately 2.2 μm thick (estimated average, the microcapsules may be somewhat larger).

A three-CCD digital color video camera, SONY DCR-TRY 900E, was used in the experiments. Some critical camera settings were controlled by the user, by using manual settings; the white balance was set to the fixed value (indoor light), and the shutter time and aperture were set to fixed values. The "progressive scan" mode was activated, which allowed the camera to record images using all pixels at the same time.

The light source used was a Philips EXZ halogen lamp, 24°, 12 V, 50 W, with built-in UV and IR filters, mounted 70 mm from the camera lens, parallel to the optical path between the lens and the TLC (Fig. 2). The distance between the camera lens and the TLC surface was 1080 mm, the angle ϕ between this nearly coaxial lighting–viewing arrangement, measured from the normal to the TLC surface, was 23°. Visual observation indicated that the light distribution over the TLC surface was uniform. A black cover was placed over the experimental system to prevent surrounding light sources and reflections from illuminating the target.

It is noteworthy that this experimental setup utilizes commercially available and relatively inexpensive components, and is easy to apply to most industrial situations where the TLC temperature measurement technique is to be used. If windows cannot be installed in the industrial application, it is possible to either insert ruggedized video cameras into the enclosure, or to use fiberoptic access from the target to an external camera.

III. EXPERIMENTAL PROCEDURE

The temperature of the TLC-coated aluminum block was initially maintained at 55 °C for 10 min, after which photos of the TLC were taken. The block was then again held at 55 °C for about 45–50 min. The first of three full calibrations of the TLC was performed after this heating period. The start temperature for the calibration was well below the TLC red color start temperature, where the TLC is transparent (the black paint can be seen through the TLC). The TLC temperature was then raised in 16 steps within 10–15 min to the upper temperature limit, where the TLC turned from blue to transparent again. At each temperature level, a photograph of the TLC was taken, with the camera aperture set to F3.4.

The TLC was then kept at 55 °C for 60–65 min before the second calibration, which was performed in the same way as the first, but the camera aperture was now set to "open," because of some darkening of the TLC since the first calibration. The TLC was again kept at 55 °C for 115–120 min before the third full calibration was performed. The color images captured during the calibrations were transferred using firewire (IEEE 1394) to a Macintosh computer, and the software Radius Photo DV was used. The images were then stored into bitmap files, having 510 $\times$ 680 pixels and 3×8 color resolution.

Hue H was calculated from the R, G, and B values of the recorded image, using Eqs. (1)–(4). Hue obtained from this operation was for each TLC film averaged over a 28 mm^2 TLC area containing 1500 pixels, and was then fitted to the temperature readings using linear interpolation followed by a polynomial fit.

IV. EXPERIMENTAL RESULTS

A. Effect of light intensity on hue

An important question is whether hue is dependent on the light quantity I into the camera CCDs. Hue H, which is calculated using Eqs. (1)–(4) indicate that hue is not dependent on the light quantity for cases where R, G, and B respond linearly to the light quantity.

The response was investigated for the camera, by varying the light and taking photos of three differently colored test surfaces, a red surface for which $R>(G,B)$, a green surface for which $G>(R,B)$ and a blue surface for which $B>(R,G)$. The colors of these surfaces were similar to those typically received from a 20 μm thick TLC film, using the present equipment. The light quantity was varied by changing the camera aperture number n. With all other camera settings kept fixed, I is proportional to $1/n^2$. The aperture number was varied from $n=9.6$ to 3.4 at a constant shutter time of $1/75$ s, hence varying the relative amount of light $I/I_{\max}$ from 0.12 to 1.0.

The measured color intensities R, G, and B (dimensionless in the range 0–255) were increasing with light quantity as expected, and as can be seen in Fig. 3. The increase is nonlinear, with its rate diminishing for the higher light levels. Hue at the highest light level $I/I_{\max}=1.0$ was calculated from these R, G, and B values and found to be $H=0.064$, 0.314, and 0.647 for the red, green, and blue surface, respectively.

