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A NEW APPROACH TO THERMOCHROMIC LIQUID CRYSTALS CALIBRATION FOR MICROFLUIDIC SYSTEMS

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Liquid Crystal Thermography, Thermochromic Liquid Crystals calibration, microfluidics, gas flow, temperature gradient

ABSTRACT

Non-intrusive Liquid Crystal Thermography technique (LCT) has been proven as a powerful tool for low-temperature application in micro-scale systems. It provides high-spatial resolution temperature maps dependent on the colour response of heated thermochromic liquid crystal material (TLC). Different types of TLCs have been widely used in the form of coated paints or water-based droplets in different carrier fluids. In order to convert the colour components of paint or droplets into temperature values, reliable calibration approach is necessary. However, up to now, a lack of a simple and accurate calibration procedure is still present. Most of already existing procedures are based on the improvements of 'hue-temperature' approaches (HSI, HSB, HSL), which are intuitive closer to human perception of colours, but are considered ambiguous and noise susceptible. Therefore, considering the need for precise temperature mapping, a novel TLCs colour-temperature calibration approach is presented in this paper. It introduces two angles φ *and* θ*, calculated from raw RGB colour components, on a 3D vectorial sphere space in order to achieve a better fit and to extend the useful temperature range of TLCs by increasing the accuracy linked to the colour reading.*

1. INTRODUCTION

The continuous trend towards miniaturization and multi-functionality over the last few decades has led to development of densly packed and fast products and processes with enhanced efficiency in terms of energy or yield [1]. A 'new generation' micro-devices are introducing new approaches and measurement techniques to tackle problems regarding the reduction of observed and controlled volume. In many cases, heat transfer in micro-devices, in which a heat carrier is present, must be taken under control and a full-field temperature

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investigation is required. However, the existing techniques for measuring local process parameters in the new generation miniaturized devices are still not applied in a reliable and accurate way.

Even though several different techniques have been used for temperature measurements at macro scale, yet not all of them can be directly applied at micro scale [2]. One of the techniques seeming attractive to the research community as a powerful, non-intrusive optical tool, with a possibility to extend on micro scale, is Liquid Crystal Thermography (LCT). Introduced in early 1968 by Klein et al., it stood out with its lower cost and ease of use, nevertheless, numerous complexities regarding optical access, low seeding density, sedimentation and colour interpretation still remain challenging [3]. As it combines optical detection of reflected light of Thermochromic Liquid Crystals (TLC) with the temperature of the surrounding in which they are applied [4, 5], many researchers used this technique for local temperature mapping of both non-isothermal microstructures and liquid fluid flows [6, 7]. Just recently, a new approach with the aim to extract information about local temperature in gaseous fluid flows at macro scale was introduced [8]. Consequently, this opened a new discussion for an additional possibility of applying TLCs based on a similar approach at micro scale, despite the difference in densities [9]. One of the main obstacles remains TLCs particle size (50–100 µm), which is in general large for micro-channels. To remove this obstacle, different research groups proposed emulsification techniques to reduce the particle size down to 10 µm [3, 10]. Along with the TLCs size decrease, an optimization of the reflected light reading must be obtained simultaneously in order to maintain good signal-to-noise ratio. Optical system can be improved by adding polarizing filters, more powerful cameras and optimal light-source’s angle [6], but the major issue is still the lack of a simple and reliable calibration procedure. Most of already existing procedures are based on the improvement of ‘hue saturation intensity’ approach (HSI), which is still considered incomplete. Therefore, in this paper, a novel TLCs colour-temperature calibration approach is presented in order to extend the temperature range of TLCs by increasing the accuracy linked to the colour reading.

1.1 Principles of Liquid Crystal Thermography

Unlike conventional methods based on thermocouples and resistance thermometers, Liquid Crystal Thermography (LCT) is capable of measuring temperature fields on solid surfaces and in fluid flows [4, 5]. The principle of measuring the local temperature within a fluid flow is based on an observation of the reflected colour change of seeded temperature-sensitive tracer particles along the flow. As temperature-sensitive tracers, thermochromic liquid crystals (TLC) are used, mostly seeded either in a form of water-based droplets or as an aerosol. Their unique arrangement of molecules in chiral rotated planes produces a volume grating with a pitch – the distance between two planes aligned in the same direction. As the fluid temperature increases and being illuminated with a white light source, every TLC’s particle pitch starts to change, resulting in a certain colour wavelength reflection at a particular position in the fluid. The colour (dominant wavelengths) intensity can then be identified with intensity-based image processing and converted to a certain temperature value (calibration procedure). Consequently, that gives an insight in the developed temperature gradient along the fluid flow dependent on colour changes, and highlights the significance of a calibration procedure, which determines the accuracy of the technique itself.

