The basics and issues of Thermochromic Liquid Crystal Calibrations


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Abstract

Thermochromic Liquid Crystals (TLCs) have been widely used by researchers in heat transfer and fluid flow communities as a thermal imaging tool for mapping surface and spatial temperature distributions. In order to utilize TLCs for quantitative temperature measurements, calibration is first necessary to determine the colour-temperature relationship of TLCs. This paper is aimed to provide novice and intermediate users of TLCs with a review on the basics and issues pertaining to calibrations of TLCs, particularly for surface thermography. A general overview of TLCs, the basic elements of a TLC calibration rig, and the common calibration methods of TLCs are described. The crucial issues associated with calibrations of TLCs, namely, imaging, colourimetry, illumination, hysteresis, film thickness and aging, and the methods used to compensate for these effects are discussed. This paper is intended to provide useful information to novice and intermediate users of TLCs, particularly on TLC calibrations.

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1. Introduction

It is known that solution to heat transfer problems have led to the development of sophisticated thermal control systems for on-board satellites, spacecrafts and International Space Station (ISS), improved heating techniques for the design of water heaters and cooking appliances, and enhanced cooling technologies for gas turbine propulsion systems, air-conditioning systems, refrigeration and freezing of perishable food products and electronics thermal management. Due to the fact that heat transfer is a form of energy transfer by virtue of temperature difference knowledge of the surface and spatial temperature distributions in a flow field is an essential element in solving heat transfer problems [1,2].

The use of Thermochromic Liquid Crystals (TLCs) is commonplace among researchers in heat transfer and fluid flow communities for mapping surface and spatial temperature distributions. TLCs have been employed as thermal imaging tools in applications such as gas turbine heat transfer [3–5], flow visualization [6–8], electronics thermal management [9,10], microfluidic devices [11,12] and medical diagnostics [13,14]. In typical temperature measurements, TLCs are applied to the model surface in which the temperature distribution is to be determined. Images of the colour play are captured by commercial imaging hardware such as digital video cameras, and processed after the experiment using in-house image-processing algorithms to yield full-field temperature measurements. Measurements of the temperature distribution allow researchers to infer useful thermal parameters such as heat transfer coefficient (h), adiabatic wall temperature (Taw), film cooling effectiveness (η), et cetera. The method of using temperature-sensitive TLCs for mapping surface and spatial temperature distributions is called Liquid Crystal Thermography, otherwise known as Liquid Crystal Thermal Imaging.

In order to utilize TLCs for quantitative temperature measurements, calibration is first necessary to determine the colour-temperature relationship of TLCs. This paper is aimed to provide novice and intermediate users of TLCs with a review on the basics and issues pertaining to calibrations of TLCs, particularly for surface thermography. Section 2 is focused on a general overview of TLCs, their molecular structures, commercial availability and nomenclature. Section 3 is focused on the basics of TLC calibrations. The need for calibrations of TLCs, the basic elements of a TLC calibration rig and the common TLC calibration methods are presented in this section. The crucial issues associated with calibrations of TLCs are the subjects of Sections 4–9. Section 4 is focused on imaging, which includes a description of the human visual system, the similarities and dissimilarities between the digital video camera and the human visual system (i.e. imaging sensor, camera components, white balance and gamma). Section 5 is focused on colourimetry, which includes a general description of colour, colour spaces such as CIE XYZ, RGB and HSI, as well as a description of hue-based and intensity-based calibrations. Section...
it is hoped that the paper serves as a helpful reference. The basics and issues of Thermochromic Liquid Crystal Calibrations. Exp. Therm. Fluid Sci. (2010) xxx–xxx

2. Thermochromic Liquid Crystals

2.1. Molecular structure of TLCs

Thermochromic Liquid Crystals (TLCs) are a special classification of Thermotropic Liquid Crystals (TTLCs). TTLCs are complex organic substances which exhibit an intermediate phase of matter between pure liquids and pure crystalline solids as function of temperature. All TLCs are thermotropic; however, all TTLCs are not necessarily thermochromic. The extent to which TTLCs are thermochromic is determined by the molecular arrangement of Thermochromic Liquid Crystals (TLCs) are a special classifica-

### Nomenclature

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Description</th>
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<tbody>
<tr>
<td>CCD</td>
<td>charge coupled device</td>
</tr>
<tr>
<td>CCT</td>
<td>correlated colour–temperature</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de l’Eclairage</td>
</tr>
<tr>
<td>CLC</td>
<td>Cholesteric Liquid Crystal</td>
</tr>
<tr>
<td>CMOS</td>
<td>complementary metal oxide semiconductor</td>
</tr>
<tr>
<td>CNLC</td>
<td>Chiral-Nematic Liquid Crystal</td>
</tr>
<tr>
<td>CRI</td>
<td>Colour Rendering Index</td>
</tr>
<tr>
<td>CT</td>
<td>colour–temperature</td>
</tr>
<tr>
<td>DVD</td>
<td>digital versatile disc</td>
</tr>
<tr>
<td>FSCI</td>
<td>Full-Spectrum Colour Index</td>
</tr>
<tr>
<td>HSI</td>
<td>Hue–Saturation–Intensity</td>
</tr>
<tr>
<td>HSV</td>
<td>Hue–Saturation–Value</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>MATLAB</td>
<td>matrix laboratory</td>
</tr>
<tr>
<td>NTSC</td>
<td>National Television Systems Committee</td>
</tr>
<tr>
<td>PAL</td>
<td>Phase Alternating Line</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional–Derivative–Integral</td>
</tr>
<tr>
<td>QVGA</td>
<td>Quarter Video Graphics Array</td>
</tr>
<tr>
<td>RGB</td>
<td>Red–Green–Blue</td>
</tr>
<tr>
<td>ROI</td>
<td>region of interest</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SVG A</td>
<td>Super Video Graphics Array</td>
</tr>
<tr>
<td>TLC</td>
<td>Thermochromic Liquid Crystal</td>
</tr>
<tr>
<td>TLCS</td>
<td>Thermochromic Liquid Crystals</td>
</tr>
<tr>
<td>TTLC</td>
<td>Thermotropic Liquid Crystal</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>UXGA</td>
<td>Ultra Extended Graphics Array</td>
</tr>
<tr>
<td>VGA</td>
<td>Video Graphics Array</td>
</tr>
<tr>
<td>XGA</td>
<td>Extended Graphics Array</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>colour correction matrix (dimensionless)</td>
</tr>
<tr>
<td>A_{surface}</td>
<td>surface area (m²)</td>
</tr>
<tr>
<td>B_{cal}</td>
<td>blue intensity from calibration (dimensionless)</td>
</tr>
<tr>
<td>B_{act}</td>
<td>blue intensity from actual test (dimensionless)</td>
</tr>
<tr>
<td>C_{pixel}</td>
<td>a colour pixel within an image (pixel)</td>
</tr>
<tr>
<td>D_{nth}</td>
<td>distance between nth node and generic pixel (m)</td>
</tr>
<tr>
<td>DSC_{TLC}</td>
<td>dry solids content of TLC (%)</td>
</tr>
<tr>
<td>E_{(TLC)}</td>
<td>relative spectral power distribution of illumination source</td>
</tr>
<tr>
<td>G_{cal}</td>
<td>green intensity from calibration (dimensionless)</td>
</tr>
<tr>
<td>G_{act}</td>
<td>green intensity from actual test (dimensionless)</td>
</tr>
<tr>
<td>γ</td>
<td>gamma used for power-law transformation (dimensionless)</td>
</tr>
<tr>
<td>H</td>
<td>hue in the HSI colour space (dimensionless)</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient (W/m² K)</td>
</tr>
<tr>
<td>I</td>
<td>intensity in the HSI colour space (dimensionless)</td>
</tr>
<tr>
<td>I_0</td>
<td>input intensity or grey level (arbitrary units)</td>
</tr>
<tr>
<td>I_0</td>
<td>output intensity or grey level (arbitrary units)</td>
</tr>
<tr>
<td>M</td>
<td>RGB to CIE XYZ transformation matrix (dimensionless)</td>
</tr>
<tr>
<td>NT_c</td>
<td>number of tones for a colour component (dimensionless)</td>
</tr>
<tr>
<td>η</td>
<td>film cooling effectiveness (dimensionless)</td>
</tr>
<tr>
<td>P</td>
<td>generic pixel in an image (pixel)</td>
</tr>
<tr>
<td>P(λ)</td>
<td>spectral reflectance of the surface</td>
</tr>
<tr>
<td>p</td>
<td>pitch length of TLC (nm)</td>
</tr>
<tr>
<td>Q</td>
<td>optimization parameter (dimensionless)</td>
</tr>
<tr>
<td>RGB</td>
<td>red, green and blue tristimulus values (arbitrary units)</td>
</tr>
<tr>
<td>R_{cal}</td>
<td>red intensity from calibration (dimensionless)</td>
</tr>
<tr>
<td>R_{act}</td>
<td>red intensity from actual test (dimensionless)</td>
</tr>
<tr>
<td>r</td>
<td>measured RGB tristimulus vector (dimensionless)</td>
</tr>
<tr>
<td>r_{cal}</td>
<td>corrected RGB tristimulus vector (dimensionless)</td>
</tr>
<tr>
<td>r(λ), g(λ), b(λ)</td>
<td>RGB colour-matching functions for 2° standard observer</td>
</tr>
<tr>
<td>S</td>
<td>saturation in the HSI colour space (dimensionless)</td>
</tr>
<tr>
<td>T_{aw}</td>
<td>adiabatic wall temperature (°C)</td>
</tr>
<tr>
<td>T_{BS}</td>
<td>blue start temperature of TLC (°C)</td>
</tr>
<tr>
<td>T_{BS,new}</td>
<td>new blue start temperature of TLC (°C)</td>
</tr>
<tr>
<td>T_{CL}</td>
<td>clearing point temperature of TLC (°C)</td>
</tr>
<tr>
<td>T_{calibration}</td>
<td>temperature at ith node in an image (°C)</td>
</tr>
<tr>
<td>T_c</td>
<td>temperature at peak green intensity (°C)</td>
</tr>
<tr>
<td>T_f</td>
<td>temperature at higher end of useful calibration range (°C)</td>
</tr>
<tr>
<td>T_l</td>
<td>temperature at lower end of useful calibration range (°C)</td>
</tr>
<tr>
<td>T_M</td>
<td>temperature in middle of useful calibration range (°C)</td>
</tr>
<tr>
<td>T_R</td>
<td>temperature at a generic pixel in an image (°C)</td>
</tr>
<tr>
<td>T_g</td>
<td>temperature at peak red intensity (°C)</td>
</tr>
<tr>
<td>T_{BS}</td>
<td>red start temperature of TLC (°C)</td>
</tr>
<tr>
<td>t_{film,dry}</td>
<td>desired dry film thickness (μm)</td>
</tr>
<tr>
<td>θ</td>
<td>dimensionless temperature (dimensionless)</td>
</tr>
<tr>
<td>θ_λ</td>
<td>illumination angle (°)</td>
</tr>
<tr>
<td>θ_φ</td>
<td>viewing angle (°)</td>
</tr>
<tr>
<td>UVW</td>
<td>imaginary tristimulus values developed by CIE in 1960 (arbitrary units)</td>
</tr>
<tr>
<td>u^<em>, v^</em></td>
<td>chromaticity coordinates in the CIE 1976 u^<em>–v^</em> Uniform Chromacity Scale diagram (dimensionless)</td>
</tr>
<tr>
<td>V_{TLC}</td>
<td>volume of sprayable coating (ml)</td>
</tr>
<tr>
<td>W_{TLC,dry}</td>
<td>weight of TLC dry solids (g)</td>
</tr>
<tr>
<td>W_{TLC,wet}</td>
<td>weight of TLC solution (g)</td>
</tr>
<tr>
<td>XYZ</td>
<td>imaginary tristimulus values developed by CIE in 1931 [arbitrary units]</td>
</tr>
<tr>
<td>x, y</td>
<td>chromaticity coordinates in the CIE 1931 x–y chromaticity diagram (dimensionless)</td>
</tr>
</tbody>
</table>
| x_0, y_0 | chromaticity coordinates of the standard illuminant used as hue origin in CIE 1931 x–y chromaticity dia-
| ξ | normalized temperature (dimensionless) |
the mesophase.\(^1\) TTLCs are generally classified as nematic, smectic and chiral-nematic, based on the molecular arrangement of the mesophase. In the nematic mesophase, the molecules\(^2\) possess low positional order and high orientational order. The direction of the molecules is dominant towards one direction; however, the molecules are not positioned systematically as in a lattice. In the smectic mesophase, the molecules possess both high positional and orientational order, and therefore the molecules are packed in a systematic pattern. The nematic and smectic mesophases are both optically inactive, and therefore they are not thermochronic.\(^{15–17}\)

The chiral-nematic mesophase, also used interchangeably with the cholesteric mesophase, is characterized by the formation of helical structures called helices due to the distinctive shape of nematic molecules containing chiral centres. The distinction between Chiral-Nematic Liquid Crystals (CNLCs) and Cholesteric Liquid Crystals (CLCs) are that the latter is derived from cholesterol esters whereas the former is derived from non-sterol chemicals such as phenyl-benzoate esters.\(^{7,18}\) The helix can be visualized as a stack of two-dimensional microlayers, whereby each microlayer consists of chiral molecules. The molecules produce intermolecular forces such that the director of each microlayer is twisted at a certain angle relative to adjacent microlayers, forming a continuous helical pattern, as shown in Fig. 1. The extent to which CNLCs are thermochromic is dependent on their textures. The common textures for CNLCs are focal-conic and planar.\(^{15,20}\)

In the focal-conic texture, the helices are packed in helical and hyperbolic paths, whereby the helical axes are parallel with the direction of incident light. Thus, CNLCs in the focal-conic texture are optically inactive and consequently not thermochromic. The focal-conic texture is formed when TTLCs are cooled from the isotropic liquid phase to the chiral-nematic mesophase. In the planar texture,\(^3\) the helices are packed such that the helical axes are aligned parallel with the incident light. The planar texture is formed when CNLCs are heated from the smectic to chiral-nematic mesophase.\(^{15,20}\) This characteristic molecular arrangement gives CNLCs in the planar texture their unique optical properties such as birefringence, optical activity, circular dichroism and selective reflection of visible light as function of temperature, and thus being termed Thermochromic Liquid Crystals. The optical properties of TLCs are beyond the scope of this paper, and the reader is referred to excellent references by Dabiri and Gharib,\(^8\) Kasagi et al.,\(^{16}\) Hallcrest,\(^{21}\) and Platzter et al.\(^{22}\) for a treatment of some of the optical properties.

2.2. Commercial availability of TLCs

TLCs are commercially available in several formats, the common ones being pure TLCs and microencapsulated TLCs. Pure TLCs are also known as raw, unencapsulated or unsealed TLCs, and are available as aqueous slurries and pre-manufactured sheets. Pure TLCs are preferable due to their brilliant colour play and high spatial resolution in the sub-micron range. A spatial resolution of 0.83 μm was achievable.\(^{23}\) However, pure TLCs require special handling as they are highly susceptible to degradation from the atmosphere, dust, fibre particles, ultraviolet (UV) radiation, fats, greases and organic solvents, which would cause alteration to the colour play characteristics of TLCs. This in turn, reduces the shelf life of pure TLCs within the range of several hours to several days.\(^{7,21,24,25}\)

Microencapsulated TLCs are basically TLCs which are encased within spherical polymer capsules with diameters varying between 10 and 15 μm through a process called microencapsulation. They are preferable because they are chemically more stable and protected against degradation compared with pure TLCs. Microencapsulated TLCs are available as water-soluble and water-resistant aqueous slurries which can be mixed with binder material and water to form sprayable coatings. They are also available as pre-manufactured sheets, whereby microencapsulated TLCs are readily deposited on thin, clear polyester sheets with black backing, and can be supplied with pressure-sensitive adhesives. Sprayable coatings are generally preferable for models with complex geometries due to their flexibility in application methods. Sprayable coatings can be applied to the surface by airbrushing, brushing, rolling, dipping, pouring, and screen printing. Pre-manufactured sheets are preferable due to their ease of surface preparation as they can be readily attached onto the surface; however, they are limited for use on flat surfaces.\(^{7,16,21,24,25}\)

From Fergason (cited by Sillekens et al.,\(^{26}\) and Wiberg and Lior,\(^{27}\)), the response time of TLCs is the time required by the molecules to attain a new molecular configuration due to a slight difference in temperature. According to Parsley,\(^{18}\) the response time of TLCs is dependent on the chemical composition of TLCs; it was stated that CLCs possess response times on the order of hundredths of a millisecond, whereas CNLCs possess response times on the order of tenths of a millisecond. From Fergason (cited by Sillekens et al.,\(^{26}\)), the intrinsic response time of a liquid crystal is on the order of 0.1 s, whereas the response time of the encapsulating material is estimated to be less than 1 s. Ireland and Jones\(^{28}\) showed that the response time of a microencapsulated chiral-nematic TLC applied to a film thickness of 10 μm is 0.003 s. Höhmann and Stephan (cited by Wagner and Stephan,\(^{23}\)) computed a response time for a cholesteric TLC tracer particle to be...
0.15 s. Hence, the response time of TLCs is indeed dependent on the chemical composition of TLCs, where CNLCs generally have faster response times than CLCs.

2.3. Nomenclature of TLCs

From the nomenclature given by Hallcrest [24], TLCs are identified by their red start temperatures and bandwidths. The red start temperature is the temperature at which TLCs first reflect colour in the visible spectrum (red), and is also referred to as the event temperature [13,14,29–32], lower clearing point temperature [33], lower temperature limit [27] or activation temperature [34]. Below the red start temperature, TLCs appear transparent. The bandwidth is the temperature range at which TLCs actively reflect visible light, and is also referred to as the blue start temperature [13,14,29,30,35], colour bandwidth [14,31], activation bandwidth [33], activation range [36–38], optical activation range [23] or the ambiguity band [16]. When the TLCs pass through their bandwidths, they reflect visible light from longer wavelengths (red) to shorter wavelengths (blue) as temperature increases until their clearing point temperatures are reached. The clearing point temperature is the temperature at which TLCs cease to reflect colours in the visible spectrum, and is also referred to as the blue stop temperature [39,40], upper clearing point temperature [33], upper temperature limit [27] or the critical temperature [41]. Beyond the clearing point temperature, TLCs appear transparent again.