The differences in hue at lower light levels from hue at the highest light level, are displayed in Fig. 4. It is seen that hue indeed varied with the light intensity, and in an irregular way for the different colored test surfaces. The maximal change in hue due to the 88% decrease in the light quantity was found to be 0.025, which is 4% of the useful hue range for the typical TLC films studied in this work. The result compares well with past studies.[26]

In the upper range of the light levels for which $120<\max(R,G,B)<255$, the maximal change in hue was only 1.5% of the hue range. All changes are of the same

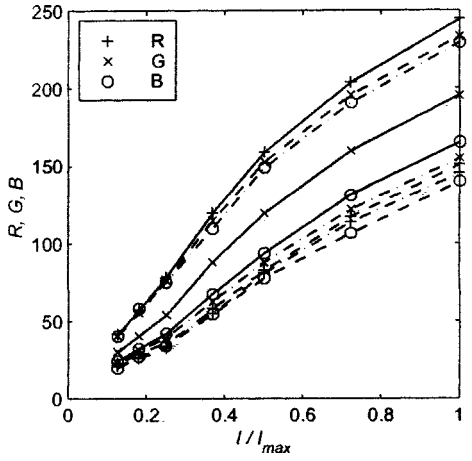

FIG. 3. R, G, and B values for different relative quantities of light $I/I_{\max}$ into the camera and for three different colored test surfaces; (−) the red surface, (−−) the green surface, and (−·−) the blue surface.

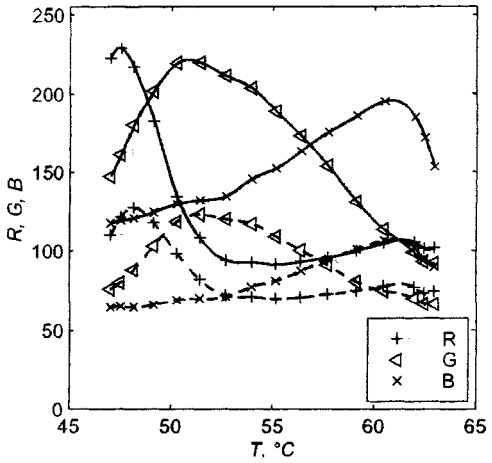

FIG. 5. Measured R, G, and B at different temperature for TLC R45C10, after an aging period of 70 min at 55 °C. The curves were fitted to the measured data. TLC film thickness, 9 μm (−−) and 38 μm (−).

order as those arising from the color digitization errors discussed below, and were possibly also in part caused by them. To minimize these two possible errors, the $\max(R,G,B)$ level should therefore be maintained in the upper half of the R,G,B range.

B. Effects of the thermochromic liquid crystal film thickness

Our measurements have confirmed past investigators' observations that the TLC film thickness causes changes in the TLC color response to the temperature, and this effect was therefore investigated in more detail. The R, G, and B values in the images were measured as a function of the temperature, and are shown in Fig. 5 for the TLC R45C10 for the film thicknesses of 9 and 38 μm.

R was seen to be dominant in the lower-temperature range, G in the temperature midrange, and B in the higher-temperature range. Noteworthy is the fact that the R, G, and B levels were higher for the thicker TLC film. The measured relation between T and H for the film thicknesses of 9, 11, 20, and 38 μm is shown in Fig. 6. It exhibits considerable and somewhat inconsistent variation with the TLC film thickness. For a fixed hue value in the upper part of the TLC temperature range, a thicker TLC films shows a higher-temperature reading, but the opposite appeared in the lower part of the TLC temperature range. Between these two temperature intervals, there is a narrow region where hue was almost constant for all thicknesses.

The greater sensitivity of the temperature to the TLC film thickness was found in the central green part of the TLC range, at about $H=0.37$, and the indicated temperatures at this hue were investigated more closely, with results shown in Fig. 7. The indicated temperature are seen to decrease with increasing TLC film thickness, and the highest rate of change was found for the thinner TLC layers. The indicated temperature difference between the TLC film thicknesses 9 and 20 μm, was found to be 12% of the TLC temperature range, and only 7% between the thicknesses of 20 and 38 μm. The sensitivity in the indicated temperatures to variations in the TLC film thickness was therefore considerably lower for the thicker layers. These figures compares well with other experimental data.[26]

Since even the thickest film, 38 μm, would generate a temperature drop of only 0.1 °C between the aluminum–film