2. MATERIALS AND METHODS

2.1 Experimental Setup

In this paper, different calibration approaches were tested. All experiments were performed at the microfluidics laboratory of the University of Bologna (DIN-UNIBO). The imaging system used to capture the digital images is schematically shown in Fig. 1. During the measurements, the TLC bulk material sample (*Hallcrest UN R25C10W*) was deposited on a copper block (12.3 × 6.9 cm, 3 mm thick), previously coated with black paint. The temperature of the block surface was increasing by changing the electrical voltage applied to a series of electical resistances placed under the block. Three thermocouples, mounted on the block surface around the sample, were measuring this temperature change. As the temperature readings were very close to each other (±0.5 K), it confirmed a uniform temperature distribution of the block. Another thermocouple was positioned close to the copper block to monitor the room temperature. To capture digital colour images, a USB camera coupled with a white light-emitting diode source (*Digital USB microscope camera, Conrad Electronic SE, ×800, 2MP*) was used. The camera was aligned perpendicular to the surface of the block to avoid the bias errors in the temperature estimation. However, as the central part of the captured images was the best focused, a Matlab Image Toolbox algorithm was used to extract a central field-of-view (290 × 342 px) which was further analyzed pixel by pixel.

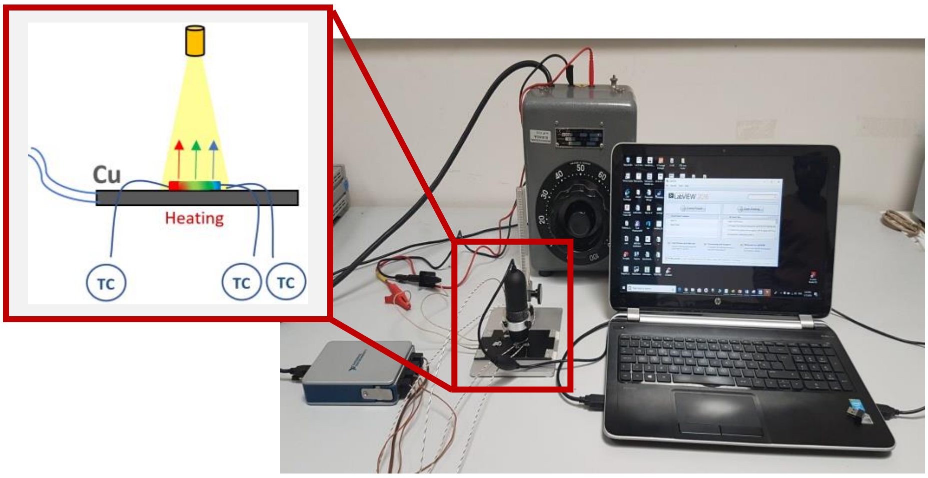


Figure 1: Calibration setup consists of: USB camera, copper block, TLC sample, T-type thermocouples, NI module, el. power supply, PC

2.2 Methods

2.2.1 RGB calibration approach

There are several independent methods that have been used to extract a reliable relationship between TLCs colour and their absolute temperature value [5]. In one of the methods, a colour intensity is observed as a triplet of numbers (0, 255), which represent the combination of red (R), green (G) and blue (B) primary colours, or RGB colour space. Among many researchers, Vejrazka and Marty [11] have directly correlated the RGB colour components of an image with temperature, and proved that this approach has a perfect sense when it is addressed to an imaging device. Thus, in this paper, this approach was tested first and the trends of the RGB intensities were obtained by averaging the data contained in each image for a fixed surface temperature value by using five sets of data (Fig. 2). By means of a Matlab routine, the captured digital images (640 × 480 px) were first cut on a central region with the best focus (290 × 342 px), and then divided on 10×10 px interrogation windows, from which the RGB values were decomposed. Since the block temperature is nearly uniform within the observed region, each interrogation window is expected to have almost the same temperature and RGB values. For a fixed block temperature, the average of the RGB values associated to each interrogation window has been calculated and, finally, the obtained RGB values have been averaged for the whole central region. These RGB values have been reported as a function of the block temperature in Fig. 2.