From a theoretical perspective, the bandwidth is the temperature range between the red start and clearing point temperature of the TLC, as this is the range at which TLC actively reflects visible light. However, the bandwidth is defined by Hallcrest [24] as the temperature range between the red start and blue start temperature of the TLC. There are two types of TLCs commercially available based on their bandwidths, namely narrowband and wideband. Narrowband TLCs typically have bandwidths ranging from 0.5 to 4 °C, whereas wideband TLCs typically have bandwidths ranging from 5 to 30 °C. The red start temperatures range from −30 to 120 °C [24]. The nomenclature given by Hallcrest Technologies Limited, now known as LCR Hallcrest Limited, is adopted in this paper for simplification purposes, and due to the fact that the TLCs commonly used by researchers in heat transfer and fluid flow communities are manufactured by Hallcrest. As an example, a microencapsulated chiral-nematic TLC having the designation ‘R30C1W’ indicates that the TLC possesses a red start temperature of 30 °C and a bandwidth of 1 °C. The symbols ‘R’ and ‘W’ in the above nomenclature indicate the red start temperature and bandwidth, respectively, and the symbol ‘C’ indicates that the specified temperatures are in degree Celsius.

3. Thermochromic Liquid Crystal Calibration

3.1. The need for calibration

The key element in using a particular sensor is to obtain a relationship between the input and output of the sensor. Similarly in Liquid Crystal Thermography, the key difficulty is to determine the colour–temperature relationship of the TLC, which is converting the colour information available as an image into an estimate of temperature [42]. Calibration is therefore essential to verify the colour–temperature relationship of the TLC, as such information provided by the manufacturers is insufficient for quantitative temperature measurements [43]. For example, let us say the reader has a microencapsulated chiral-nematic wideband TLC in hand, having the designation R35C5W. From the nomenclature given by Hallcrest, the reader expects that the TLC will display red at a temperature of 35 °C, and will begin to display blue at a temperature of 40 °C. The reader also expects that the TLC will reflect colours in the visible spectrum from red, then passes through orange, yellow, green, blue to violet, as the temperature increases within the colour play interval of the TLC. However, what will be the temperature at which the TLC displays a specific colour? The correlation between colour and temperature can only be obtained by calibrating the TLC. Although the colour–temperature profiles of TLCs can be supplied by the manufacturers upon request, the profiles may be dissimilar due to differences in surface preparation, experimental setups and conditions between the reader and the manufacturer. In addition, Lazarra [44] stated that the colour–temperature profiles of TLCs may be different due to time – a profile obtained from a calibration conducted prior to shipping of the TLC may differ from a profile obtained when the TLC reaches the customer. This further emphasizes the need for calibration of TLCs.

3.2. Basic elements of a TLC calibration rig

Now that the reader knows the need for calibrating TLCs, the reader is faced with the question, “How do I calibrate TLCs?” The construction of an experimental rig used for calibrating TLCs generally depends on the reader’s application – an experimental rig used for surface thermography will be different than that used for flow visualization. In this section, a basic TLC calibration rig is described, particularly for surface thermography. A basic experimental rig for calibrating TLCs generally consists of a calibration surface, with point temperature sensor(s), imaging system, heating and/or cooling system, illumination source and dark enclosure. These elements are described briefly as follows.

3.2.1. Calibration surface with point temperature sensor(s)

A calibration surface is needed for calibrating TLCs. If calibration is conducted in situ, the calibration surface is the actual test surface used for heat transfer measurements. For example, if Liquid Crystal Thermography is used to determine the heat transfer coefficient and adiabatic wall temperature distributions on a turbine blade and calibration of TLC is conducted in situ, the calibration surface is the turbine blade surface. If calibration is conducted non-in situ, a separate surface is used as the calibration surface rather than the actual test surface. In such cases, a block or flat plate made of high thermal conductivity material such as aluminium or copper is typically used as the calibration surface. High thermal conductivity material is often chosen to provide a nearly isothermal surface during calibrations of TLCs, which therefore gives a more uniform temperature distribution [40]. A point temperature sensor or multiple point temperature sensors such as thermocouples or thermistors are usually embedded within the calibration surface using thermally conductive adhesive or grease in order to monitor the surface temperature during calibrations. Black backing is applied on the calibration surface prior to deposition of TLCs to provide improved colour display for the TLCs. Generally, flat black paints are preferable compared to gloss paints to provide a matte black finish, as the light reflected by gloss paints may cause attenuation to the light reflected by TLCs.

3.2.2. Imaging system

An imaging system which comprises of hardware and software is required for the acquisition, processing and storage of images and data obtained during calibrations of TLCs. Video cameras, also known as camera recorders or camcorders, are typically used for recording the colour play of TLCs. In the 1990s, videos are typically recorded in analogue format and stored in video tapes. Therefore, frame grabbers (also called image processing boards [35]) are required to ‘grab’ a frame or multiple frames from the analogue video and convert the signals into digital format for storage and processing.
manipulation [45]. This can be clearly seen in the earlier works by Platzter et al. [22], Farina et al. [29], Behle et al. [35], Hay and Hollingsworth [37,38], Babinsky and Edwards [42], Wang et al. [46] and Sun et al. [47], among others. In recent years, videos are directly recorded in digital format and saved in storage media such as mini digital versatile discs (DVDs), digital tapes, solid state flash memory or hard disc drives. The point temperature sensor(s) embedded within the calibration surface are typically connected to a data acquisition card and inserted into a data logger to record the surface temperature history during calibrations. The color information from the image frames and surface temperature history from the data logger are processed and synchronized using image-processing algorithms written by the reader in programming software such as MATLAB in order to yield the color–temperature curve of the TLC.

3.2.3. Heating and/or cooling system

Since TLC selectively reflects colors in the visible spectrum as a function of temperature, a heating and/or cooling system is needed to provide a direction of temperature change for the TLC. An example of a heating system is a silicone rubber heater placed under the calibration surface with the lead wires of the heater are connected to a variable alternating current transformer (variac) or a Proportional–Derivative–Integral (PID) controller [48,49]. The settings of the variac or PID controller can be adjusted to control the heating rate of the calibration surface. Other heaters can also be used such as coil heaters [40] and thermostatic baths [33]. An example of a cooling system is a coldstream air gun connected to an air filter and an air compressor. The coldstream air gun basically functions to supply cold air for cooling the calibration surface. The outlet gage pressure of the air compressor and generator within the coldstream air gun can be changed to control the cooling rate of the calibration surface [50]. A standard fan can also be used for cooling the calibration surface [32]. If heat transfer measurements in the actual application are carried out in heating, then heating calibrations are required, and if the actual application involves heating and cooling, then both heating and cooling calibrations are required. The choice of a suitable heating and/or cooling system generally depends on the requirements of the reader’s application.

3.2.4. Illumination source and dark enclosure

An illumination source is needed to illuminate the calibration surface and is referred to as the primary illumination source. A variety of illumination sources have been used for calibrations of TLCs such as tungsten [51], halogen [27,31–33,35,43], fluorescent [11,37–39,43,46,48], xenon short arc lamp [8], slide projector [52] and strobe light [34]. The main objective of the illumination source, however, is to provide white light. A dark enclosure is needed to shield the experimental rig from illumination disturbances resulting from secondary sources such as sunlight and room light. A dark enclosure can be constructed simply using supporting frames covered with black cloth or black drapes.

3.3. Common TLC calibration methods

The previous section gives a general overview of the elements of a basic experimental rig for calibrating TLCs. There are a number of methods for calibrating TLCs available from the literature, however, only the three common methods are presented here, as follows.

3.3.1. Linear temperature gradient method

The linear temperature gradient method is a form of steady-state method for calibrating TLCs. The term steady-state essentially means that the temperature of the surface does not vary with time at all points of the surface [53]. The temperature however, may vary at different locations on the surface. In this method, a linear temperature gradient is imposed on the calibration surface by maintaining the ends of the surface at constant and different temperatures. The end temperatures are chosen such that they span the color play interval of the TLC. The hot and cold ends can be maintained using thermostatic baths. When the entire color play of the TLC becomes visible, the calibration surface is maintained at a steady-state condition, typically for a duration of 30 min. The color play of the TLC is captured by digital video camera and processed after the experiment to yield the color–temperature relationship of the TLC. The linear temperature gradient method is illustrated in Fig. 2, and has been employed by Farina et al. [29], Vejrazka and Marty [41], Chan et al. [43], Sun et al. [47] and Ou and Rivir [54]. This method possesses the main advantage that the entire color play of the TLC can be obtained from a single image, and is particularly useful for wideband TLCs.

3.3.2. Uniform surface temperature method

The uniform surface temperature method is a variant of steady-state method for calibrating TLCs. In this method, the calibration surface is heated at predefined temperatures between the color play interval of the TLC. The predefined temperatures can be set at increments of 0.1, 0.2, 0.5, 1 °C, et cetera, depending on the reader’s judgement. Generally, the smaller the temperature increment, the better the calibration will be, due to the increase in number of points for resolving the color–temperature relationship of the TLC. However, this comes at the expense of additional experimental and image processing time, particularly if wideband TLCs are used. When a predefined temperature is reached, the calibration surface is maintained at steady-state condition, and an image of the calibration surface is captured by digital video camera. The process is repeated until the clearing point temperature of the TLC is reached. The sequence of images is processed after the experiment to yield the color–temperature relationship of the TLC. The uniform surface temperature method is illustrated in Fig. 3, and has been employed by Wiberg and Lior [27], Grassi et al. [30], Grewal et al. [31], Bakrania and Anderson [32], Sabatino et al. [33], and Hay and Hollingsworth [37,38].

3.3.3. Transient calibration method

Contrary to steady-state, the term transient essentially means that the temperature of the surface varies with time, although the temperature is uniform over the surface [53]. Transient methods can be carried out either in heating or cooling. In transient heating methods, the calibration surface is heated to a predefined temperature, which is generally kept below the clearing point temperature of the TLC in order to avoid hysteresis. Images of the color play are recorded by digital video camera until the predefined temperature is reached. After the experiment, the color–time history obtained from the sequence of images and temperature–time history obtained from the data logger are synchronized and interpolated to yield the color–temperature relationship of the TLC, as illustrated in Fig. 4. Transient cooling methods can be carried out in a similar manner by cooling a preheated calibration surface to a temperature below the red start temperature of the TLC. Images of the color play are captured by digital video camera until the calibration surface becomes transparent. Transient calibrations have been employed by Bakrania and Anderson [32], Anderson and Baughn [39], Abu Talib et al. [48], Abdullah et al. [50], Grodzka and Facemire [55] and Chambers et al. [56]. It is noteworthy that care must be taken such that the chosen heating or cooling rates does not cause a significant delay in response time of the point temperature sensors used in transient methods, and that the frame rate chosen for post-processing is large enough to capture changes in the color play.
Transient methods possess the main advantage that they are less time-consuming compared with steady-state methods. In addition, transient methods require less complex experimental setup compared with steady-state methods, which often require thermostatic baths to maintain a linear temperature gradient method or uniform surface temperature. Mizell (cited in Chan et al. [43]), reported difficulties in maintaining a linear temperature gradient due to changes in ambient conditions, and due to the material used for their calibration surface. However, transient methods possess the disadvantage of additional post-processing time due to the large number of image frames. Although steady-state and transient methods differ in the manner of bringing TLCs to the desired temperatures, calibration results obtained from both methods are essentially the same. Bakrania and Anderson [32] showed that the calibration curves obtained for R25C10W TLC using steady-state and transient methods compare well for heating and cooling rates up to 0.03 °C/s.

The methods described in this section are intended to provide the reader with a general overview of the common methods for calibrating TLCs, and did not consider the factors which affect calibrations of TLCs. Calibrations of TLCs are influenced by a number of factors such as imaging, illumination, hysteresis, film thickness and aging, and these crucial issues form the subject of subsequent sections.

4. Imaging

4.1. The human visual system

Imaging is an essential element of calibrations of TLCs. In imaging, it is important for the reader to acquire some knowledge on the human visual system, the similarities and dissimilarities between the digital video camera and the human visual system with
In recent times, digital video cameras are typically used for recording images of the colour play of TLCs. The digital video camera is designed to emulate the human visual system. The human eye’s imaging sensor is the retina, which consists of rods and cones responsible for achromatic and chromatic vision. The imaging sensor of the digital video camera is a microchip, which can be classified as charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS) depending on the chip’s technology. The general structure of the microchip is illustrated in Fig. 6, which indicates that the microchip consists of several layers, each having a specific function. The top layer of the microchip contains minute micro lenses; one lens for one photodiode. Unlike the collection of lens which focuses the incoming light onto the focal plane, the micro lenses function to direct the incoming light onto the light-sensitive photodiodes, which otherwise would fall onto the dead regions between the photodiodes. In some digital video cameras, the microchip has an additional layer below the minute micro lenses, which is the hot mirror. The hot mirror functions as an IR cut-off filter, by passing through light in the visible spectrum and reflecting IR radiation to heat sinks in the video camera. IR radiation can distort light measurements in the photodiodes and is therefore undesirable [59]. The hot mirror is similar to the proteins in the lens of the human eye; the primary difference being that the proteins absorb IR radiation whereas the hot mirror reflects IR radiation [57,59].

Following the hot mirror, the microchip consists of a colour filter matrix (also called colour filter array) located directly above the photodiodes. The colour filter matrix is responsible for converting the colour information from the incoming light into a form that can be processed by the camera’s imaging sensor. The colour filter matrix contains red, green, and blue filters that are designed to capture the dominant wavelengths of light in the visible spectrum. The filters are positioned in a specific pattern to ensure that each photodiode receives the correct amount of light. The output of the photodiodes is then processed by the camera’s circuitry to generate an electronic image that is transmitted to a display device. The digital video camera’s imaging sensor is designed to capture the full range of visible light, from the ultraviolet to the infrared, and convert it into a digital signal that can be processed by the camera’s software. The software then uses this signal to enhance the image, adjust the exposure, and convert it into a format that can be displayed on a computer or printed on paper.
the photodiodes. Since the photodiodes are insensitive to colour, a colour filter matrix is needed to detect colour. The colour filter matrix consists of a separate filter for each photodiode, which is red, green or blue. The most common design for the colour filter matrix is the Bayer matrix. In the Bayer matrix, the filters are patterned in a way such that no two filters of the same colour are located next to each other and that the amount of green filters is twice the amount of red and blue filters. The Bayer matrix is designed with the rationale that the human eye has a greater sensitivity to green, and more green filters lead to a higher degree of colour accuracy [45, 59]. A colour filter matrix having a mosaic structure of complementary colours such as cyan, magenta, yellow and green is also available in the market, such as that used by Vogel and Boelcs [4]. The colour filter matrix is analogous to the cones in the retina.

The above description applies for a 1-chip digital video camera, in which a single microchip is used for the imaging sensor. However, 3-chip digital video cameras are also available in the market, in which three microchips are used for the imaging sensors. In 3-chip digital video cameras, a beam splitter is used to split the incoming light into three beams, with each beam directed to a red, green and blue filter, respectively. The beam splitter is typically a pure prism with semi-mirrored faces. Another variant of 3-chip digital video cameras utilizes dichroic coating in the prism, which splits the incoming light into red, green and blue beams, which eliminates the need for red, green and blue filters for the microchips [59]. The 3-chip digital video cameras emulate the human visual system more naturally due to the fact that the light entering the human eye is decomposed into red, green and blue and more green filters lead to a higher degree of colour accuracy [45, 59]. The colour filter matrix is analogous to the cones in the retina.

The components in the digital video camera are also designed to emulate the human visual system. Like the human eye, the digital video camera consists of lens, which functions to focus the incoming light onto the focal plane. The primary difference between the lens of the digital video camera and the lens of the human eye is that the former is not flexible, and therefore the shape of the lens cannot be adjusted automatically to focus the image. To overcome this limitation, the digital video camera consists of a collection of lenses, having different shapes and sizes in order to focus a clear image. The collection of lenses (also called elements) enables the digital video camera to focus objects at a multitude of distances using simple adjustments on the video camera [57, 59].

In order to emulate the human visual system, the lens of the digital video camera is fitted with an iris diaphragm, which functions to control the amount of light entering the video camera. The iris diaphragm is made of overlapping, overlapped leaves which form an approximately circular opening in the centre of the diaphragm. This circular opening is called aperture, which is similar to the eye’s pupil. The size of the aperture is represented by a parameter called f-stop, which is the ratio of the focal length of the lens to the diameter of the aperture’s opening. The f-stop is usually expressed by the letter f, followed by a number between 1.2 and 32. The larger the f-stop number, the smaller the size of the aperture, which in turn decreases the amount of light entering the video camera. For example, an aperture size of f8 allows half as much light into the video camera as an aperture size of f4 [59].

Light enters the human eye continuously as long as the eye remains open. Unlike the human eye, the digital video camera consists of a device called shutter, which opens and closes to allow light into the video camera. The length of time in which the shutter remains open is referred to as the shutter speed, and is measured in fractions of a second. Different shutter speeds are available in the digital video camera which can range from 1/50 up to 1/8000 s, depending on the camera type. The smaller the value of the shutter speed, the shorter the time in which the shutter is open, which in turn increases the capability of the video camera to capture fast-motion objects. The combination of the aperture’s opening and shutter speed forms the exposure system of the digital video camera, and plays an important role in determining the depth of field of the image [45, 59]. From Cope [45], the depth of field refers to the distance in front of and behind the point of focus in the image in which the subject remains acceptably sharp or focused. A smaller aperture size gives a greater depth of field.