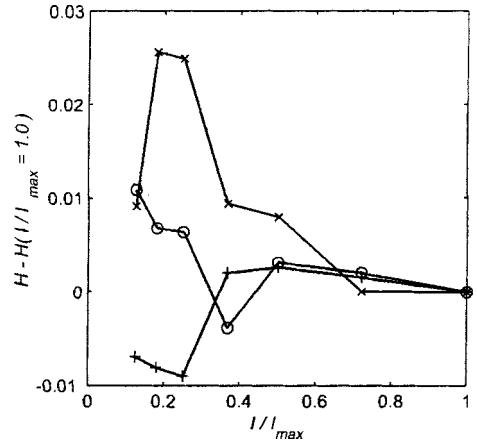

FIG. 4. Variation in hue for different light quantities into the camera, measured on three different colored surfaces; (+) a red surface, (x) a green surface, and (o) a blue surface.

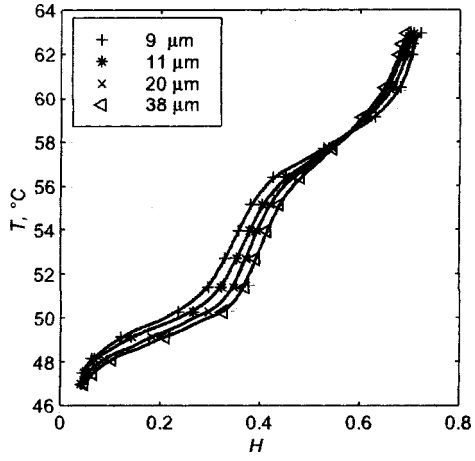

FIG. 6. Hue as a function of temperature for different TLC (R45C10) film thicknesses (the curves were fitted to the measured data).

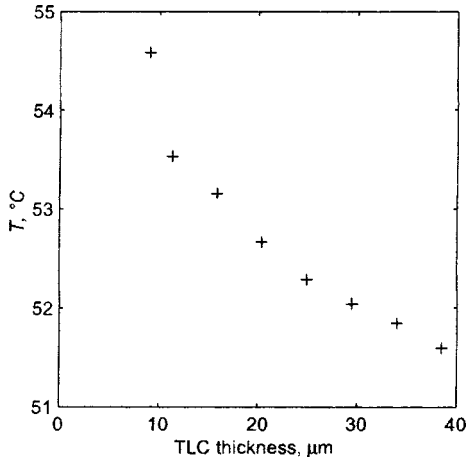

FIG. 7. Evaluated temperatures for varying TLC thickness, at the value of $H=0.37$ that gave the largest variation in temperature due to thickness change.

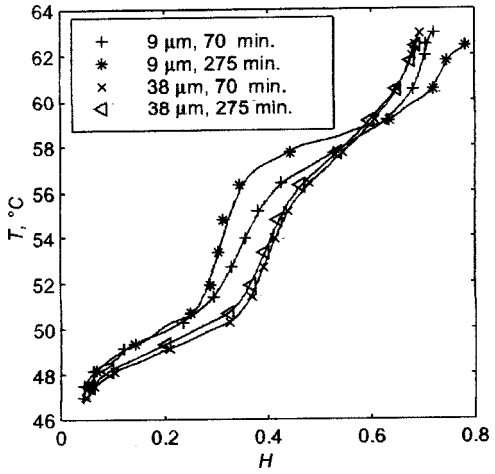

FIG. 8. Temperature–hue relations for the TLC R45C10, measured after two different aging periods at 55 °C, and for two different TLC layer thickness.

interface and the TLC film external surface, this heat conduction phenomenon cannot account for the above-observed much higher hue–thickness dependence.

C. Effect of thermochromic liquid crystal aging

Our experiments indicated that the TLC temperature–color relationship changes with time in normal use, and the aging of the TLC was therefore investigated in more detail. The stability of the complete system was investigated, including light, camera, reference thermometer, and TLC, using the TLC C35R20 (36–64 °C), which was sprayed on the aluminum block in a few layers until the TLC surface appeared rather grey (i.e., obscuring the black primer color, probably about 30–40 μm thick).

Four different full-range calibrations were then performed within six days, with the TLC stored in normal room conditions between these calibrations. The maximal difference in the temperatures indicated, for all hue values, was 0.4 °C, which is 1.4% of the effective TLC temperature range. This provides an estimate of the stability of the whole measurement system, including any possible effects of the TLC aging at room temperature during the test period.