In our case, the selected TLC bulk material (*Hallcrest UN R25C10W*) was capable of measuring the local temperature starting from 25 °C up to 35 °C; it is evident that the red component (R) is predominant close to 25 °C as well as the blue component close to 35 °C. From local temperature values larger than 35 °C, the RGB components become constant due to the saturation of the TLC colour.

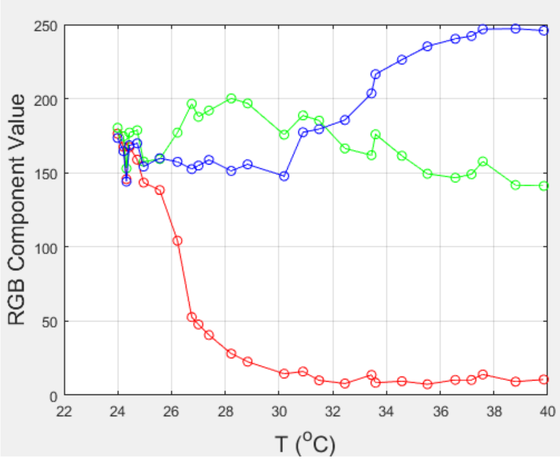


Figure 2: Average RGB intensities of the five sets of images, obtained by using the RGB values linked to 10×10 px interrogation windows contained in the central region of each image, as a function of the block temperature

2.2.2 HSI calibration approach

The RGB components shown in Fig. 2 as a function of temperature can be directly used as indicators of the local temperature, but it has been demonstrated that this approach is not so efficient.
An alternative approach is to mix these three colour components in one, and use it as indicator of the local colour value (and temperature). This approach, similar to the human perception of colours and nowadays very popular among research community, is the Hue-Saturation-Intensity (HSI) colour space. In this case, the color is individuated by means of 3 components:

- *H*: which represents a shade of a particular colour (red, green, yellow, orange, purple, magenta, blue);
- *S*: which represents a degree of mixture of the real colour with white, or so-called saturation (higher saturation means more pure and vibrant colour, while lower saturation means muted and grayish colour);
- *I*: which represents the brightness of the colour between a black and white version of the image.

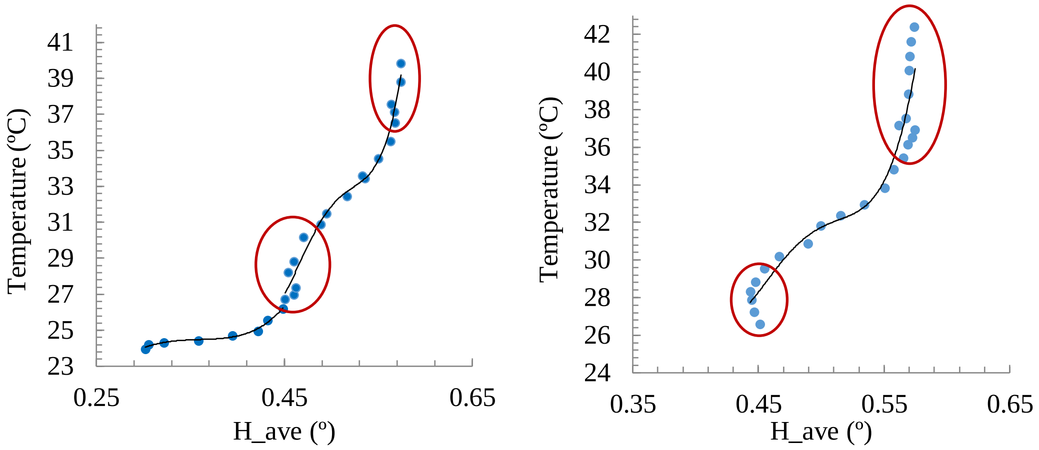
There are several formulations to calculate *HSI* from *RGB* colour space [5, 12]. A simplified version of Hay and Hollingsworth's formulation [13], in form of the '*rgb2hsv*' Matlab function, is frequently used due to its simplicity and independence from illumination intensity.
The following equations are applied in order to obtain H, S and I from the primary colors (RGB):

$$\mathrm{I} = \max\ (\mathrm{R}, \mathrm{G}, \mathrm{B})$$

$$S = \min\ \left(\mathrm{I} - \frac{\min(\mathrm{R},\mathrm{G},\mathrm{B})}{\mathrm{I}}\right) \tag{1}$$

$$H = \frac{1}{6}\left\{\begin{cases} \dfrac{G-B}{S} & if\ R = I \\ 2 + \dfrac{B-R}{S} & if\ G = I \\ 4 + \dfrac{R-G}{S} & if\ B = I \end{cases}\right\}$$