It is important to set the correct exposure system for calibrations of TLCs as it is undesirable if the captured image is too bright or too dark. The exposure system can be set by adjusting the iris and shutter speed settings of the digital video camera, as well as adjusting the illumination-viewing arrangement of the experimental rig. Fig. 7a and b show a comparison of two images of a matte black calibration plate captured using Panasonic VDR-D310 digital video camera using manual white balance and a shutter speed of 1/50 s. Since the plate was stationary, a slow shutter speed was deemed sufficient. The plate was illuminated by two Phillips Fluotone™ cool daylight fluorescent sources having a CT of 6200 K. The fluorescent sources in Fig. 7a were left bare and the iris was set to 6 dB, and it can be observed that the black plate appears grey, indicating that the image was too bright. The fluorescent sources in the P-layer are drawn into the depletion area by the positive charges. The amount of negative charge drawn into the depletion area increases with increasing light intensity. The collected negative charges at each photodiode are then amplified and converted to electrical voltage, which is proportional to the amount of light intensity. Photodiodes are highly sensitive to light, and are analogous to the rods in the retina [45, 59].

### 4.2.2. Camera components

The components in the digital video camera are also designed to emulate the human visual system. Like the human eye, the digital video camera consists of lens, which functions to focus the incoming light onto the focal plane. The primary difference between the lens of the digital video camera and the lens of the human eye is that the former is not flexible, and therefore the shape of the lens cannot be adjusted automatically to focus the image. To overcome this limitation, the digital video camera consists of a collection of lenses, having different shapes and sizes in order to focus a clear image. The collection of lenses (also called elements) enables the digital video camera to focus objects at a multitude of distances using simple adjustments on the video camera [57, 59].

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**Fig. 6.** General structure of an imaging sensor in a digital video camera (reproduced and modified from White [59]).
is known, the reader should use a preset white balance setting having a value closest to the CT or CCT of the illumination source. For example, if the CT of a halogen lamp is specified to be 3000 K and the preset white balance settings available on the video camera are 3200 K and 5600 K, the 3200 K setting is more desirable. Recent models, however, provide preset white balance settings which are more intuitive, such as ‘indoor’ and ‘outdoor’. As the name implies, the indoor setting is used for indoor illumination sources such as tungsten, halogen, fluorescent or a mixture of these sources, whereas the outdoor setting is used for outdoor illumination sources such as direct afternoon sunlight, daylight from overcast skies, et cetera. The preset white balance setting works well provided the chosen setting closely matches the CT or CCT of the illumination source [60].

In the absence of CT or CCT of the illumination source, it is best to use the manual white balance setting. Manual white balance can be set simply by focusing the viewfinder of the digital video camera on a neutral white or grey reference card illuminated by the illumination source, and pressing the white balance button. The manual white balance setting allows the video camera to act as a colour–temperature metre, and therefore removes unrealistic colour casts in the image [60]. Fig. 8a and b show a comparison of two images of a matte black calibration plate captured using Panasonic VDR-D310 digital video camera, using automatic and manual white balance, respectively. The plate was illuminated by two Phillips Fluotone™ cool daylight fluorescent sources having a CT of 6200 K. The iris setting for both images were set to 9 dB. In the absence of a white patch within the field of view of the video camera, it can be seen that the image of the black plate in Fig. 8a appears blue, indicating that the use of automatic white balance was incorrect. However, it can be seen from Fig. 8b that this unsightly bluish colour cast was corrected when the manual white balance was used, and the black plate appears black, as it was supposed to be. The human eye, however, will perceive the black plate as black, regardless of the illumination source used to illuminate the plate. This is one of the considerable dissimilarities between the human visual system and digital video camera.

4.2.4. Gamma

The human visual system exhibits a non-linear logarithmic response to luminance rather than a linear response. The range of intensities to which the human visual system is able to adapt is on the order of 10^{10} from the scotopic level to the glare limit, indicating that the human visual system possesses a high dynamic range. The digital video camera however, does not possess this capability and the range of discrete intensities to which a typical 8-bit digital video camera is able to capture is 256 grey levels. Consequently, the digital video camera possesses low dynamic range [57,62]. From Jähne [62], it is for this reason that images with high contrast appear inferior when captured by the digital video camera, such that the dark regions appear too dark (underexposed) and the bright regions appear too bright (overexposed). To compensate for the deficiency in dynamic range, the digital video camera is designed to emulate the non-linear, logarithmic response of the human visual system. Hence, the imaging sensor of the digital

Fig. 7b were diffused with plain white paper to reduce glare and the iris was set to 9 dB, and it can be observed that the black plate appears black, as it was supposed to be. Setting the correct exposure system generally depends on the reader’s illumination-viewing arrangement, which is also a matter of trial and error.

4.2.3. White balance

The human eye possesses the remarkable capability to determine a white object as ‘white’ under different types of illumination. This means that the human eye is able to perceive a white object as ‘white’ regardless whether the illumination source is tungsten, halogen, fluorescent, metal halide, et cetera. The digital video camera however, does not possess this capability, and a white object may not necessarily be reproduced as white in the image. Rather, the appearance of the white object is skewed towards the colour of white light emitted by the illumination source, which in turn results in an unrealistic colour cast in the image. The image may appear yellowish, reddish or bluish, depending on the colour of white light. To compensate for this unsightly effect, the digital video camera possesses a feature called ‘white balance’. Commercial digital video cameras are equipped with a number of white balance settings – automatic, preset and manual. Since colour appearance is a crucial element in calibrations of TLCs, it is important that the correct white balance setting is used for calibrations.

The automatic white balance setting is the default setting in most digital video cameras, which automatically compensates for the colour of white light emitted by the illumination source by searching for the whitest point in the field of view and applying a best-guess algorithm. Automatic white balance works fine if there is a patch of white within the field of view. In the absence of white within the field of view, the use of automatic white balance setting may produce undesirable colour casts in the image [60].

The preset white balance setting is based on the colour–temperature of the illumination source. The term ‘colour–temperature’ (CT) refers to the colour of light emitted by a natural or artificial illumination source which perfectly matches the colour of light emitted by a blackbody when the blackbody is heated to a certain temperature in degrees Kelvin. Not all illumination sources emit white light whose colour perfectly matches the colour of light emitted by an ideal radiator. In such cases, the colour of white light emitted by a natural or artificial illumination source approximately matches the colour of light of a blackbody, and the term ‘correlated colour–temperature’ (CCT) is used to describe the colour of white light emitted by such illumination sources. Different natural and artificial illumination sources possess different colour–temperature or correlated colour–temperature, as listed in Table 1. From Table 1, it can be seen that the colour of white light changes from warm to cool as the colour–temperature or correlated colour–temperature increases.

In the 1990s, digital video cameras provide preset white balance settings using CT values such as 3200 K and 5600 K. In such models, the preset white balance setting can be used provided the reader knows the CT or CCT of the illumination source, which can be readily obtained from the manufacturer. Once this information is obtained, the reader can set the correct white balance setting by focusing the viewfinder of the digital video camera on a neutral white or grey reference card illuminated by the illumination source of interest, and pressing the white balance button.

Recent models, however, provide preset white balance settings which are more intuitive, such as ‘indoor’ and ‘outdoor’. As the name implies, the indoor setting is used for indoor illumination sources such as tungsten, halogen, fluorescent or a mixture of these sources, whereas the outdoor setting is used for outdoor illumination sources such as direct afternoon sunlight, daylight from overcast skies, et cetera. The preset white balance setting works well provided the chosen setting closely matches the CT or CCT of the illumination source [60].

In the absence of CT or CCT of the illumination source, it is best to use the manual white balance setting. Manual white balance can be set simply by focusing the viewfinder of the digital video camera on a neutral white or grey reference card illuminated by the illumination source, and pressing the white balance button. The manual white balance setting allows the video camera to act as a colour–temperature metre, and therefore removes unrealistic colour casts in the image [60]. Fig. 8a and b show a comparison of two images of a matte black calibration plate captured using Panasonic VDR-D310 digital video camera, using automatic and manual white balance, respectively. The plate was illuminated by two Phillips Fluotone™ cool daylight fluorescent sources having a CT of 6200 K. The iris setting for both images were set to 9 dB. In the absence of a white patch within the field of view of the video camera, it can be seen that the image of the black plate in Fig. 8a appears blue, indicating that the use of automatic white balance was incorrect. However, it can be seen from Fig. 8b that this unsightly bluish colour cast was corrected when the manual white balance was used, and the black plate appears black, as it was supposed to be. The human eye, however, will perceive the black plate as black, regardless of the illumination source used to illuminate the plate. This is one of the considerable dissimilarities between the human visual system and digital video camera.
video camera is designed such that it captures light intensities according to the power-law transformation:

$$I_o = (I_i)^{\gamma}$$  \hspace{1cm} (1)

where $I_o$ and $I_i$ represent the output and input intensity (grey level), respectively, and $\gamma$ represents the exponent responsible for the power-law transformation, and is called gamma. Typically, $\gamma$ has a value of 0.4, and may vary according to the imaging device [62].

With the power-law transformation, the contrast range of the image captured by the digital video camera is significantly enhanced. It shall be noted that there is a significant difference between the terms contrast range and dynamic range. From Zuber [63], contrast range refers to the greyscale range from darkest to brightest, whereas dynamic range refers to the greyscale range from darkest to brightest, with detail, as shown in Fig. 9. With the power-law transformation, the dynamic range of the image essentially remains; however, the contrast range is significantly enhanced, giving a smoother greyscale gradation. From Jähne [62], the contrast range is obtained to be 25 and 316 for $\gamma$ values of 1 and 0.4, on a 8-bit greyscale range, assuming a relative luminance of 1%, which is the smallest discernible intensity perceivable by the human eye. Hence, it can be seen from the above example that the contrast range is significantly improved for a non-linear imaging sensor ($\gamma = 0.4$) rather than a linear imaging sensor ($\gamma = 1$).

The gamma response of the digital video camera was referred to as the non-linear amplitude characteristic inherent in the imaging sensor reported by Wiberg and Lior [27], Frey (cited by Behle et al. [35]) and Behle et al. [35]. Wiberg and Lior [27] and Behle et al. [35] observed that the magnitudes of the output RGB intensities were non-linear with respect to changes in input illumination intensity. It is important for the reader to have some knowledge on gamma as gamma is related to the white balance of the digital video camera. A change in the white balance setting causes a change in the magnitudes of the RGB intensities. In the research of Behle et al. [35], the white balance was set manually by focusing the digital video camera on neutral reference grey cards and it was expected that the magnitudes of RGB intensities for colourless objects were supposed to be equal. However, it was shown that an ideal white balance setting was not achievable because of the gamma response of the digital video camera, whereby changing the white balance setting causes a mismatch in the magnitudes of RGB intensities and the RGB intensities respond non-linearly with changes in illumination intensity. In such cases, the optimum white balance setting was chosen such that the magnitudes of the RGB intensities do not differ significantly.

## 5. Colourimetry

### 5.1. Colour

The main objective of calibration of TLCs is to determine the colour–temperature relationship of TLCs. Hence, the keyword in calibrations of TLCs is colour. The reader may now ask, “What is colour?” From Wolsey et al. [64], colour is a human perception constructed from the combination of the spectral power distribution of the illumination source, spectral reflectance of the materials being illuminated by the illumination source, and the trichromatic nature of the human visual system. These elements are described briefly below, in order to aid the reader.

#### 5.1.1. Illumination spectrum

The spectral power distribution of the illumination source (also called illumination spectrum) is a graph of the radiant intensity.
emitted by the illumination source as function of wavelength of the electromagnetic spectrum. An illumination source which emits radiant intensity in the visible range of the electromagnetic spectrum, which is approximately within 380–780 nm, is referred to as a chromatic source. A monochromatic illumination source emits light at a single wavelength or a narrow range of wavelengths in the visible spectrum. The range of wavelengths in the visible spectrum for a monochromatic illumination source is provided by Rossotti (cited by Elert [65]), as shown in Table 2. Monochromatic illumination source, however, emits light at multiple ranges of wavelengths in the visible spectrum. An illumination source which provides white light is an example of a polychromatic source. The colour of white light emitted by such sources may be reddish white, yellowish white or bluish white, depending on the CT or CCT of the illumination source. An illumination source may also emit radiant intensity in portions of the electromagnetic spectrum invisible to the human eye such as ultraviolet (UV) and infrared (IR).

Illumination spectrum varies from one illumination source to another. This is illustrated in Fig. 10, which shows the spectrum of six illumination sources used in the work of Anderson and Baughn [66], namely, GE 100 W soft white tungsten lamp with a CT of 3200 K, SoLux full-spectrum halogen lamp with a CT of 4700 K, GE 20 W cool white fluorescent lamp fitted with a Spectrum 574 UV cut-off filter, GE 20 W cool white fluorescent lamp with a CT of 4100 K, Vita-Lite full-spectrum fluorescent lamp with a CT of 5500 K, and a hypothetical flat spectrum. It can be clearly seen from Fig. 10 that the illumination spectrum is different for each illumination source. The GE tungsten lamp possesses a relatively high radiant content in the red region of the visible spectrum. The SoLux and Vita-Lite full-spectrum lamps both possess a flatter radiant distribution in the visible spectrum. The GE fluorescent lamp possesses a high radiant content in the yellow and green regions of the visible spectrum, and exhibits spikes associated with the spectral lines of the mercury vapour used to cause the phosphors to fluoresce. The use of the Spectrum 574 UV cut-off filter functions to eliminate UV radiation from the GE fluorescent lamp, however, the spectrum of the lamp is altered [66]. Hence, illumination spectrum is unique, and is dependent on the type of illumination source as well as the use of UV and IR cut-off filters. Also, no two illumination sources possess exactly the same illumination spectrum even though the sources are of the same type, the same brand, and having the same technical specifications. Since illumination spectrum is related to the CT or CCT of the illumination source, which in turn determines the colour of white light emitted by the source, illumination spectrum is an important element which influences the colour appearance of objects.

5.1.2. Spectral characteristics of objects

An object illuminated by an illumination source is made of a type of material, and therefore, the object possesses different spectral absorptivity, reflectivity and transmissivity characteristics. For semi-transparent objects such as a glass plate, portions of the incident radiation are absorbed, reflected and transmitted. For opaque objects, portions of the incident radiation are absorbed and reflected. The magnitudes of absorbed and reflected radiation are dependent on the nature of the material [1]. For example, a smooth, polished copper block will have higher reflectivity compared with a wood block. The absorptivity and reflectivity characteristics of the material influence the colour appearance of objects. From Incropera and DeWitt [1], a leaf appears green because the cells of the leaf contain chlorophyll, which is a pigment showing strong absorption in red and blue, and a preferential reflection in green. Hence, the spectral characteristics of objects, particularly reflectivity characteristics, are also important elements which influence the colour appearance of objects.

Table 2

<table>
<thead>
<tr>
<th>Colour of light</th>
<th>Red</th>
<th>Orange</th>
<th>Yellow</th>
<th>Green</th>
<th>Blue</th>
<th>Violet</th>
</tr>
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</table>
5.1.3. Trichromatic nature of human visual system

The cones in the human eye are responsible for chromatic vision. From Healey and Luong [67] and Westland and Ripamonti [68], there are three classes of cones based on their response to the wavelengths in the visible spectrum, namely, L, M and S cones. The L cones respond to long wavelengths (red) with peak sensitivities at 560 nm, the M cones respond to medium wavelengths (green) with peak sensitivities at 530 nm, while the S cones respond to short wavelengths (blue) with peak sensitivities at 420 nm. From Williams et al. (cited by Westland and Ripamonti [68]), the cones in the human eye are responsible for chromatic vision. From Gonzalez and Woods [57], the CIE XYZ colour space can be visualized using the two-dimensional CIE x–y chromaticity diagram, as shown in Fig. 11. The diagram, which is still widely used today, represents the colours perceived by the human visual system for fields of view less than 4°. The boundary of the horseshoe-shaped diagram represents the locus of monochromatic colours in the visible spectrum and is termed the spectrum locus. The straight line connecting the ends of the spectrum locus is termed the purple line. The colours perceived by the human visual system lie within the spectral locus [57,69,70].

The CIE x–y chromaticity diagram is a useful plot of colour, saturation and colours resulting from additive mixing of other colours. A colour is represented by a point on the diagram, given by the chromaticity coordinates x and y. The chromaticity coordinates are calculated from the CIE XYZ primaries using the following relations [57]:

\[
X = \frac{X}{X + Y + Z}, \quad Y = \frac{Y}{X + Y + Z}
\]

where x and y represent the chromaticity coordinate on the abscissa and ordinate of the CIE x–y chromaticity diagram, respectively, and X, Y and Z represent the primaries in the CIE XYZ colour space. Colours which fall on the spectral locus are fully saturated, and they appear pure and vibrant. The white region lies near the centre of the diagram. Colours are less saturated at points near the white region of the diagram. A line on the diagram represents the range of colours achievable by additive mixing of two primaries, whereas a triangle represents the range of colours achievable by additive mixing of three primaries, as shown in Fig. 11. The blackbody curve lies nearby the white region of the diagram, whereby the chromaticity coordinates for standard illuminants defined by CIE are located nearby the blackbody curve [57,70]. It can be seen from Fig. 11 that only five of the standard illuminants are shown on the diagram, namely, Illuminant A–E, with Illuminant A showing a high orange content. A description of the CIE standard illuminants and their corresponding chromaticity coordinates in the CIE 1931 x–y chromaticity diagram is given by Pascale [71], and is presented in Table 3. The full range of colours perceived by the human visual system is represented by the colour gamut of the diagram. Different imaging devices such as display monitors, digital still and video cameras, scanners and printers possess different colour gamuts, which are actually smaller in size compared with the colour gamut of the diagram. To date, no imaging device fully captures the entire colour gamut of the CIE x–y chromaticity diagram.