The temperature–hue relation as a function of time (aging) of the TLC was further investigated at more elevated temperature. The TLC R45C10 was used in these tests in different thickness films (Table I). During the test the TLC was held at 55 °C, which is roughly in the middle of the temperature range of this TLC, and the temperature–hue relations were measured after 70 and 275 min of heating and are shown in Fig. 8. Aging is seen to be considerably stronger for the thinner TLC film, and to have a qualitatively similar effect to that of the film thickness, on the temperature–hue relation shown earlier.

The aging was investigated more closely at $H=0.37$, where it had the maximal effect on the temperature–hue relation. The temperature differences at this hue, in the period between 70 and 275 min of heating, were evaluated using the fitted temperature–hue data curves from our experiments, and are shown in Fig. 9. The aging effect was seen to diminish as the film thickness increased. The relationship is nonlinear, accerlerating significantly for the thinner films. For the thinnest film (9 μm), the temperature difference was found to be 2.2 °C, and for the thickest one (38 μm) 0.50 °C. That is 13% and 4%, respectively, of the effective TLC temperature range. Hence, the effects of aging can be reduced by applying thicker TLC coatings.

The change of the temperature–hue relationship with time of the 20 μm thick TLC was investigated more closely. The temperatures were read from the curves fitted to the measured temperature–hue data at $H=0.33$, measured at 10, 70, 145, and 275 min of heating at 55 °C. The differences between these temperatures and the temperature read after 10 min of heating, are shown in Fig. 10. The temperature differences (i.e., the aging error) increased with time, while the rate of change decreased with time. Furthermore, the TLC was also becoming darker during this period, measured as a 25% decrease in $\max(R,G,B)$, at a constant camera aperture setting.

D. Digital resolution

An interesting question is how disturbances in the light propagate into R, G, and B values, and thereby further into

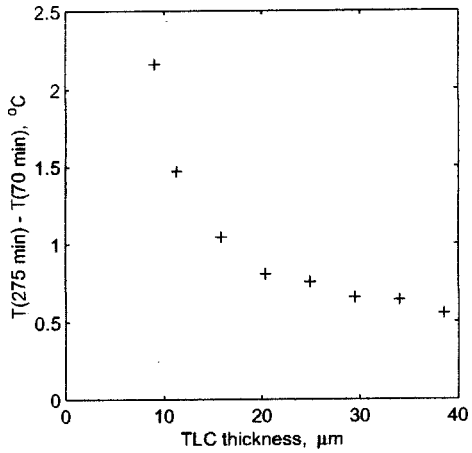

FIG. 9. The read temperature differences between 275 and 70 min of heating at 55 °C and for different TLC film thicknesses, at $H=0.37$ for the TLC R45C10.

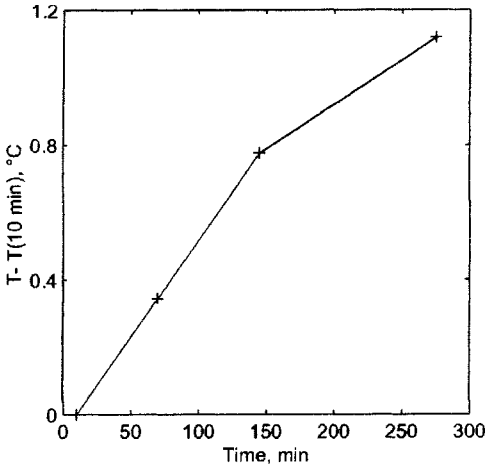

FIG. 10. The difference between the read temperature at times between 10 and 300 min, and that read at 10 min from the start of heating period in which the temperature was maintained at 55 °C, for a 20 μm thick TLC R45C10 film at $H=0.33$.