In our experimental data, a 4th-degree polynomial fitting has been used in order to link the mean hue value (*H_ave*) to the temperature measured by the thermocouples (Fig. 3) in the central window. In Fig. 3a, two separate calibration curves, obtained from 5 experimental data sets are presented. In this specific case, the data from the whole temperature range could be calibrated with only one curve, however it would result in obtaining a non-monotonic trend with higher uncertainty. Another possibility is to exclude the data obtained for the red-colour range, as shown in Fig. 3b for only one data set measurement. In both cases, it can be observed that not all of the data points match the calibration curve. The average Hue values in separate regions corresponded to more than one temperature value (see the regions within the circles). This decreased the technique's accuracy and narrowed the curve range further, which limited the calibration of the TLCs only on the range of temperature between the circles, where a biunivocal correspondence between *T* and *H_ave* is observed.



(a) (b)

Figure 3: Calibration curve for 10×10 px interrogation windows, contained in one image per temperature value of (a) 5 calibration experiments and (b) one calibration experiment by using HSI approach

2.2.3 *New 3D vectorial sphere space calibration approach*

In order to expand the calibration range, a new approach is introduced, where the same value of *H_ave* can be obtained with different combinations of primary colors. First, all raw RGB values were normalized and accounted for calculation of two angles, φ and θ as shown in Eq. (2-3):

For $0 \leq \varphi \leq 2\pi$:

$$\varphi = \tan^{-1}\frac{g}{r} \tag{2}$$

For $-\pi \leq \theta \leq \pi$:

$$\theta = \tan^{-1}\frac{b}{\sqrt{r^2+g^2}} \tag{3}$$

The red colour was introduced as a radius of 3D vectorial spherical surface (Fig. 4), on which by calculating the two angles, the real position of RGB data set could be identified. As the 3D vectorial spherical surface colour map rotates, the position of each data can be located and further better fitted in spherical coordinates (angles vs temperature). In Fig. 4, the averaged RGB data from 5 experiments (red colour) and one experiment (black colour) are represented and compared in a 3D sphere. As the trend is quite similar, the same calibration curve can be used for both multiple and single measurement data set.

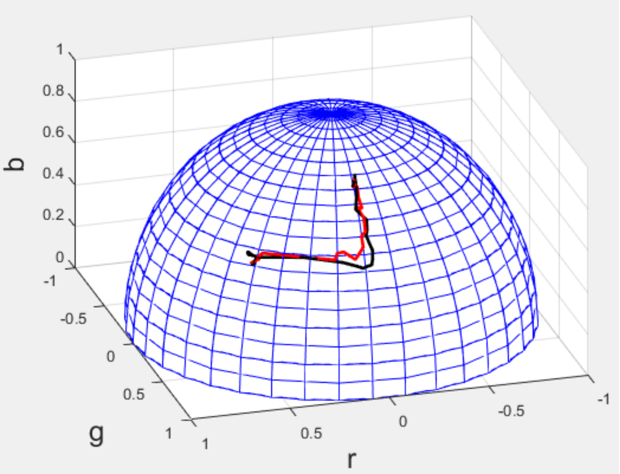


Figure 4: Comparison of the averaged RGB data from 5 experiments (red colour) and one experiment (black colour) by using a new 3D vectorial sphere space approach

3. RESULTS AND DISCUSSION

3.1 New calibration curves

In order to directly calculate the real temperature value from raw RGB data, through φ and θ angles, the following equations Eq. (4-5) have been proposed for the tested TLC bulk material:

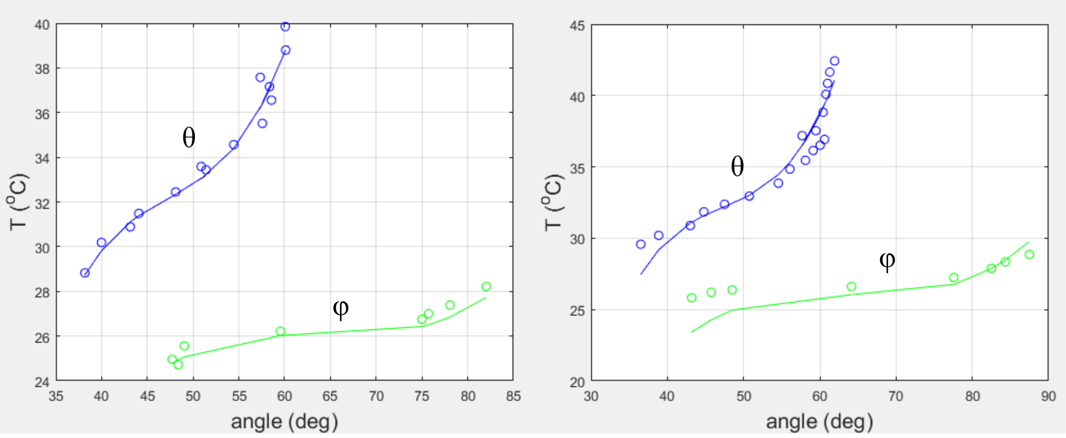
For green-colour zone:

$$T = 0.00029 \cdot \varphi^3 - 0.0557 \cdot \varphi^2 + 3.566 \cdot \varphi - 50.05 \tag{4}$$

For blue-colour zone:

$$T = 0.001828 \cdot \theta^3 - 0.2596 \cdot \theta^2 + 12.51 \cdot \theta - 172.2 \tag{5}$$

The 3rd-degree fit for bulk TLCs has been divided in two calibration curves: for temperature ranges between 26–29 °C (where green colour is dominant) and 29–41 °C (where blue colour is dominant) (Fig. 5). The two curves were fitted due to the 5 experimental data sets and afterwards applied on the single measurement data set. The curves fit the data from 5 experiments quite well (Fig. 5a), whereas within the single measurement data set show the higher uncertainty only in the first three points (Fig. 5b).



(a) (b)

Figure 5: (a) Better fitted calibration curves for two angles: φ (where green colour is dominant) and θ (where blue colour is dominant) obtained for (a) 5 and (b) a single measurement data set

To check the accuracy of the newly proposed approach, the errors in measured temperature by using HSI colour space and 3D vectorial sphere space were calculated and shown in Tab. 1. As observed in the table, the average error in these two approaches for the green and blue colour range is lower than 0.5 K for HSI and lower than 0.4 K for the newly proposed method.

In the red colour range, i.e. between 24–24.7 ºC, where temperature is dependent on both φ and θ angles, further development is necessary.

No.	Real temperature, *Tr* (ºC)	Measured temperature with HSI, *Tm* (ºC)	Error in HSI (K)	Measured temperature with 3D vectorial sphere space, *Tm* (ºC)	Error in 3D vectorial sphere space (K)
1	24.0	24.1	0.1	-	-
2	24.2	24.1	0.1	-	-
3	24.3	24.3	0	-	-
4	24.4	24.5	0.1	-	-
5	24.7	24.6	0.1	24.9	0.2
6	25.0	25.1	0.1	24.8	0.2
7	25.6	25.4	0.2	25.1	0.5
8	26.2	26.2	0	26.0	0.2
9	26.7	27.1	0.4	26.4	0.3
10	27.0	28.1	1.1	26.5	0.5
11	27.4	28.3	0.9	26.8	0.5
12	28.2	27.4	0.8	27.7	0.5
13	28.8	28.1	0.7	28.7	0.1
14	30.2	29.2	1	29.8	0.4
15	30.9	31.1	0.2	31.1	0.2
16	31.5	31.6	0.1	31.4	0.1
17	32.4	32.8	0.4	32.3	0.1
18	33.4	33.5	0.1	33.2	0.2
19	33.6	33.4	0.2	33.0	0.6
20	34.6	34.5	0.1	34.4	0.2
21	35.5	36.4	0.9	36.4	0.9
22	36.6	37.5	0.9	37.2	0.6
23	37.2	37.3	0.1	37.0	0.2
24	37.6	36.6	1	36.2	1.4
25	38.0	39.2	1.2	38.8	0.8
26	39.8	39.3	0.5	38.8	1.0

Table 1: Errors in measured temperature from 5 experimental data sets by using HSI colour space and 3D vectorial sphere space

4. CONCLUSIONS

A new approach proposed here combines all RGB data by means of two angles (φ and θ), which results in an extended calibration curve of TLC particles with good data points fitting with the calibration curve. The critical regions, in which the *H_ave* values were not indicating the accurate temperature measurements, especially in single measurement data set, were significantly reduced. Further improvements in obtaining temperature values in a red-colour range are highly necessary as this may be useful and simplified approach for the thermochromic liquid crystals calibration, which was up-to-date considered incomplete.

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