5.2. Colour space

5.2.1. CIE XYZ and CIE x–y chromaticity diagram

From the previous section, it can be clearly seen that colour is a perceptual quantity, rather than a physical quantity, which is derived from the combination of illumination spectrum, spectral characteristics of the objects and the physiological response of the human visual system. Due to the complexity of these elements, colour is a subjective matter, which is difficult to quantify. As Stasiek et al. [13] states, “Accidentally if you asked several people what colour a sunset is, their answers would be diverse. Some would say “red”. Others would say “dark red” or “saturated red”. The diversity of replies indicates the difficulties of describing colours.”

To reduce the subjectivity of describing colours, the Commission Internationale de l’Eclairage (International Commission on Illumination, CIE) developed the CIE XYZ colour space in 1931 based on the colour-matching experiments conducted by Wright and Guild. The colour-matching experiments were carried out using a bipartite colourimeter, in which observers viewed a 2° circular split field. One side of the field consists of a given colour in the visible spectrum, whereas the other side of the field consists of Red–Green–Blue (RGB) primaries. In the experiments, the observers adjusted the amounts of RGB intensities so that the resulting colour obtained from the additive mixture of the primaries, matches the given colour in the visible spectrum. The tristimulus values were recorded from the bipartite colourimeter, and the experiments were repeated for different colours spaced at small wavelength intervals in the visible spectrum. Following this, the RGB colour-matching functions \( r(\lambda) \), \( g(\lambda) \) and \( b(\lambda) \) were derived for the 2° standard observer, and were later transformed into the CIE 1931 colour-matching functions \( x(\lambda) \), \( y(\lambda) \) and \( z(\lambda) \) to eliminate negative values [68,69]. The CIE XYZ primaries were defined as [68]:

\[
X = k \int E(\lambda)P(\lambda)x(\lambda)d\lambda \quad (2a)
\]
\[
Y = k \int E(\lambda)P(\lambda)y(\lambda)d\lambda \quad (2b)
\]
\[
Z = k \int E(\lambda)P(\lambda)z(\lambda)d\lambda \quad (2c)
\]

where \( E(\lambda) \) represents the relative spectral power distribution of the illumination source, \( P(\lambda) \) represents the spectral reflectance of the surface, \( x(\lambda) \), \( y(\lambda) \) and \( z(\lambda) \) represent the CIE 1931 colour-matching functions for the 2° standard observer, and \( k \) represents a normalizing function given by [68]:

\[
k = \frac{100}{\int E(\lambda)y(\lambda)d\lambda}
\]

For interpretation of colour in Figs. 1–6, 8, 11–23 the reader is referred to the web version of this article.
A colour pixel in an RGB image is represented by a triplet of numbers, expressed mathematically as:

$$\mathbf{C}_{\text{pixel}} = (R, G, B)$$

where \( \mathbf{C}_{\text{pixel}} \) represents colour at a pixel within the image, and \( R, G \) and \( B \) represent red, green and blue intensities, whereby the values are positive integers.

The most common RGB image is the 24-bit representation, in which the image is encoded 8 bits (1 byte) per colour component. Such an image is also referred to as a ‘full-colour’ or ‘true-colour’ image. The number of tones for each colour component is given by:

$$N_{Tc} = 2^k \quad \text{and} \quad c = R, G, B$$

where \( N_{Tc} \) represents the number of tones for red, green and blue primaries in the RGB colour space, and \( k \) represents the number of bits per colour component. Due to the fact that a 24-bit RGB image comprises of 8 bits per colour component, it follows from Eq. (5) that a 24-bit RGB image consists of 256 tones of red, green and blue. Consequently, the RGB triplet values range from 0 to 255, and the total number of colour combinations for a pixel in a 24-bit RGB image is \((256)^3 \) which results in 16,777,216 million colours [57].

Another form of the RGB image is the 48-bit representation, which is available in some professional image-editing applications such as Adobe Photoshop. In the 48-bit representation, the image is encoded 16 bits (2 bytes) per colour component. From Eq. (5), a 48-bit RGB image consists of 65,536 tones of red, green and blue. Consequently, the RGB triplet values range from 0 to 65,535, and the total number of colour combinations for a pixel in a 48-bit RGB image is \((65,536)^3 \) which results in 281,474,976 million colours. Hence, it can be clearly seen that the 48-bit RGB representation has superior colour depth compared with the 24-bit RGB

![Fig. 11. The CIE 1931 x-y chromaticity diagram (copyright by Photo Research, Inc. All rights reserved).](image)

<table>
<thead>
<tr>
<th>CIE standard illuminant</th>
<th>Description</th>
<th>Chromaticity coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Incandescent lighting with CT = 2856 K</td>
<td>(0.4476 \quad 0.4074)</td>
</tr>
<tr>
<td>B</td>
<td>Direct sunlight at noon with CCT = 4874 K</td>
<td>(0.3484 \quad 0.3516)</td>
</tr>
<tr>
<td>C</td>
<td>North sky daylight with CCT = 6774 K</td>
<td>(0.3101 \quad 0.3162)</td>
</tr>
<tr>
<td>D50</td>
<td>Daylight used for colour rendering with CCT = 5000 K</td>
<td>(0.3457 \quad 0.3585)</td>
</tr>
<tr>
<td>D55</td>
<td>Daylight used for photography with CCT = 5000 K</td>
<td>(0.3324 \quad 0.3474)</td>
</tr>
<tr>
<td>D65</td>
<td>New version of north sky daylight, with CCT = 6500 K</td>
<td>(0.3127 \quad 0.3290)</td>
</tr>
<tr>
<td>D75</td>
<td>Daylight, with CCT = 7500 K</td>
<td>(0.2990 \quad 0.3149)</td>
</tr>
<tr>
<td>E</td>
<td>Equal energy spectrum, with CCT = 5400 K</td>
<td>(0.3333 \quad 0.3333)</td>
</tr>
<tr>
<td>F2</td>
<td>Cool white fluorescent, with CCT = 4200 K</td>
<td>(0.3721 \quad 0.3751)</td>
</tr>
<tr>
<td>F7</td>
<td>Broadband daylight fluorescent, with CCT = 6500 K</td>
<td>(0.3129 \quad 0.3292)</td>
</tr>
<tr>
<td>F11</td>
<td>Narrowband white fluorescent, with CCT = 4000 K</td>
<td>(0.3805 \quad 0.3769)</td>
</tr>
</tbody>
</table>

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representation, however, at the expense of increased image storage requirements [57].

The RGB colour space is widely used in imaging devices such as display monitors, digital still and video cameras, as well as scanners. The RGB colour space is device-dependent, whereby the colour gamut captured or displayed by the imaging device is different depending on the device. Pascale [71,72] provides an excellent review on the various types of RGB colour spaces, whereby a number of the RGB variants are presented in this section. The main principle of all RGB colour spaces is the same, whereby colours are generated by additive combinations of RGB primaries, however, the primary difference being that the colour gamut size encompassed by the RGB primaries is different depending on the RGB colour space.

A comparison of gamut size for six RGB colour spaces, namely, CIE RGB, sRGB, Adobe RGB, ProPhoto RGB, NTSC RGB and PAL RGB, is shown in Fig. 12. The colour gamuts of the abovementioned RGB colour spaces are plotted on the CIE x–y chromaticity diagram for comparison with the colour gamut perceived by the human visual system. From Fig. 12, it can be seen that CIE RGB has a fairly large colour gamut, covering more than 50% of the chromaticity diagram. CIE RGB is developed by CIE and is capable of handling images encoded in the 48-bit RGB representation. However, CIE RGB provides poor handling of certain colours, notably cyan and blue [45,71]. sRGB is the most common RGB colour space and is pioneered by the Hewlett Packard Company and Microsoft Corporation. sRGB assumes the characteristics of an average personal computer monitor, and is designed to be a universal Internet standard. Therefore, sRGB possesses a compromised colour gamut, covering 35% of the chromaticity diagram [71,72], as shown in Fig. 12. sRGB is capable of handling images encoded in the 24-bit RGB representation, and is commonly used for display monitors.

Adobe RGB is developed by Adobe Systems Incorporated and possesses a colour gamut covering approximately 50% of the chromaticity diagram, as shown in Fig. 12. Therefore, Adobe RGB offers higher colour depth compared with sRGB, particularly in the cyan and green regions. Due to the large colour gamut, the 48-bit representation is more preferable when encoding images using the Adobe RGB colour space [71,72]. Adobe RGB is used in some display monitors, digital still cameras and image-editing applications such as Adobe Photoshop. ProPhoto RGB is developed by the Eastman Kodak Company and possesses an extensive colour gamut, covering more than 90% of the chromaticity diagram, as shown in Fig. 12. Since the colour gamut extends beyond the spectrum locus and purple line of the chromaticity diagram, approximately 13% of the colours in the ProPhoto RGB colour space are non-existent colours. Due to the extensive colour gamut, the 48-bit representation is necessary for images encoded in ProPhoto RGB [72]. ProPhoto RGB is used for image-editing applications such as Adobe Photoshop.

NTSC RGB is developed by the National Television Systems Committee (NTSC) and is defined for images used for broadcasting in systems employing the NTSC standard such as display monitors and digital video cameras. The NTSC standard is an analogue television standard used in United States and some Asian countries, which consists of 30 interlaced video frames per second, and each video frame consists of 525 scan lines. NTSC RGB possesses a colour gamut similar to Adobe RGB. PAL RGB is developed by Telefunken, and is defined for images used for broadcasting in systems employing the Phase Alternating Line (PAL) standard. The PAL standard is an analogue television standard used in Western European, Middle East and South-East Asian countries, which consists of 25 interlaced video frames per second, and each frame consists of 625 scan lines [45,71]. PAL RGB possesses a colour gamut similar to sRGB, hence showing a restricted colour gamut.

Fig. 12. Comparison of gamut size for six RGB **colour spaces in the CIE 1931 x–y chromaticity diagram.**
5.2.3. HSI

It has been described in the preceding section that in the RGB colour space, a colour is represented by a triplet of numbers. The triplet of numbers makes sense to the imaging device, but it does not make much sense to humans when it comes to describing colours. The Hue–Saturation–Intensity (HSI) colour space describes colours in a manner which is natural and intuitive to humans, and is highly preferable in image processing applications compared with the RGB colour space. Hue is a parameter which represents a colour shade. Red, green, blue, yellow, orange, purple, magenta, violet are all examples of hue. Saturation represents the degree to which a colour is diluted with white, and is a parameter which describes the purity of a colour. A colour having high saturation will appear pure and vibrant, whereas a colour having low saturation will appear muted and grey. Intensity is a colour-neutral attribute which describes the relative brightness or darkness. The intensity of a colour image corresponds to the greyscale (black and white) version of the image [13].

From Gonzalez and Woods [57], hue, saturation and intensity are calculated from RGB intensities using the following equations:

\[
H = \varphi = \begin{cases} \text{if } B \leq G \\ 360 - \varphi \text{ if } B > G \\ \text{undefined if } R = G = B \\ \varphi = \cos^{-1} \left( \frac{\sqrt{\left( R - G \right)^2 + \left( R - B \right)^2}}{R + G + B} \right) \end{cases}
\]

\[
S = 1 - \frac{3 \min(R, G, B)}{R + G + B}
\]

\[
I = \frac{R + G + B}{3}
\]

where \(H, S\) and \(I\) represent hue, saturation and intensity, respectively, and \(R, G\) and \(B\) represent hue, red, green and blue intensities, respectively. Eqs. (6a)–(6e) assume that the RGB intensities are first normalized to be within the range of 0–1. \(H\) is defined as an angle within the range of 0–360°, and can be normalized to be within the range of 0–1 by dividing \(H\) with 360°.

It has been described in the previous section that the RGB colour space is device-dependent. From Eqs. (6a)–(6e), it can be seen that hue, saturation and intensity are all calculated from red, green and blue intensities in the RGB colour space, and therefore, the HSI colour space is also device-dependent. In calibrations of TLCs, it is desirable if hue, which represents the dominant reflected wavelength of the TLC, is defined in a colour space which is independent of the imaging device and brightness information. This can be achieved by defining hue as a polar coordinate in the CIE XYZ colour space, such as that implemented by Sun et al. [47]. The methodology is described below, which consists of pre-calibration and post-calibration steps.

There are three steps prior to calibrations of TLCs, presented as follows:

1. **Identification of RGB colour space**: The first step involves identifying the RGB colour space employed by the imaging device. For example, if the imaging device used is a PAL digital video camera, the RGB colour space employed by the digital video camera will be PAL RGB.

2. **Identification of CIE standard illuminant**: The second step involves identifying the CIE standard illuminant referenced in the RGB colour space of the imaging device. For example, PAL RGB colour space is referenced to the CIE standard illuminant D65, which represents a new version of north sky daylight having a CCT of 6500 K. A list of various standard illuminants defined by CIE and a description of the illuminants is presented in Table 3.

3. **Selection of illumination source**: The third step involves selecting an illumination source having a spectrum which approximately matches the spectrum of the standard illuminant referenced in the RGB colour space of the imaging device. For example, since the standard illuminant referenced in PAL RGB is Illuminant D65, the reader should select a white light illumination source having a spectrum which approximately matches the spectrum of Illuminant D65. This can be achieved by selecting an illumination source which possesses a high Colour Rendering Index (CRI) with a value above 90, whereby the CRI of the illumination source is calculated based on Illuminant D65.

Following calibrations of TLCs, the steps used to define hue in the CIE XYZ colour space are incorporated into the image-processing algorithm, as follows:

1. **Determination of x–y chromaticity coordinates**: The first step involves converting the RGB intensities for each TLC colour into CIE XYZ tristimulus values, and calculating the corresponding x–y chromaticity coordinates. The RGB intensities are converted into CIE XYZ tristimulus values using the following linear transformation:

\[
(X, Y, Z)^T = \begin{bmatrix} R G B \end{bmatrix}^T
\]

where \((X, Y, Z)^T\) represents the transposed vector consisting of the CIE XYZ tristimulus values, \((R, G, B)^T\) represents the transposed vector consisting of the RGB intensities, and \(M\) represents the RGB to CIE XYZ scalar transformation matrix. A list of transformation matrices for six RGB colour spaces is presented in Table 4. For PAL RGB, the transformation matrix is located in row 6 of Table 4.

If the linear temperature gradient method is used, the RGB intensities for each TLC colour are converted into CIE XYZ tristimulus values. The CIE XYZ tristimulus values are then used to determine the chromaticity coordinates of the TLC colours in the CIE 1931 x–y chromaticity diagram.

### Table 4

<table>
<thead>
<tr>
<th>RGB colour space</th>
<th>Reference CIE standard illuminant</th>
<th>Transformation matrix from RGB to XYZ M</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE RGB</td>
<td>E</td>
<td>[0.4887 0.3107 0.2006; 0.1762 0.8130 0.0108; 0.0000 0.0102 0.9898]</td>
</tr>
<tr>
<td>sRGB</td>
<td>D65</td>
<td>[0.4125 0.3576 0.1804; 0.2127 0.7152 0.0722; 0.0193 0.1192 0.9503]</td>
</tr>
<tr>
<td>Adobe RGB</td>
<td>D65</td>
<td>[0.5767 0.1856 0.1882; 0.2974 0.6273 0.0753; 0.0270 0.0707 0.9911]</td>
</tr>
<tr>
<td>ProPhoto RGB</td>
<td>D50</td>
<td>[0.7977 0.1352 0.0314; 0.2880 0.7119 0.0001; 0.0000 0.0000 0.8252]</td>
</tr>
<tr>
<td>NTSC RGB (1953)</td>
<td>C</td>
<td>[0.6069 0.1735 0.2003; 0.2989 0.5866 0.1145; 0.0000 0.0661 1.1162]</td>
</tr>
<tr>
<td>PAL RGB</td>
<td>D65</td>
<td>[0.4306 0.3415 0.1783; 0.2220 0.7066 0.0713; 0.0202 0.1296 0.9391]</td>
</tr>
</tbody>
</table>

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2. Plot of CIE 1931 $x$-$y$ chromaticity diagram: The second step involves plotting the coordinates of the CIE 1931 $x$-$y$ chromaticity diagram, coordinates of the primaries of the RGB colour space employed by the imaging device, coordinates of the CIE standard illuminant in which the imaging device is based, and coordinates of the TLC colours, as shown in Fig. 13. The chromaticity coordinates used for plotting the spectrum locus of the CIE 1931 $x$-$y$ chromaticity diagram shown in Fig. 13 were provided by Pascale via email, however, these coordinates can be obtained from references established by CIE, for $2^o/C176$ and $10^o/C176$ standard observers. The $2^o$ standard observer is suitable for fields of view less than $4^o$, whereas the $10^o$ standard observer is appropriate for fields of view greater than $4^o$. The chromaticity diagram represents the colour gamut of the human visual system.

The chromaticity coordinates for the primaries of six RGB colour spaces is presented in Table 5. For PAL RGB, the chromaticity coordinates are obtained to be $(x_{\text{red}}, y_{\text{red}}) = (0.6400, 0.3300)$, $(x_{\text{green}}, y_{\text{green}}) = (0.2900, 0.6000)$, and $(x_{\text{blue}}, y_{\text{blue}}) = (0.1500, 0.0600)$.

The triangle formed by connecting the coordinates of the RGB primaries represents the colour gamut of the RGB colour space.

From Fig. 13, it can be seen that PAL RGB has a restricted colour gamut in comparison with the colour gamut of the human visual system. The chromaticity coordinates for various CIE standard illuminants are presented in Table 3. Since PAL RGB is based on Illuminant D65, the chromaticity coordinates for Illuminant D65 are obtained to be $(x_o, y_o) = (0.3127, 0.3290)$. The coordinates of the CIE standard illuminant represent the ‘real white-light point’, and is used as the origin of hue. The chromaticity coordinates of the TLC colours calculated from Step 1 are then plotted on the chromaticity diagram.