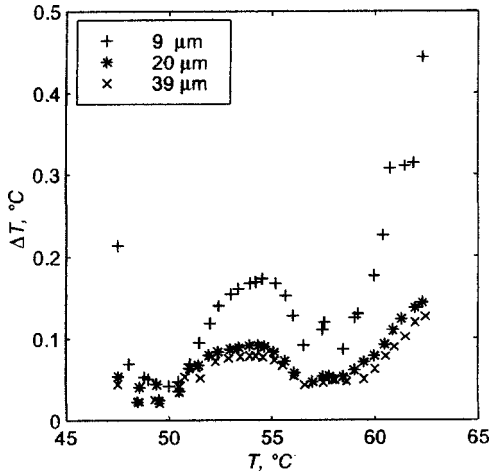

FIG. 11. Changes in the indicated temperature as a result of simulated 3 $\times 8$ bit digital representation of the R,G,B colors, based on measured $R-,G-,B-$ temperature relations for three different TLC film thicknesses.

hue and then into the read TLC temperatures. Hue H is a function of R, G, and B, as expressed by Eqs. (1)–(4) and its derivatives indicating that the sensitivity in H to disturbances in R, G, and B will decrease with an increase in the difference, $\max(R,G,B)$–$\min(R,G,B)$. It is therefore of interest to keep that difference as large as possible.

One disturbance comes from the digital image representation of R, G, and B, which propagates into H and further into the TLC measured temperatures T. Recall that the R, G, and B values are obtained in 3×8 bits as integers in the range 0–255. Curves fitted to the measured R, G, and B values as a function of the temperature, shown in Fig. 5, were expressed as integers in the range of 0–255, hence simulating the present digital image representation.

Hue was calculated from these integer values, and the steps in hue, ΔH, were found to be for the 9 μm thick TLC film within 0.008, for the 20 μm thick film within 0.004 and for the 38 μm thick TLC film within 0.003. Temperatures were then calculated from hue, using the fitted temperature–hue relations seen in Fig. 6.

The resulting temperature steps ΔT were found to vary within the TLC temperature range. Maximal values were identified within each temperature interval of 0.5 °C, giving the trend shown in Fig. 11. Three maxima were found, in the lowest red region, in the green region, and the largest values were found in the upper blue region. For the 20 μm and 38 μm thick TLC films, the maximal ΔT was about 1%, and the average about 0.5% of the effective TLC temperature range. These figures compare well with previous investigators' experimental data.[26]

The effect was larger for the thinner, 9 μm, film with maximal and average values of about 3% and 1%, respectively. Films thinner than 20 μm reflected less light and the difference $\max(R,G,B)$–$\min(R,G,B)$, was therefore smaller, which may had increased the error. It is interesting to note that comparison of Figs. 6 and 11 shows a direct correlation between the derivatives dT/dH and the temperature measurement error ΔT; the error was larger for a locally larger derivative dT/dH. Consequently, it is expected that temperature measurement errors due to digitization can be made more uniform throughout the used temperature range for TLCs that have a more linear temperature–hue relation. The value dT/dH may be used for a rule of thumb for limiting these errors as follows.

By characterizing the nonlinearity by the parameter $[dT/dH]/[dT/dH]_{av}$, it was observed in our tests that its magnitude was within 3.0 for all the TLC films thicker than 20 μm. Ratios larger than this will magnify the local errors. As a rule of thumb and based on these simple facts, the TLC setup may not be used in cases when the parameter $[dT/dH]/[dT/dH]_{av}$, which can be known after a calibration, exceeds 3.0.

While the 3×8 bit digital representation of the R, G, B values is standard for color images, the error due to the digitization will be reduced if more bits are used, and 3×9 bit will halve the error, and 3×10 bits will halve it again.

V. DISCUSSION

The TLC technique allows the noncontact measurement of spatially resolved steady or transient surface temperatures, using relatively simple and inexpensive equipment and procedures when compared with other noncontact methods, such as infrared thermography, thermographic phosphor, and other fluorescent coatings. The application of the TLC to the measured surface is easy, by using an air brush or by using prefabricated sheets.

One of the many advantages of the technique is that the reflected light is within the visible spectrum, allowing viewing and photography of an object through fluids and solids which are transparent in the visible spectrum, and spatial resolved temperatures can be obtained from a single surface photograph. A commercial halogen lamp can be used as the light source, the photos of the TLC can be taken using commercial digital color cameras, and the images can be analyzed using a standard personal computer.