3. Definition of hue: Finally, the third step involves defining hue in the CIE 1931 $x$-$y$ chromaticity diagram, as shown in Fig. 14. The coordinates of the CIE standard illuminant $(x_o, y_o)$ are used as the origin of hue, and a reference line is drawn, which may be horizontal or vertical, depending on the reader’s preference. Following this, another line is drawn, which connects the hue origin and a TLC colour. Hue is defined as the angle between the reference and TLC colour lines, and is given by:

$$H = \tan^{-1} \left( \frac{y - y_o}{x - x_o} \right)$$

where $(x_o, y_o)$ represents the chromaticity coordinates of the CIE standard illuminant used as hue origin, and $(x, y)$ represents the chromaticity coordinates of a TLC colour. This step is repeated for each TLC colour in the diagram, as shown in Fig. 14. This gives hue which is independent of the imaging device and brightness information, since hue is defined in a colour space as perceived by the human visual system.

Although the method presented here uses CIE XYZ colour space, the method is also applicable for other device-independent colour spaces such as CIE UVW, which was implemented by Hay and Hollingsworth [37]. Hay and Hollingsworth [37] utilized the

---

**Table 5**

<table>
<thead>
<tr>
<th>RGB colour space</th>
<th>Red intensity</th>
<th>Green intensity</th>
<th>Blue intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x$</td>
<td>$y$</td>
<td>$x$</td>
</tr>
<tr>
<td>CIE RGB</td>
<td>0.7350</td>
<td>0.2650</td>
<td>0.2740</td>
</tr>
<tr>
<td>sRGB</td>
<td>0.6300</td>
<td>0.3400</td>
<td>0.3000</td>
</tr>
<tr>
<td>Adobe RGB</td>
<td>0.6400</td>
<td>0.3300</td>
<td>0.2100</td>
</tr>
<tr>
<td>ProPhoto RGB</td>
<td>0.7347</td>
<td>0.2653</td>
<td>0.1596</td>
</tr>
<tr>
<td>NTSC RGB</td>
<td>0.6700</td>
<td>0.3300</td>
<td>0.2100</td>
</tr>
<tr>
<td>PAL RGB</td>
<td>0.6400</td>
<td>0.3300</td>
<td>0.2900</td>
</tr>
</tbody>
</table>

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uniform surface temperature calibration method and the RGB colour space employed by their imaging device was NTSC RGB. Similarly, the RGB intensities for each calibration image were converted into UVW tristimulus values using a suitable scalar transformation matrix and the chromaticity coordinates were determined by Hay and Hollingsworth [37]:

\[
 u = \frac{U}{U + V + W} \\
 v = \frac{V}{U + V + W}
\]  

The chromaticity coordinates were then used to plot the \( u - v \) chromaticity diagram, and hue was defined as a polar coordinate referenced to the ‘real white-light point’ of the imaging device. The \( u - v \) chromaticity diagram, which was developed by CIE in 1960, possesses the main advantage that the colours represented by the diagram are more perceptually uniform compared with the \( x - y \) chromaticity diagram developed in 1931. CIE further improved the diagram and developed the \( u' - v' \) chromaticity diagram in 1976, which was called the Uniform Chromaticity Scale. The colours represented by the \( u' - v' \) chromaticity diagram were claimed to be more perceptually uniform compared with the \( x - y \) and \( u - v \) chromaticity diagrams. The uniformity of the colours can be clearly seen by the difference in size of MacAdam ellipses, as illustrated by Ohno [69]. The method presented here can also be used to define hue in the \( u' - v' \) chromaticity diagram by converting the CIE XYZ tristimulus values into \( u' - v' \) chromaticity coordinates using the following formula [69]:

\[
 u' = \frac{4X}{X + 15Y + 3Z} \\
 v' = \frac{9Y}{X + 15Y + 3Z}
\]  

The Uniform Chromaticity Scale is also device-independent.

5.3. Common colour–temperature representations of TLCs

Now that the reader knows the various types of colour spaces used for quantifying colour such as CIE XYZ, RGB and HSI, the reader is faced with the question, “What are the common colour–temperature representations of TLCs?” To date, there are two common colour–temperature representations of TLCs, namely, hue–temperature and intensity–temperature calibrations, which are described briefly as follows.

5.3.1. Hue–temperature calibration

In hue–temperature calibrations, the hue parameter is used to represent the dominant reflected wavelength of the TLC. Typically, hue from the Hue–Saturation–Intensity (HSI) and Hue–Saturation–Value (HSV) colour space is mapped to the surface temperature to yield the colour–temperature relationship of the TLC. Although not described in this paper, the HSV colour space is similar to the HSI colour space, whereby hue represents the colour shade, saturation represents the colour purity and value represents the brightness attribute.

Hue–temperature calibrations are typically characterized by a non-linear, monotonically increasing curve, in which an nth-order polynomial is fitted through the calibration points to correlate hue with temperature. The portion whereby hue increases monotonically with temperature is known as the effective temperature range [27], hue bandwidth [33] and useful calibration range [37,38,66,70]. Hue–temperature calibrations are the most common colour–temperature representations of TLCs and have been widely used by researchers [8,11,17,27–43,46,47,51,52,73,74] due to their simplicity and independence with respect to illumination intensity [46]. ‘Single colour band’ and ‘multiple colour band’ hue-based methods have been employed in steady-state and transient heat transfer tests to determine surface temperature and useful thermal

Fig. 14. Definition of hue in the CIE 1931 \( x - y \) chromaticity diagram.
parameters such as heat transfer coefficient, adiabatic wall temperature and film cooling effectiveness.

Although being a common representation of the colour–temperature relationship of TLCs, hue–temperature calibrations possess several disadvantages, as follows:

1. **Ambiguous definition:** From colourimetry theory, hue is deemed as an inappropriate parameter for describing colour due to its ambiguous definition [41]. Various definitions have been used for hue, and researchers have different opinions regarding the ‘best’ definition of hue. Hay and Hollingsworth [37] compared three definitions of hue, which were defined as polar coordinates on the CIE u–v chromaticity diagram, and recommended the following definition:

\[
H = \tan^{-1} \left( \frac{\sqrt{3}(R - G)}{2R - G - B} \right)
\]

Since hue was constructed directly from RGB intensities in the RGB colour space, the proposed definition was reported to be computationally expedient, and gives the lowest average uncertainty in temperature to useful calibration range ratio of 8–10% for the polymer-dispersed TLCs tested in their research [37]. This definition also possesses the advantage that it is equivalent to the RGB2HSV function in MATLAB [40]. Hacker and Eaton (cited by Kodzwa and Eaton [74]) proposed a different definition of hue, as follows:

\[
H = \left( \frac{255}{2\pi} \right) \tan^{-1} \left[ \frac{0.5(R - G)}{0.25(R - G) + 0.5B} \right]
\]

The factor \( \frac{255}{2\pi} \) was used to obtain hue within the range of 0–255. A factor of \( 2\pi/255 \) was added or subtracted from the hue definition to ensure that hue falls within the range of 0–255. The above definition was claimed to give a hue–temperature calibration which is monotonic for all TLCs, invariant to linear changes in illumination intensity, and reflection-invariant to white light [74].

1. **Illumination intensity dependency:** It is often thought that hue is independent of illumination intensity. Hue is only independent of illumination intensity provided the spectrum of the illumination source is fixed [20]. The illumination spectrum is difficult to control due to aging of the illumination source, spectral characteristics of the surface, and non-linearities in amplitude characteristics of the light-sensitive elements of the imaging sensors, and the effect is intensified when the characteristics of RGB intensities differ significantly from one another [31,35].

2. **Reduction in useful calibration range:** The useful calibration range of hue–temperature calibrations is actually less than the colour play range of the TLC. The reduction in useful calibration range was attributed to the shift in location of the hue origin from the ‘ideal white-light point’. The ‘ideal white-light point’ corresponds to the point on the chromaticity diagram where the magnitudes of RGB intensities are equal, and is referred to as an equal energy spectrum illuminant. The CIE Illuminant E is an equal energy spectrum which has a hypothetical spectral power distribution. In most imaging systems however, the ‘real white-light point’ used as hue origin is somewhat shifted from the ‘ideal white-light point’, which causes a reduction in useful calibration range up to half of the colour play interval of the TLC [37,47]. In addition, the useful calibration range of hue–temperature calibrations can also be reduced if background reflection dominates the light reflected by the TLC [73].

3. **Decrease in measurement sensitivity:** Since hue–temperature calibrations are non-linear, the sensitivity of hue varies across the temperature measurement range [20,41]. The sensitivity of hue decreases particularly in the blue region of the calibration curve, whereby small changes in temperature do not cause significant changes in hue. This poses a limitation, especially when ‘multiple colour band’ methods are used for heat transfer measurements.

4. **Noise susceptibility and discontinuity:** Apart from the above, hue is undefined for grey, and therefore instrument noise causes appreciable change to the hue signals before the TLC first displays colour. Consequently, setting a threshold for a particular hue can be difficult, which poses a problem when ‘single colour band’ methods are used for heat transfer measurements [75]. Hue sometimes exhibit a discontinuity which corresponds to a certain angle in the colour space, and this discontinuity needs to be removed before a polynomial curve can be fitted to correlate hue with temperature, which poses additional complexity during image processing [31].

### 5.3.2. Intensity–temperature calibration

An alternative representation of the colour–temperature relationship of TLCs is intensity–temperature calibration. As the name implies, the intensity parameter is mapped to the surface temperature to yield the calibration curve of the TLC. Earlier versions of intensity–temperature calibrations were developed by Wang et al. [76], which utilizes the Y signal in the YUV colour space. There are two types of intensity–temperature calibrations developed by Wang et al. [76], namely, peak intensity-based and full intensity-based calibrations. In the former method, only the peak intensities of the calibration curve are mapped to the surface temperatures, whereas in the latter method, all intensities are mapped to their corresponding surface temperatures.

Intensity–temperature calibrations were developed for use with intensity-matching methods in transient heat transfer tests. In intensity-matching methods, the values of the thermal parameters to be determined from transient heat transfer tests were first assumed, and different combinations of values were generated to give predicted surface temperature histories. The predicted surface temperature histories were combined with the intensity–temperature curve obtained from calibrations to generate a lookup table of predicted (ideal) intensity histories. The predicted intensity histories were compared with experimental intensity histories obtained from transient heat transfer tests via residue minimization technique to determine the best fit of thermal parameters [48,77]. Full intensity-matching methods possess the advantage of being a more robust image processing method compared with peak intensity-matching methods [76].

An alternative version of full intensity-based calibrations was developed by Abu Talib et al. [48], Chambers et al. [56] and Ling et al. [77], in which a single colour intensity from the RGB colour space was mapped to the surface temperature. Typically, green intensity was used as it provides a well-defined calibration curve compared with red and blue intensities. The full intensity-matching methods were then employed in conjunction with narrowband TLCs in transient heat transfer tests to derive multiple thermal parameters from a single test, as well as to minimize problems due to illumination disturbance such as illumination-viewing angles and internal surface reflections [48,56,76,77]. Although intensity-based methods offer some advantages over hue-based methods, intensity-based methods are also subjected to the same issues as hue-based methods such as effects of illumination spectrum, UV and IR radiation, hysteresis, film thickness, and aging.

### 6. Illumination

#### 6.1. Illumination source

Illumination is an important element in calibrations of TLCs since the calibration surface needs to be illuminated by a primary illumination source. From Anderson and Baughn [73], some of the
illuminance sources reported in the literature were used to provide white light, some for their high intensity, some for their low UV and IR emission, while some for mere convenience. This raises the question, “What are the criteria for selecting an illumination source? Is there a particular illumination source which is significantly better than others for calibrations of TLCs?” The general guidelines for selecting an illumination source are presented as follows.

6.1.1. White light

For calibrations of TLCs, the first criterion is to select an illumination source which provides white light. The choice of white light is complicated by the fact that there are several types of white light such as ‘warm white’ and ‘cool white’, which are generally dependent on the CT or CCT of the illumination source, as shown in Table 1. From Table 1, it can be seen that the colour of white light changes from reddish white to bluish white as the CT or CCT of the illumination source increases. Hence, it is important for the reader to know the CT or CCT of the illumination source as the colour of white light emitted by the illumination source influences the colour appearance of objects. For stationary calibrations, in which the calibration surface is fixed, it is desirable to use an illumination source which provides continuous white light. For dynamic calibrations, in which the calibration surface is moving (a rotating disc, for example), it is desirable to use a strobe light which can operate at different frequencies corresponding to the rotational speed such as that used by Kakade et al. [34].

When selecting an illumination source for calibrations of TLCs, it is also desirable to obtain information on the colour rendering characteristics of the illumination source. From Wolsey et al. [78], the most common colour rendering metric used in the lighting industry is the Colour Rendering Index (CRI), which is a measure of the difference between the colour appearance of an object when viewed under a reference illuminant and the colour appearance of the object when viewed under the illumination source. CRI values vary from 0 to 100, and a high CRI with values above 90, indicate that the colours of the object will appear natural when viewed under the illumination source. It is noteworthy that although two illumination sources possess the same CRI, this does not necessarily mean that the two sources will render the same colour appearance. For example, a tungsten lamp having a CRI of 90 and referenced to the CIE standard illuminant A will have a different colour appearance from a fluorescent lamp having the same CRI but referenced to the CIE standard illuminant F7. Hence, it is important for the reader to know the reference illuminant to which the CRI value is based. The CRI of an illumination source is usually based on one of the standard illuminants defined by CIE.

Another colour rendering metric useful for calibrations of TLCs, is the Full-Spectrum Colour Index (FSCI), which was a metric proposed by Wolsey et al. [78]. FSCI is a measure of the deviation between the spectral power distribution of an equal energy spectrum and the spectral power distribution of the illumination source. In order for an illumination source to have good colour discrimination, it is important that the illumination source possesses the capability to emit radiant energy at all wavelengths in the visible spectrum. If gaps or large variations exist in the spectral power distribution of the illumination source, colour discrimination will be poor and consequently, different colours may appear to be the same [78]. FSCI values vary from 0 to 100, whereby an equal energy spectrum possesses a FSCI of 100 and a monochromatic illumination source possesses a FSCI of 0. A high FSCI indicates that the illumination source provides excellent colour discrimination, which is an essential element for calibrations of TLCs. Codes written in MATLAB are provided by Wolsey et al. [78] to compute the CRI and FSCI of an illumination source, provided the spectral power distribution of the source is known.

6.1.2. Full-spectrum

The second criterion is to select an illumination source which is full-spectrum. From Wolsey et al. [78], the term ‘full-spectrum’ is a marketing term rather than a technical term, and it is used to describe illumination sources having a continuous spectral power distribution in the visible spectrum without the gaps and troughs. It has been shown from the work of Anderson and Baughn [73] that full-spectrum illumination sources generally provide better calibration attributes compared with ordinary illumination sources. Anderson and Baughn [73] conducted a detailed investigation on the effects of illumination spectrum on hue–temperature calibrations of R35CW TLC. The five illumination sources investigated were GE 100 W soft white tungsten lamp with a CT of 3200 K, SoLux halogen lamp with a CT of 4700 K, GE 20 W cool white fluorescent lamp fitted with a Spectrum 574 UV cut-off filter, GE 20 W cool white fluorescent lamp with a CT of 4100 K, and Vita-Lite fluorescent lamp with a CT of 5500 K. The SoLux and Vita-Lite lamps were marketed as full-spectrum.

The results of their research showed that the full-spectrum sources provide the best calibration attributes for the R35CW TLC – broadest useful calibration range and lowest uncertainty in measured surface temperature, with a maximum uncertainty of approximately 0.36 and 0.40 °C for the SoLux and Vita-Lite sources, respectively. The GE fluorescent sources provide calibration attributes comparable to the full-spectrum sources, however, with a reduction of 20% of the useful calibration range. The GE tungsten lamp resulted in a severe attenuation in hue, and was therefore not recommended. Hence, the full-spectrum sources were determined to be the ‘best’ sources for calibrations of TLCs. From Wolsey et al. [78], full-spectrum illumination sources possess a continuous spectral power distribution in the visible spectrum, which in turn reduces potential confusion in the colour appearance of objects. For example, if an illumination source does not emit radiant energy in the long wavelength portion of the visible spectrum (~600–700 nm), some shades of red and orange will be missing, and therefore, subtle differences in the spectral characteristics of objects are not discernible. Hence, full-spectrum illumination sources generally provide excellent colour discrimination, which is recommended for calibrations of TLCs.

6.1.3. Low UV and IR emission

The final criterion is to select an illumination source with minimum UV and IR emission. UV radiation is known to cause degradation to TLCs, and therefore, prolonged exposure of a surface coated with TLCs to UV radiation should be prevented [24]. IR radiation is known to cause radiative heating to TLCs and therefore should be avoided [24]. Generally, halogen bulbs were preferred by researchers [27,31–33,35,43] due to their uniformity in illumination and low UV emission compared with fluorescent bulbs. Fluorescent bulbs were preferred by researchers [11,37–39,43,46,48], however, due to their high luminosity and low IR emission compared with halogen and tungsten bulbs. The emission of UV and IR can be minimized by using special UV and IR cut-off filters for the illumination source.

6.2. Illumination disturbance

Illumination disturbance has a major influence on calibrations of TLCs. A number of works were focused on investigating the effects of illumination disturbance on calibrations of TLCs and proposing methods to minimize their effects. The sources of illumination disturbance reported in the literature are identified and presented briefly as follows.
6.2.1. Illumination-viewing angles

The light reflected from the calibration surface is dependent on the angle of incidence of the incoming light and the angle of incidence of light entering the lens of the video camera. These angles are known as illumination angle and viewing angle, respectively, as illustrated in Fig. 15. Variations in illumination-viewing angles are one of the factors known to affect calibrations of TLCs, and have been the topic of many years of research.