It is very noteworthy that even just visual observation of the colors, without quantitative image analysis, provides quick and very useful information about the temperature

field. The main limitation compared to the other techniques is the relatively narrow temperature range in which the TLCs are useful, typically about −30 to 120 °C.

The different sources of error associated with TLC temperature measurement found were analyzed in the article: (1) TLC hysteresis, (2) TLC aging, (3) surrounding illumination disturbance, (4) illumination and viewing angles, (5) variation in TLC film thickness, (6) TLC response time, (7) varying amount of light into the camera, (8) digital resolution of the image conversion system, (9) electric fields, (10) pressure, (11) acceleration, and (12) measurement noise. For normal use of the TLC technique, it may be expected that the first five parameters in the list may influence the measurements more than the other parameters.

The total error is dependent on the specific situation for the measurements, but each source of error should be considered and a method for calibration should be chosen for which the desired accuracy can be achieved. The best accuracy is expected using an *in situ* local calibration procedure for which the same camera/light setup and TLC film are used as for the following measurements. A unique calibration relation is then used for each position on the surface (or for each pixel in the digital image).[22] The calibration of the TLC may then be repeated after some period of use, to include any possible effects of aging. The error is expected to be higher when a single calibration relation is used for an entire surface.

Some of the affecting parameters related to the hue-based TLC measure technique were investigated further in the present study, such as: (1) the amount of light into the camera, (2) the digital color resolution, (3) the TLC film thickness, and (4) the aging of the TLC film and its relation to the TLC film thickness. The experimental setup used for the investigations, the CCD camera, the light source, the view angle, and the camera/light source distances to the TLC, may also be seen as representative for industrial use.

The effects of an eight-fold variation of the amount of light into the camera was found to be relatively small, of the same order as the errors due to the 3×8 bits digital image color representation of the red, green and blue signals, resulting in errors of typically 1% of the effective TLC temperature range. The error due to the variation of the amount of light into the camera can be reduced further by using cameras in which the red, green, and blue signals have a linear response to the received amount of light.

The error due to the digital color representation was reduced here by keeping the red, green, and blue signals high within the range 0 to 255. This error was up to three times higher for the thinnest film investigated, mainly because of a smaller amount of reflected light. This error, and the sensitivity to optical disturbances, may be reduced by increasing the saturation of the colors by: (1) using a view angle which minimize the direct reflected white light from the TLC surface, and (2) using crossed polarizers in front of the light source and the camera.[13]

Variation of the TLC film thickness was shown to have an influence on the reflected colors. The sensitivity to film thickness variation was lower for the thicker layers; the indicated maximal temperature difference, at a constant hue, was found to be 12% of the effective TLC temperature range for films between 9 μm and a 20 μm thick, reduced to 7% for those between 20 and 38 μm. TLC coating by spraying a number of thin layers on top of each other gives better control of film thickness magnitude and uniformity than one where a thick film is applied all at once.

In cases where only one $T-H$ calibration relation is used for the entire surface, it can be recommended that the uniformity over the TLC film be tested inside an isothermal chamber prior to use, which allows for photographs of the TLC film. Variations in hue (variations in film thickness and surface structure) will then be revealed, which can used as a measure of the quality of the TLC film.

The reflected TLC colors were found to change with time when the TLC film was stored at elevated temperatures, while this aging was found to be relatively small at room temperature. Different thickness TLC films were investigated, and maintenance at 55 °C (a temperature in the middle of the reading range for the investigated TLC) for 205 min (a time representative for normal use of TLC in industrial situations) has shown, that at constant hue, the maximal read temperature change was 13% for a 9 μm thick TLC film, and 4% for a 38 μm thick TLC film, of the effective TLC temperature range. It can thus also be seen that the detrimental effects of aging are reduced for thicker TLC film.

All of the above mentioned methods for reducing the TLC technique measurement error are possible to realize, ensuring the accuracy of this technique in both laboratory and industrial applications.

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NOMENCLATURE

B = quantity of blue colored light, dimensionsless;
G = quantity of green colored light, dimensionless;
H = color variable hue, dimensionless;
I = total quantity of light (J);
n = aperture number of the camera;
R = quantity of red colored light, dimensionless;
T = temperature °C;
ΔT = difference in temperature (°C); and
ϕ = incidence angle (degrees).

Subscripts

av = average.

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