6.2.2. Illumination intensity

The intensity of light measured by the photodiodes in the imaging sensors of the video camera is dependent on a factor called illumination intensity. In Liquid Crystal Thermography, illumination intensity is defined as the distance between the illumination source and video camera with the surface [35,49], and illumination intensity is also defined as the amount of light emitted by the illumination source [31,46]. Variations in illumination intensity arise due to differences in distance between the illumination source and surface, differences in distance between the video camera and surface, differences in video camera settings such as iris, shutter speed, and white balance, and due to aging of the illumination source. Variations in illumination intensity can be significant, particularly for non-in situ calibrations using wideband TLCs, and have also been the topic of many years of research.

6.2.3. Background reflection

In practice, the light reflected from the calibration surface is a complex combination of:

a. The light reflected by the TLC, vinyl encapsulating material (if microencapsulated TLC is used), binder material, and black paint used to provide black background for optimum colour display of the TLC. Anderson and Baughn [66] reported that the total solar reflections (reflectivity in the visible region) for black paints are within the range of 0.03–0.12. The reflectivity of the vinyl encapsulating material and binder material was unknown [66].

b. The incident light from the primary illumination source and secondary sources such as sunlight and room light (if a dark enclosure is not used), and specular reflections from other objects within the vicinity of the calibration surface.

Unfortunately, it is not possible to isolate the various components of reflected light, such that the light comes solely from the TLC. The combination of the various components of reflected light is referred to as background reflection. Background reflection is also a source of illumination disturbance, and has been the subject of interest in several works.

6.3. Correction methods

Having identified the sources of illumination disturbance which influence calibrations of TLCs at varying degrees, the reader is faced with the question, “Is there a method to minimize and compensate effects of illumination disturbance?” There is no simple answer due to the simultaneous occurrence of various sources of illumination disturbance, and there is no single method which compensates for all sources of illumination disturbance. The methods used and developed in the existing literature are presented as follows.

6.3.1. Narrowband TLCs

The easiest method to minimize effects of illumination disturbance is to utilize narrowband TLCs, which typically have bandwidths within the range of 0.5–4°C, and therefore possess a higher precision in temperature measurements. Narrowband TLCs are preferable and have been employed by several researchers [34,48,50,56,77] due to the reasons that calibrations of narrowband TLCs are less affected by variations in illumination intensity and illumination-viewing angle, as well as disturbance due to internal surface reflections and secondary sources. Consider the following example, which is adapted from Parsley [18], relating to effects of illumination-viewing angle on calibrations of TLCs. Parsley [18] states, “For all TLCs, the reflected wavelength (colour)
will shift towards blue as the angle is moved away from the calibration surface normal. This makes the blue start temperature of the TLC to appear lower than it should be, resulting in an apparent narrowing of the bandwidth. The narrowing effect is more apparent in wideband TLCs compared with narrowband TLCs. Consequently, variations in illumination-viewing angle result in colour gradients over the calibration surface although the surface is maintained at a uniform surface temperature. When illumination-viewing angle effects are significant, a single calibration curve cannot be used to represent the colour–temperature relationship of the TLC at all regions of the surface.

The reader may now ask, “How is the narrowing effect more apparent in wideband TLCs compared with narrowband TLCs?” Say the reader has three samples of TLCs having the identification R35C1W, R35C5W and R35C10W. The samples are labelled A, B and C, respectively, as shown in Table 6. From the nomenclature given by Hallcrest [24], the three samples all have a red start temperature \( T_{RS} \) of 35 °C. However, the blue start temperature \( T_{BS} \) for each sample is different due to the different bandwidths. If a change in illumination-viewing angle of 20° from the calibration surface normal causes a 30% narrowing of the bandwidths, the new blue start temperature \( T_{BS(new)} \) for each sample will be at a lower temperature, as shown in Table 6. The values in Table 6 clearly illustrate that the narrowing effect (i.e. shift in temperature \( \Delta T \)) is larger for wideband TLCs compared with narrowband TLCs; the larger the bandwidth, the larger the narrowing effect.

It has been indeed shown that calibrations of narrowband TLCs are less affected by illumination disturbance compared with narrowband TLCs. Camci et al. (cited in Kakade et al. [34]) reported that viewing angle effects are negligible for narrowband TLCs for angles between 0° and 40°, but the effects are potentially significant for greater angles. Abu Talib [49] showed that the difference in intensity–temperature calibrations for a R30C1W TLC was negligible when the distance between the fluorescent source and calibration surface was changed from 25 to 50 cm, indicating a negligible effect due to change in illumination intensity. The difference in intensity–temperature calibrations was also found to be insignificant when calibrations were conducted with and without a dark enclosure, indicating a negligible effect due to background illumination.

In a recent research, Kakade et al. [34] showed that the effects of varying illumination angles were more prominent for R30C5W TLC compared with R30C1W TLC, as shown in Fig. 16a and b, respectively, for angles between 20° and 45°. The effects of varying illumination angles were found to be significant for the narrowband TLCs for hues greater than 0.38, which corresponds to the green-to-blue transition point. Their results indicate that illumination angle effects are negligible for narrowband TLCs only in the red and green regions of hue–temperature calibrations. Therefore the use of narrowband TLCs can minimize effects of varying illumination-viewing angles for angles between 0° and 40°, and in the red and green regions of hue–temperature calibrations. Owing to these significant advantages, the use of narrowband TLCs seems to be a natural choice for reducing the effects of illumination disturbance.

Narrowband TLCs, however, possess the disadvantage that their narrow bandwidths limit their use to applications with small temperature gradients. In heat transfer measurements with large temperature gradients, a significant number of image frames are required to follow the movement of the TLC colour bands over the entire measurement surface [42], and a single frame is all that is needed if a wideband TLC having a bandwidth which covers the entire measurement range is used. A multi-event coating consisting of multiple narrowband TLCs having non-overlapping bandwidths can be used as an alternative, however, at the expense of increased costs. For example, say the reader’s application requires a temperature measurement range of 35–45 °C. In order to increase the precision of temperature measurement and to minimize the effects of illumination disturbance, the reader decides to use three narrowband TLCs having the identification R35C1W, R40C1W and R45C1W to map the surface temperature. This can be easily achieved using a R35C10W TLC having a bandwidth of 10 °C; however, extra effort is required to ensure that the calibration methods and image-processing algorithms used will compensate for the effects of illumination disturbance. The reader incurs additional expenditure for purchasing multiple TLCs if narrowband TLCs are used. Due to the fact that the costs of TLCs are proprietary information of the manufacturers, the costs are not disclosed in this paper. At the date of writing, the price of a sprayable microencapsulated chiral-nematic R35C1W TLC manufactured by Hallcrest is the equal to the price of R35C10W TLC. Hence, the reader should consider the trade-offs between the benefits of narrowband TLCs, the overall expenditure, and the accuracy desired in temperature measurements.

6.3.2. On-axis illumination-viewing arrangement

Generally, there are three types of illumination-viewing arrangement commonly used for calibrations of TLCs, namely, on-axis arrangement, off-axis arrangement and symmetrical off-axis arrangement, as illustrated in Fig. 17a–c, respectively. Referring to Fig. 17a, the on-axis arrangement refers to a configuration whereby the illumination source is placed collinearly with the lens of the video camera, and positioned perfectly normal to the calibration surface. This configuration can be easily achieved using a ring light fitted to the video camera lens. Referring to Fig. 17b, the off-axis arrangement refers to a configuration whereby the video camera is positioned normal to the calibration surface, and only the angle of the illumination source is varied, or vice versa. Referring to Fig. 17c, the symmetrical off-axis arrangement refers to a configuration whereby the video camera and the illumination source are positioned symmetrically with respect to the calibration surface normal.

The reader may now ask, “Which illumination-viewing arrangement is best to minimize illumination disturbance?” From the findings of existing literature, the on-axis arrangement is generally the best illumination-viewing arrangement to minimize illumination disturbance, particularly in minimizing effects of varying illumination-viewing angles on calibrations of wideband TLCs. Farina et al. [29] calibrated R35C5W TLC and reported a shift in hue–temperature calibration of 0.6 °C when the illumination source was deviated at an angle above 20° from the calibration surface normal using off-axis arrangement. They reported a negligible shift in hue–temperature calibration of ±0.25 °C for illumination-viewing angles up to 25° using on-axis arrangement. Farina et al. [29] further recommended that cross polarizing filters (cross polarizers) should be used in conjunction with on-axis arrangement in order to maximize the transmission of circular polarized light reflected by the TLC and to reduce stray reflections. Polarizing filter is basically a filter comprising of Polaroid material and is designed to remove polarized light from an image. Polarized light includes specular reflections from surrounding objects, and the use of

<table>
<thead>
<tr>
<th>Sample</th>
<th>TLC</th>
<th>Bandwidth (°C)</th>
<th>( T_{RS} ) (°C)</th>
<th>( T_{BS} ) (°C)</th>
<th>( T_{BS(new)} ) (°C)</th>
<th>( \Delta T ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>R35C1W</td>
<td>1</td>
<td>35</td>
<td>36.3</td>
<td>35.7</td>
<td>0.3</td>
</tr>
<tr>
<td>B</td>
<td>R35C5W</td>
<td>5</td>
<td>35</td>
<td>40</td>
<td>38.5</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>R35C10W</td>
<td>10</td>
<td>35</td>
<td>45</td>
<td>42.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

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polarizing filters removes specular reflections, and therefore results in vibrant, richer colours in the image [45].

In another research, Behle et al. [35] reported a percentage shift in hue of 45% for R30C5W TLC when the illumination and viewing angles were deviated 70° from the calibration surface normal using symmetrical off-axis arrangement. They also reported a negligible percentage shift in hue for illumination-viewing angles up to 70° using on-axis arrangement. Chan et al. [43] investigated variations in illumination-viewing angles up to 69° on hue-temperature calibrations of R30C5W TLC using on-axis arrangement. Their results indicated that the measured hue was 152 when the surface temperature was approximately 36.5 °C for an illumination-viewing angle of 69° whereas the measured hue decreased to 128 when the illumination-viewing angle was 0°. This, in turn, gives a maximum percentage difference in hue of approximately 18.75% when the illumination-viewing angle was deviated 69° from the calibration surface normal, which is consistent with the findings of Farina et al. [29] and Behle et al. [35]. Hence, the use of an on-axis illumination-viewing arrangement can be used to minimize the effects of illumination disturbance, particularly illumination-viewing angle effects on calibrations of TLCs.

However, in certain applications which do not permit the use of an on-axis arrangement due to internal surface reflections from the view port [7,33], which is common in convective heat transfer facilities made of transparent acrylic plastics, an off-axis arrangement is more desirable. When an off-axis arrangement is used, it is desirable to position the video camera normal to the calibration surface and keep the angle between the video camera and illumination source as minimum as possible, such that the configuration approaches an on-axis arrangement. From Hay and Hollingsworth [38], the wavelength of light reflected by the TLC is \( \lambda \cos(\theta) \), where \( \lambda \) represents the pitch length of the TLCs and \( \theta \) represents the angle between the incident light and surface normal. For small values of \( \theta \) (\( \theta \approx 0°, \cos(\theta) \approx 1 \)), the reflected light closely represents the light reflected by the TLC. Hence, Hay and Hollingsworth [38] recommended that if there exists no

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**Fig. 16.** Effects of varying illumination angles on hue-temperature calibrations of: (a) R30C5W TLC and (b) R30C1W TLC (adapted with permission from Kakade et al. [34]. Copyright (2009), Elsevier).

**Fig. 17.** Illumination-viewing arrangements for calibrations of TLCs.
mechanism for handling the uncertainty in calibrations of TLCs due to variations in illumination angle, the chosen angle should be as close to 0° as possible. In such cases, an angle of 20° and below is considered acceptable [38].

6.3.3. In situ calibration

In concise form, in situ means ‘in the original position’. In situ calibration means that calibration of the TLC is carried out on the actual test surface. Therefore measurements of thermal parameters are carried out under the same experimental conditions as calibrations. This, in turn, minimizes the discrepancies in illumination spectrum, illumination intensity, illumination-viewing arrangement, imaging system settings and surface preparation between calibrations and actual tests. It is for the above reasons in situ calibrations are highly professed by a number of researchers [9,27,33,42,73,74] and seem to be a natural choice for minimizing illumination disturbance. In order to obtain the benefits of in situ calibrations, Elkins et al. [36] developed a mini calibrator which utilizes a Peltier device and thermoelectric cooler for heating and cooling hue–temperature calibrations. The compact size of the mini calibrator, having a length of 21.3 mm, width of 20.3 mm and thickness of 10 mm, enables the calibrator to be placed at multiple sites over complicated geometries, which therefore facilitates the implementation of in situ calibrations. They reported that the accuracy in measured surface temperature was ±0.1°C across the bandwidth of the R25CSW TLC tested in their research.

Although highly advantageous, in situ calibrations may not be permissible in applications involving complicated geometries and experimental configurations. Kenning and Yan [79], in their investigation of pool nucleate boiling heat transfer of water on an electrically heated plate, reported difficulties to implement in situ calibrations due to the complex nature of their experimental configuration. Due to the free surface of the water tank used in their experiments, the water could not be pressurized to attain temperatures above 100°C without boiling, and the use of high-boiling liquids such as silicone oil would cause chemical contamination in the TLC. Thus, non-in situ calibration, in which calibration was conducted on a separate surface than the actual test surface, was desirable in their application. Abu Talib [49] implemented non-in situ calibration to attain a more controlled experimental condition, which gives a well-defined intensity–temperature calibration curve. Due to the short duration required for validity of one-dimensional semi-infinite solid assumption used in transient heat transfer tests, the peaks of the intensity–temperature curves were not clearly distinguishable if calibrations were conducted in situ.

Non-in situ calibrations pose a major problem as variations in illumination spectrum, illumination intensity, illumination-viewing angles, imaging system settings and surface preparation lead to biases in calibration curves at varying degrees. For applications requiring the implementation of non-in situ calibrations, it is important for the reader to maintain consistency in the following matters:

a. Consistency in calibration and test surfaces: This involves preparing both surfaces using the same type of TLC, the same coating batch number, the same application procedure, and if possible, both surfaces are prepared at the same time. For example, if a sprayable microencapsulated chiral-nematic R30CTW TLC is prepared on 13th July 2009, it is highly recommended that both calibration and test surfaces are prepared with the same coating to ensure consistency in proportions of TLC, binder and water. If the application procedure chosen is airbrushing, it is highly recommended that both calibration and test surfaces are prepared using airbrushing with the same number of sprays, the same distance between the nozzle of the airbrush and the surface, and with the same film thickness. It is also important that both calibration and test surfaces are prepared at the same time, if possible, and that the surfaces are stored at the same storage temperature.

b. Consistency in illumination and imaging system settings: This involves the use of the same type of illumination source, the same illumination-viewing arrangement, the same distance between the illumination source and surface, the same distance between the video camera and surface, and the same video camera settings. For example, say the reader uses the settings listed in Table 7 during calibrations. The reader should use the same settings during actual tests in order to minimize discrepancies in illumination and imaging. Furthermore, if the test surface is viewed through an optical window in actual tests, it is important that the calibration surface is also viewed through an optical window made of the same material. The results of Kakade et al. [34] showed a similar shape in hue–temperature calibrations for R40CTW TLC when calibrations were conducted with and without a polycarbonate optical window; however, with a shift in temperature of 0.6°C at a constant hue. They believed that the use of an optical window, such as when the test surface is viewed behind a transparent acrylic plastic in actual tests, may have altered the spectral characteristics of the light reflected by the TLC, which results in a shift in hue–temperature calibrations. Consistency is the keyword in non-in situ calibrations and although it may seem trivial, nevertheless it helps to minimize illumination disturbance between calibrations and actual tests.

6.3.4. Correction algorithms

The development of correction algorithms for compensating effects of illumination disturbance on calibrations of TLCs has been a main subject of many years of research. This method involves incorporating specialized functions in the image-processing algorithms and only a reference to the literature is given in this paper. Farina et al. [29] carried out one of the major works to compensate for different illumination conditions, which were common in non-in situ calibrations. They utilized a Macbeth ColorChecker colour rendition chart, which is an international reference colour and greyscale chart produced by Gretag Macbeth. The chart consists of 24 scientifically prepared colour swatches, comprising of additive primary colours such as red, green and blue, subtractive primary colours such as yellow, cyan and magenta, and specialist colours relating to the real world such as blue sky, foliage and sample skin tones [45,60]. A photograph of the Macbeth ColorChecker chart is given by Yang [80], as shown in Fig. 18.

Table 7

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Illumination source</strong></td>
<td>Philips Fluotone™ cool daylight</td>
</tr>
<tr>
<td></td>
<td>fluorescent</td>
</tr>
<tr>
<td></td>
<td>Colour-temperature 6200 K</td>
</tr>
<tr>
<td></td>
<td>Tube length 0.6 m</td>
</tr>
<tr>
<td><strong>Illumination-viewing arrangement</strong></td>
<td>Off-axis arrangement</td>
</tr>
<tr>
<td></td>
<td>Illumination angle 20°</td>
</tr>
<tr>
<td></td>
<td>Viewing angle 0°</td>
</tr>
<tr>
<td></td>
<td>Distance between illumination source and surface 0.6 m</td>
</tr>
<tr>
<td></td>
<td>Distance between video camera and surface 0.3 m</td>
</tr>
<tr>
<td><strong>Video camera settings</strong></td>
<td>Iris</td>
</tr>
<tr>
<td></td>
<td>Shutter speed 1/50 s</td>
</tr>
<tr>
<td></td>
<td>White balance Manual</td>
</tr>
</tbody>
</table>

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Similar to the method of Farina et al. [29], Vejrazka and Marty [41] utilized a table of reference colours, compared images between calibration and actual test surfaces, and applied corrections to the RGB tristimulus. Since calibrations were carried out non-in situ, the reliability in temperature measurement in actual tests was determined using and optimization parameter, Q, which represents the sum of differences between measured RGB tristimulus obtained from calibrations and actual tests. The optimization parameter was defined as:

$$Q = |R_m - R_{cal}| + |G_m - G_{cal}| + |B_m - B_{cal}|$$  \( (14) \)

where \(R_m, G_m\) and \(B_m\) represent red, green and blue tristimulus values in actual tests, and \(R_{cal}, G_{cal}\) and \(B_{cal}\) represent red, green and blue tristimulus values in calibrations. The image-processing algorithm was written such that if the value of the optimization parameter is small, the value suggests that the difference between RGB tristimulus obtained from calibrations and actual tests is small. A small value of \(Q\) indicates that a colour at a particular pixel in the image captured in actual tests exists in calibrations, and therefore the corresponding surface temperature measurement is reliable. Vejrazka and Marty [41] reported a precision in temperature measurement of 0.3 °C when the illumination conditions for calibrations and actual tests were identical.

Hay and Hollingsworth [37] utilized a different approach to compensate the effects of varying illumination conditions on calibrations of TLCs. They proposed a hue-dimensionless temperature calibration curve as an alternative to the conventional hue–temperature calibration. The dimensionless temperature was defined as:

$$\Theta = \frac{T - T_M}{\Delta T}$$  \( (15) \)

where \(\Delta T = T_M - T_{\text{ref}}\) if \(T > T_M\) and \(\Delta T = T_M - T_i\) if \(T < T_M\). \(T\) represents the surface temperature which corresponds to a particular hue, whereas \(T_M, T_{\text{ref}}\) and \(T_i\) represent the surface temperature corresponding to hue at the lower end, higher end and in the middle of the monotonically increasing hue–temperature calibration curve. Selection of \(T_i\) and \(T_{\text{ref}}\) was arbitrary, and \(T_M\) was calculated from the mean of \(T_i\) and \(T_{\text{ref}}\). The method was shown to collapse different hue–temperature calibrations to a general calibration curve, which is independent of the bandwidths of TLC coatings and varying illumination conditions. They reported an average uncertainty in temperature to useful calibration range ratio of ±7–9% for the TLCs tested in their research. The method was applicable for both polymer-dispersed TLCs [37] and microencapsulated TLCs [38].

Similar to the method of Hay and Hollingsworth [37,38], Kakade et al. [34] utilized a hue-normalized temperature calibration curve to compensate the effects of varying illumination angles. The normalized temperature was defined as:

$$\zeta = \frac{T - T_M}{\Delta T}$$  \( (16) \)

where \(\Delta T = T_C - T_{\text{ref}}\) if \(T > T_M\) and \(\Delta T = T_M - T_R\) if \(T < T_M\). \(T_R\) and \(T_C\) represent the surface temperature which corresponds to the peak red intensity and peak green intensity, respectively. In this method, the red and green intensity–temperature curves and hue–temperature curve were first plotted on the same graph. The surface temperature (in their case, the copper block temperature), corresponding to the peak red and peak green intensities were then derived from the graph, and the values were used to calculate \(T_M\). Finally, the normalized temperature was calculated and the hue-normalized temperature calibration curve was constructed. The normalized temperature was obtained to be within the range of \(-1 < \zeta < 1\), and was shown to effectively collapse the hue–temperature calibrations of R30CSW TLC to a single calibration curve, for illumination angles up to 45° from the calibration surface normal.
Hence, from the findings of Hay and Hollingsworth [37,38] and Kakade et al. [34], hue-dimensionless temperature calibration appears to be a possible alternative to produce a global calibration which is independent of varying illumination conditions and illumination-viewing angles, as well as different TLC bandwidths.

Illumination intensity is known to be a source of illumination disturbance. Camci et al. (cited in Behle et al. [35]) reported a mean temperature error of ±0.08 °C for a change in illumination intensity of 40% for a narrowband TLC having a bandwidth of 1 °C. Grewal et al. [31] reported a temperature error of ±1 °C when the illumination intensity was increased by 50%, which results in a significant shift in hue–temperature calibrations. They developed a artificial intelligence calibration system using neural networks based on the Levenberg–Marquadt method, and showed that the hue–temperature curves for different illumination intensities collapsed to a single calibration curve, with a mean temperature error of ±0.12 °C. Hence, neural networks appear to be a potential method to compensate for variations in illumination intensity, particularly for hue–temperature calibrations.

Background reflection is also known to be a source of illumination disturbance, and was shown [29,73] to cause severe attenuation in hue–temperature calibrations when background reflection dominates the light reflected from TLCs. Anderson and Baughn [73] proposed two methods to compensate for illumination disturbance due to background reflection. The first method proposed by Anderson and Baughn [73] was the Background Subtraction method, which involves modifying the RGB tristimulus. For the red intensity–temperature curve, the background red was determined by identifying the region before colour play, and extracting the red intensities within that region. The mean of the red intensities before colour play was then calculated, and was used as the background red value. Following this, the background red value was subtracted from each point in the red intensity–temperature curve. The procedure was repeated for green and blue intensity–temperature curves. Anderson and Baughn [73] observed indifference in shape of the RGB curves; however, the curves were shifted down with an estimated uncertainty varying between ±1.2% and 2% across the bandwidth of the R25C7W TLC tested in their research.

The second method proposed by Anderson and Baughn [73] was the White Balancing method, which involves normalizing the red, green and blue background values. Contrary to the common white balancing method which involves focusing the video camera on a neutral reference and pressing the appropriate white balance settings, the proposed method was carried out during post-processing. The RGB tristimulus data were white balanced independently by multiplying red and blue data with constants so that the resulting average red and blue background values were equal to the average green background value. The White Balancing method was shown to give similar results as the Background Subtraction method. Hence, the methods offer possibilities to reduce attenuation in hue–temperature calibrations due to an increase in saturation for the R35C5W TLC tested in their research.

The second method proposed by Anderson and Baughn [73] was the White Balancing method, which involves normalizing the red, green and blue background values. Contrary to the common white balancing method which involves focusing the video camera on a neutral reference and pressing the appropriate white balance settings, the proposed method was carried out during post-processing. The RGB tristimulus data were white balanced independently by multiplying red and blue data with constants so that the resulting average red and blue background values were equal to the average green background value. The White Balancing method was shown to give similar results as the Background Subtraction method. Hence, the methods offer possibilities to reduce attenuation in hue–temperature calibrations, particularly due to background reflection.

In the uniform surface temperature method, it is expected that the hue is uniform over a calibration surface maintained at a uniform surface temperature. However, such is not the case when the illumination-viewing angle is large, and gradients in hue are obtained although the calibration surface is maintained at a uniform surface temperature. When compared with hue–temperature calibrations used in conventional reflection-based methods, hue–temperature calibration offers a useful calibration range of 7 °C, whereas transmission-based calibration offers a useful calibration range exceeding 20 °C for the R25C10W TLC tested in their research.

6.3.5. Transmission-based calibration

At present, a majority of the calibration methods used is based on the light reflected by the TLCs and are subjected to the issue of illumination disturbance. Due to the circular dichroism property of TLCs, TLCs reflect a component of visible light, while the other component is transmitted through the TLCs, and therefore it is possible to develop a calibration method based on light transmission rather than light reflection employed in conventional calibration methods. A light transmission-based calibration method was developed successfully by Roth and Anderson [81], in their investigation of film thickness, light polarization and light intensity effects on the transmission characteristics of a microencapsulated R25C10W TLC. The illumination source was placed behind the calibration surface, and the light transmitted through the TLC was measured using a spectrophotometer. They observed that the inflection wavelength, which is characteristic of the transmission spectra, was independent of the illumination intensity and film thickness, as shown in Fig. 19. They also observed that the red and green intensities of the transmitted light vary linearly with increasing surface temperature. When compared with hue–temperature calibrations used in conventional reflection-based methods, hue–temperature calibration offers a useful calibration range of 7 °C, whereas transmission-based calibration offers a useful calibration range exceeding 20 °C for the R25C10W TLC tested in their research.
Hysteresis in TLCs is a phenomenon whereby the TLCs exhibit a different behaviour when cooled rather than heated. Hysteresis was observed by a number of researchers [32–34,39,41,48] to occur when the TLCs are heated to or cooled from temperatures above their clearing point temperatures. It is typically assumed that calibrations of TLCs are repeatable, reproducible, reversible, and exhibit no hysteresis. Hysteresis can be a significant source of bias in calibrations of TLCs due to the fact that the calibration curves are different when cooled rather than heated.

The presence of hysteresis in TLCs was observed by researchers ever since the 1970s. Dixon and Scala [83], examined thermal hysteresis curves are different when cooled rather than heated. Hysteresis can be a significant source of bias in calibrations of TLCs due to the fact that the calibration curves are different when cooled rather than heated.

Abu Talib et al. [48] investigated hysteresis effects in a multi-event coating of three microencapsulated narrowband TLCs having the designation R30C1W, R35C1W and R40C1W. The transient method was used to determine the intensity–temperature relationship of the coating, based on green intensity. The coated calibration surface was heated to 45, 50, 55 and 60 °C, and slowly cooled to a temperature below the red start temperature of the R30C1W TLC. Hysteresis was clearly observed for initial cooling temperatures of 50, 55 and 60 °C, resulting in a decrease in peak green intensities, since the temperatures exceeded the clearing point temperature of the R30C1W TLC.
which was specified by Parsley [18] to be approximately 46°C. Their results correspond to the observations of Bakrania and Anderson [32].

Anderson and Baughn [39] investigated in detail hysteresis effects on hue–temperature calibrations of two narrowband TLCs having the designation R35C1W and R50C1W, and three wideband TLCs having the designation R24C10W, R30C10W and R35C5W. Their results showed an increase in magnitude of hysteresis effects with an increase in maximum surface temperature prior to cooling, which was characterized by a decrease in magnitude of RGB intensities and a shift in temperature at which peak red and green intensities occur when cooled rather than heated. They reported that the magnitude of hysteresis effects was more severe in narrowband TLCs compared with wideband TLCs, with a maximum bias of 38% and 62% of the useful calibration range for the R35C1W and R50C1W TLC, respectively, and a maximum bias of 24%, 20% and 21% of the useful calibration range for the R24C10W, R30C10W and R35C5W TLC, respectively.

Generally the following observations can be made on the effects of hysteresis on calibrations of TLCs based on the findings of existing literature [32–34,39,41,48]:

1. Hysteresis is characterized by a non-proportional decrease in magnitudes of red, green and blue intensities when cooled rather than heated. Anderson and Baughn [39] and Parsley [18] attributed hysteresis to the formation of the focal-conic texture when the TLCs are cooled from the isotropic liquid phase to the chiral-nematic phase, which is optically inactive. The results of Roth and Anderson [81] further showed that when hysteresis occurs in the TLC, more light is transmitted through the TLC, rather than reflected. This, in turn, results in a decrease in reflected red, green and blue intensities.

2. Hysteresis is characterized by a shift towards lower temperatures at which hue occurs when cooled rather than heated, resulting in a temperature bias in hue–temperature calibrations. This is due to the non-proportional decrease in red, green and blue intensities, as well as a shift in temperatures at which peak red, green and blue intensities occur.

3. Hysteresis occurs when TLCs are cooled from temperatures exceeding their clearing point temperatures, and the magnitudes of hysteresis effects are intensified as the maximum temperature prior to cooling increases.

4. Hysteresis effects are often temporary and calibrations are restored when the TLCs are cooled to temperatures below their red start temperatures. Hysteresis effects may be permanent however, due to prolonged exposure to high temperatures exceeding the clearing point temperatures of the TLCs, and therefore calibration curves become unusable.

5. Hysteresis effects are more prominent in narrowband TLCs compared with wideband TLCs; the smaller the bandwidth, the larger the temperature bias. Hysteresis effects are also more prominent for thin film thicknesses compared with thick film thicknesses; the thinner the TLC film thickness, the larger the temperature bias.

7.2. Correction methods

Knowing that hysteresis affects calibrations of TLCs, the reader may ask, “Is there a method for compensating hysteresis effects?” To date, the presence of hysteresis can only be avoided by proper use, which means preventing from heating the TLCs to temperatures exceeding their clearing point temperatures. In order to avoid hysteresis, the reader should have knowledge on the red start temperature and clearing point temperature of the TLC. This information can be readily obtained from the manufacturers upon request. For example, Parsley [18] specified that the clearing point temperatures for the R30C1W, R35C1W and R40C1W TLCs used by Abdullah et al. [50] are approximately 46°C, 49°C and 52°C, respectively. The exact clearing point temperatures of TLCs are difficult to determine by the naked eye, and Anderson and Baughn [39] stated that the blue stop temperature (i.e., clearing point temperature) was approximately 20°C above the top of the useful calibration range for the R24C10W, R30C10W, R35C5W, R35C1W and R50C1W TLCs used in their research. It is best to obtain the red start and clearing point temperature of TLCs from the manufacturers as a rough estimation prior to calibration of TLCs.

The reader can perform a simple 3-set calibration to check on the occurrence of hysteresis for a specific TLC. The first calibration comprises of heating the TLC to a temperature below the clearing point temperature of the TLC (for example, 1°C below $T_c$), followed by cooling the TLC to a temperature below its red start temperature. The second calibration is similar to the first, except that the TLC is heated to its clearing point temperature specified by the manufacturer. The third calibration is similar to the other calibrations; however, the TLC is heated to a temperature above the clearing point temperature of the TLC (for example, 1°C above $T_c$). If the magnitudes of red, green and blue intensities decrease drastically, particularly at the clearing point temperature, hysteresis occurs and the user should avoid heating the surface to that temperature.

Fig. 20. Effects of hysteresis on hue–temperature calibrations of R23C10W TLC for: (a) Surface A and (b) Surface B (adapted with permission from Bakrania and Anderson [32]. Copyright (2002), American Society of Mechanical Engineers).
Methods to compensate hysteresis effects in TLCs would be most welcome in order to extend the usability of calibrations. Since the root of hysteresis is the molecular arrangement of TLCs, it may be possible that the solution is to induce some form of mechanism which will force the focal-conic texture back to its planar texture when the TLCs are cooled from the isotropic liquid phase to the chiral-nematic phase.

7.3. A similar hysteresis phenomenon

A phenomenon similar to hysteresis has been observed by several researchers although the TLCs are cooled from temperatures below their clearing point temperatures. In a recent research, Abdullah et al. [50] showed that it may be possible that TLCs behave differently depending on the direction of temperature change (heating or cooling) although the clearing point temperatures of the TLCs tested were not exceeded. They compared heating and cooling intensity–temperature calibrations of R30C1W, R35C1W and R40C1W narrowband TLCs applied to a film thickness of 10 μm based on red, green and blue intensities. Their results showed a consistent shift towards lower temperatures at which peak red, green and blue intensities occur when cooled rather than heated, although the initial cooling temperatures were kept 3°C below the clearing point temperatures of the TLCs. The magnitude of temperature shift between heating and cooling calibrations was found to be dependent on the type of TLC. The consistent shift towards lower temperatures at which peak red, green and blue intensities occur seems to suggest the occurrence of hysteresis in the TLCs. However, since the magnitudes of peak red, green and blue intensities were consistently higher when cooled rather than heated, indicating that the TLCs were in their planar textures, they did not categorize the temperature shift between heating and cooling calibrations as ‘hysteresis’. They cautioned that it is inappropriate to assume that heating and cooling calibrations of TLCs are equal although the clearing point temperatures of the TLCs are not exceeded.

In a recent investigation, Kakade et al. [34] observed a shift towards lower temperatures at which hue occurs when cooled rather than heated. Their results showed a similar trend to the findings of Abdullah et al. [50], although the primary difference being that hue–temperature calibrations were used in their research rather than intensity–temperature calibrations. In their research, calibrations were conducted for R30C1W, R40C1W and R30C5W TLCs applied to a film thickness of 45 μm. The samples were heated from 20°C to 42.5°C, which was slightly above the blue start temperature of the R40C1W TLC. Although it was referred in their paper that ‘42.5°C was a temperature just beyond the clearing point of R40C1W TLC’, the term ‘clearing point’ was not particularly true because the clearing point temperature refers to the temperature at which the TLC ceases to reflect visible light, which was approximately 52°C for the R40C1W TLC manufactured by Halcrest. Hence, a difference between heating and cooling calibrations was observed in their research, although the clearing point temperatures of the TLCs were not exceeded. This further supports the possibility that TLCs may exhibit a different behaviour depending on the direction of temperature change, as was observed by Abdullah et al. [50]. Ironically, a similar statement was given by Grodzka and Facemire [55] more than 30 years ago, that some liquid crystal formulations change colours at different temperatures depending on whether the samples are heated or cooled.

Consequently, if heat transfer measurements are carried out using transient Liquid Crystal Thermography, it is recommended that the transient is initiated from the same direction (heating or cooling) as that used for calibrations, and if possible, from the same initial temperatures as that used for calibrations [39].

8. Film thickness

8.1. Characteristics and observations

Film thickness, otherwise known as the coating thickness, is the thickness of the TLC layer or film, once the TLC has been applied and dried over the surface. Although not stated explicitly in the literature, film thickness of TLCs generally meant the dry film thickness.

A number of works have reported the effects of film thickness on calibrations of TLCs. Behle et al. [35] investigated the effects of three film thicknesses having magnitudes of 14, 23 and 34 μm on hue–temperature calibrations of a sprayable R30C5W TLC. Their results showed a relative standard deviation in hue of nearly 24% for a film thickness of 14 μm, and the value decreased to nearly 22% and 19% for film thicknesses of 23 and 34 μm, respectively. The high value of relative standard deviation in hue was attributed to the attenuation of reflected colours towards the incident white light resulting from the low density of TLC covering the surface. The results of Bakrania and Anderson [32] showed a similar trend to the results of Behle et al. [35], and they reported an average standard deviation in hue of 12% for a surface coated with half the amount of R25C10W TLC. The value decreased to 3% when more TLC was used. No quantifications were made however, regarding the film thickness of the samples used in their research.

Wiberg and Lior [27] investigated the effects of eight film thicknesses having magnitudes of 9, 11, 16, 20, 25, 29, 34 and 38 μm on hue–temperature calibrations of R45C10W TLC. The shift in hue–temperature calibrations due to varying film thickness is shown in Fig. 21, for film thicknesses of 9, 11, 20 and 38 μm. From Fig. 21, it can be observed that hue occurs at lower temperatures, particularly at hues below 0.6. They reported that the maximum temperature difference at a constant hue was 12% of the useful calibration range for thin film thicknesses between 9 and 20 μm, and the value decreased to 7% for thick film thicknesses between 20 and 38 μm. They attributed the temperature difference was due to the decrease in saturation of the reflected colours for thin film thicknesses. They also reported that thin film thicknesses were also more susceptible to aging effects and errors in 24-bit digital colour representation. More recently, Kakade et al. [34] showed an insignificant difference in hue–temperature calibration for thick film thicknesses of 30 and 45 μm, compared with a film thickness of 15 μm.

Fig. 21. Effects of film thickness on hue–temperature calibrations of R45C10W TLC (adapted with permission from Wiberg and Lior [27]. Copyright (2004), American Institute of Physics).
Motivated by the research of Wiberg and Lior [27], Abdullah et al. [50] investigated film thickness effects of 10, 20, 30, 40 and 50 μm on intensity–temperature calibrations of R35C1W TLC. They focused particularly on green intensity due to the observations that film thickness effects were most prominent in the green region (G > R, B) of hue–temperature calibration curves. They reported a percentage increase in peak green intensity of nearly 18% when film thickness increased from 10 to 50 μm. They also observed an inconsistent shift in temperature at which peak green intensity occurs, with a maximum temperature difference of 0.4 °C. When compared with the findings of Wiberg and Lior [27], they noted the possibility that the temperature difference due to increasing film thickness may be less significant for narrowband TLCs compared with wideband TLCs. This was due to the observation that the maximum temperature difference obtained by Abdullah et al. [50] was 0.4 °C when film thickness increased from 10 to 50 μm for R35C1W TLC, whereas the maximum temperature difference obtained by Wiberg and Lior [27] was nearly 3 °C when film thickness increased from 9 to 38 μm for R45C10W TLC. However, further work is required to confirm this possibility, using several samples of TLCs with the same red start temperatures, but with different bandwidths.

Contrary to the findings of others [27,32,35,50], Fung et al. [11] observed a negligible shift in hue–temperature calibrations of R20C20W TLC for three film thicknesses categorized as ‘thin’, ‘medium’ and ‘thick’ based on qualitative interpretation of reflectivity brightness. Since the film thicknesses were not quantified, it may be possible that the film thicknesses in their experiments did not differ significantly from one another, resulting in a negligible shift in hue–temperature calibrations.

Generally, the following observations can be made regarding the effects of film thickness on calibrations of TLCs based on the findings of previous researchers [27,32,35,50]:

1. Increasing film thickness results in an increase in magnitude of red, green and blue intensities, which in turn results in brighter reflected colours. Roth and Anderson [81] further confirmed this statement by experimental evidence, showing that the amount of light transmitted through a TLC decreases with increasing film thickness.
2. Increasing film thickness results in a shift towards lower temperatures at which hue appears, particularly in the red and green regions.
3. Thin film thicknesses with magnitudes below 20 μm gives a higher standard deviation in hue, whereas thick film thicknesses with magnitudes above 20 μm give higher repeatability in calibrations, even after repeated heating cycles and exposure to higher temperatures.

8.2. Correction methods

Knowing that film thickness affects calibrations of TLCs, the reader may ask, “Is there a method for minimizing film thickness effects?” Here are a couple of suggestions which may help minimize film thickness effects.

8.2.1. Estimate film thickness

In order to ensure consistency in film thickness between different coated surfaces, it is desirable to estimate and measure the film thickness. Based on the method of Parsley [18], a simple method can be used to estimate the volume of coating required to achieve a desired film thickness, given by the formula:

$$V_{\text{TLC}} = \frac{th_{\text{film, dry}} \times A_{\text{surface}} \times 100}{DSC_{\text{TLC}}}$$

where $V_{\text{TLC}}$ represents the volume of sprayable coating in millilitres (ml), $A_{\text{surface}}$ represents the surface area in squared metres (m²), $DSC_{\text{TLC}}$ represents the dry solids content of the TLC in percent (%) and $th_{\text{film, dry}}$ represents the desired dry film thickness in microns (μm). This formula, of course, applies only for estimating the volume required for sprayable coatings.

The dry solids content of the TLC can be obtained by knowing the dry weight and wet weight of the TLC, as follows:

$$DSC_{\text{TLC}} = \frac{W_{\text{TLC,dry}}}{W_{\text{TLC,wet}}} \times 100$$

where $W_{\text{TLC,dry}}$ represents the weight of the TLC dry solids and $W_{\text{TLC,wet}}$ represents the weight of the TLC solution.

The dry weight and wet weight of the TLC can be obtained by performing a simple oven test. In this test, a sample of coating is placed in a shallow container, similar to a glass Petri dish, and heated in a laboratory oven set at a temperature of 45 °C for a period of 12 h. The sample will evaporate slowly to dryness, forming a dry solid mass in the container. The weights of the TLC solution (before heating) and TLC dry solids (after heating) can be measured using a laboratory-grade electronic balance. Since the dry solids content of the TLC is in the units of percent, the units for the weight measurements will not make a difference in the calculations. From Parsley [18], the typical range of dry solids content for microencapsulated chiral-nematic sprayable coatings manufactured by Hallcrest is 10–15%. By knowing the dry solids content of the TLC, the surface area and the dry film thickness that the reader would like to achieve, the volume of coating required to achieve that film thickness can be readily estimated. This method can be used in conjunction with the method used by Kakade et al. [34], in which the film thickness is measured using scanning electron microscope (SEM).

8.2.2. Optimum film thickness

The optimum film thickness of TLCs is still debated, and the criteria for an optimum film thickness are still somewhat vague. From Parsley [18], the recommended film thickness of TLCs manufactured by Hallcrest is 10 μm. However, it is clearly evident from previous works [27,32,35,50] that calibrations of thin film thicknesses with magnitudes below 20 μm are more susceptible to signal noise, aging effects and degradation in surface quality. Film thicknesses above 20 μm were deemed more ideal. Based on the quality of temperature signal determined from the frequency response of pure TLCs, Wagner and Stephan [23] concluded that the optimum film thickness of TLCs lies within the range of 10 and 20 μm. Kakade et al. [34] however, used a film thickness of 45 μm in actual heat transfer measurements on a rotating disc on the basis that this film thickness gives a repeatable and reproducible hue–temperature calibration up to 10 heating cycles when the R30C1W TLC was heated to 32.5 °C. The film thickness was also less susceptible to aging when the TLC was exposed to a higher temperature of 60 °C for a prolonged period.

The reader may now ask, “Which film thickness shall I use then?” From experimental evidence, film thicknesses with magnitudes below 20 μm can be considered as ‘thin’ and therefore should be avoided. Generally, film thicknesses with magnitudes between 20 and 50 μm are not considered ‘too thick’ as they do not result in a milky appearance. Wagner and Stephan [23] reported that a film thickness of 100 μm results in a milky appearance, which is ‘too thick’. Film thicknesses with magnitudes between 20 and 50 μm are deemed sufficient for temperature measurements based on the light reflected by TLCs. Once an appropriate film thickness has been chosen, it is important to maintain consistency in the magnitude of film thickness of the coated surface. Film uniformity becomes an issue however, particularly for
sprayable coatings on complex geometries. An application method which gives film uniformity superior to existing conventional methods has yet to be devised. It is for this reason researchers often analyze a small ROI with an area of about 50 × 50 pixels, rather than an entire calibration surface.

9. Aging

9.1. Characteristics and observations

Aging is a phenomenon whereby the TLCs exhibit a different behaviour due to prolonged use. From Lazarra [44] and Parsley [18], TLCs age with time, and the colour-temperature profiles of TLCs obtained prior to shipping may be different than the colour-temperature profiles obtained when the TLCs reach the customers. Hence, Parsley [18] recommended that the user should perform regular checks on the colour-temperature profiles of TLCs.

Several works have reported on the aging effects on calibrations of TLCs. Wiberg and Lior [27] investigated aging effects on hue-temperature calibrations of R45C10W TLC applied to film thicknesses of 9 and 38 μm. The samples were heated to a temperature of 55 °C and maintained at 55 °C for a period of 205 min. The period of 205 min was chosen because it was a time representative for normal use of TLCs in industrial situations. The shift in hue-temperature calibrations due to aging at an elevated temperature is shown in Fig. 22, for film thicknesses of 9 and 38 μm. From Fig. 22, it can be observed that hue occurs at a higher temperature after aging, particularly for a film thickness of 9 μm, whereas the changes in hue are negligible for a film thickness of 38 μm. They reported a maximum temperature difference at a constant hue of 13% and 4% of the useful calibration range for a film thickness of 9 and 38 μm, respectively. They also reported a negligible temperature difference of 1.4% of the useful calibration range for R35C20W TLC when the calibration surface was kept at a temperature below the red start temperature of the TLC.

Kakade et al. [34] investigated aging effects on hue-temperature calibrations of R30C1W TLC applied to film thicknesses of 15, 30 and 45 μm. They heated the samples to 60 °C and maintained at 60 °C for a period of 150 min. The samples were then cooled to 20 °C and subsequently heated through its bandwidth. A shift towards higher temperatures at which hue occurs was observed with aging at an elevated temperature exceeding the clearing point temperature of the R30C1W TLC. Their results showed a similar trend to the results of Wiberg and Lior [27].

Generally, aging effects in TLCs are characterized by:

1. A decrease in magnitude of red, green and blue intensities. However, the decrease in red, green and blue intensities appear to be gradual rather than a drastic decrease, which is the case if hysteresis occurs in TLCs.
2. A shift towards higher temperatures at which hue occurs, thus giving a different calibration curve. Aging occurs regardless whether the TLCs are maintained at an elevated temperature within the colour play interval of the TLCs or above the clearing point temperatures of the TLCs.

9.2. Correction methods

Knowing that aging affects calibrations of TLCs, the reader may ask, “Is there a way to combat aging effects?” Although aging effects cannot be eliminated completely, they can be minimized by proper use, outlined as follows.

9.2.1. Proper preparation and storage of TLCs

Proper preparation and storage of TLCs is important to minimize aging. If pure TLCs are used, proper care must be taken to ensure that pure TLCs are not exposed to fats, greases, organic solvents and dust. Pure TLCs are also more susceptible to UV and IR radiation, and exposure to these sources reduces the shelf life of pure TLCs from several hours to several days. Therefore, microencapsulated TLCs are more preferable, which helps reduce degradation and therefore minimize aging.

In cases whereby complex geometries are used, sprayable coatings are more suitable. Sprayable microencapsulated TLCs are supplied as aqueous slurries which need to be mixed with binder material and water to form sprayable coatings. Abdullah et al. [50] used the following volume ratio which comprises of TLC: 5, binder: 1, and water: 6. They found that the coating prepared using the above volume ratio was suitable for spraying TLCs to the calibration surface by airbrush without clogging the nozzle of the airbrush. Evans et al. [84] however, utilized a volume ratio with equal parts of TLC and binder (TLC: 1, and binder: 1), and they diluted the coating with demineralised water. There are no specific rules for determining the volume ratio of sprayable coatings, and the chosen volume ratio generally depends on the reader’s preference and the method of application.

It is recommended to use the method described by Farina et al. [29] for mixing sprayable coatings. Farina et al. [29] utilized a commercial-grade handheld mixer for mixing 100 g of TLC aqueous slurry for 15 min. The coating was then diluted with distilled water and mixed with a laboratory-grade magnetic mixer for 25 min. Following this, the coating was filtered using a standard 25 mm diameter syringe filter holder containing a 43 μm pore-size polyester filter. The filter functions to remove extraneous aggregates and gives a coating of uniform consistency, which is ideal for sprayable coatings. Syringe filters are commercially available in the market, with fine membrane filters less than 10 μm. After mixing, the coatings should be stored in a cool, dry place away from sunlight and room light. The recommended storage temperature for TLCs manufactured by Hallicrest is within 5–10 °C [24].

It is generally a good practice to label each coating with the name of the TLC, the volume of coating and more importantly, the date of preparation. For example, if the reader mixes a coating consisting of three microencapsulated chiral-nematic TLCs having the designation R30C1W, R35C1W and R40C1W, with a total volume of 60 ml, on 8th June 2009, it is good practice to label the coating as illustrated in Fig. 23. Labelling is trivial, but nevertheless helps the reader to keep track of prepared coatings and facilitates identification, particularly if the reader has to prepare a number of different coatings. When coatings are prepared and stored
Sprayable black inks are also readily available from the manufacturers. The coatings can have a useful shelf life of up to 6 months from the date of preparation, which further emphasizes the importance of good labelling.

9.2.2. Proper preparation and storage of surface

Proper preparation and storage of the calibration surface is also important in order to minimize aging. It should be ensured that the calibration surface is free of dust, grease, organic solvents and other debris prior to deposition of black backing and TLCs. It is desirable that the calibration surface is smooth and this can be done by polishing the surface with abrasive papers of different grit sizes for coarse, medium, fine and extra fine sanding. There are several types of abrasive papers available in the market, the most common ones being aluminium oxide and silicon carbide, which are suitable for polishing non-ferrous metal surfaces such as copper and aluminium. However, silicon carbide abrasive papers are also suitable for transparent acrylic plastics such as Perspex™, Plexiglas™ and Lexan™ which are commonly used in convective heat transfer facilities.

After the calibration surface has been polished, black backing should be applied to the surface. If a pre-manufactured sheet is used, black backing is readily supplied, and the reader can simply attach the sheet to the surface using pressure-sensitive adhesive. However, for sprayable coatings, black backing is required prior to deposition of TLCs to provide an optimum contrast for the colour play of TLCs. Water-based black paints are preferable compared with hydrocarbon-based paints to ensure that the contents of the paints do not damage the TLCs, which may further induce aging. Sprayable black inks are also readily available from the manufacturers of TLCs, which ensure compatibility with the TLCs. After the black backing has completely dried, the TLCs can be applied to the calibration surface using any of the conventional methods such as airbrushing, brushing, rolling, dipping, pouring or screen printing. The coated surface should be stored in a clean, cool, dry place away from sunlight and room light at a storage temperature well below the red start temperature of the TLCs used. For example, if the calibration surface is coated with R30C5W TLC, a storage temperature of 15–20 °C is desirable. Again, it is recommended to label the coated surface with the name of the TLC, film thickness of the coating and the date of preparation.

9.2.3. UV and IR cut-off filters

UV and IR radiation are known to cause degradation to TLCs, and therefore it is imperative to prevent excessive exposure to these sources. Kakade et al. [34] reported the possibility that aging of TLC films is accelerated by the absorption of UV radiation. Abu Talib [49] noted an insignificant change in intensity-temperature calibration of a mixture of three microencapsulated narrowband TLCs, R30C1W, R35C1W and R40C1W, for a period of 1 month after the first calibration. Abu Talib [49] attributed the insignificant change due to time in the calibrations was due to the fact that the calibration surface was not subjected to excessive exposure to UV radiation. However, it is noteworthy to point out that the sample of Abu Talib [49] was neither subjected to repeated heating cycles, nor the sample was maintained at an elevated temperature within the colour play interval of the TLCs or above the clearing point temperatures of the TLCs. Special UV and IR cut-off filters are commercially available in the market for use with illumination sources, which functions to filter unwanted UV and IR, and passes through light in the visible spectrum. Anderson and Baughn [73] reported that hue-temperature calibrations of R35C5W TLC were repeatable even after 20 h of direct exposure to a GE cool white fluorescent source fitted with Spectrum 574 UV filter. Therefore, the use of UV and IR cut-off filters further helps minimize aging of TLCs.

9.2.4. Thick film thickness

It was shown from the findings of Wiberg and Lior [27] that thick film thicknesses with magnitudes between 20 and 38 μm were less susceptible to aging effects although the samples were maintained at an elevated temperature within the colour play interval of the R45C10W TLC for a prolonged period. Kakade et al. [34] also observed an insignificant shift in hue-temperature calibrations for R30C1W TLC with a thick film thickness of 45 μm, even after prolonged heating at high temperatures. Bakrania and Anderson [32] also noted that hue-temperature calibrations were completely repeatable after a period of two weeks for a surface coated with twice the amount of R25C10W TLC and a degradation in surface quality was not observed for the surface coated with a thicker film. Therefore, thick film thickness is recommended for minimizing aging of TLCs. However, it shall be cautioned that the film thickness should not be too thick such that it causes a milky colour appearance and large temperature gradients within the film.

10. Conclusions

A review on the basics and issues pertaining to calibrations of TLCs has been presented in this paper. A general overview of TLCs, the basic elements of a TLC calibration rig and the common TLC calibration methods have been described, and the crucial issues have been addressed, namely, imaging, colourimetry, illumination, hysteresis, film thickness and aging. The key conclusions on the issues associated with calibrations of TLCs are summarized as follows:
1. In imaging of TLC calibrations, it is important to select correct exposure and white balance settings, as well as to select a suitable colour space for processing of calibration images. Hue in the HSI colour space is generally preferable as it describes colours in a manner which is intuitive to humans. However, it is more desirable if hue is defined as a polar coordinate in a colour space which is independent of the imaging device and brightness information such as CIE XYZ and CIE UWW colour spaces.

2. A full-spectrum white light illumination source with low UV and IR emission is more desirable for calibrations of TLCs in order to give a broader useful calibration range and reduced uncertainty in temperature measurement. It is also desirable to select an illumination source which possesses a high CRI and FSCI, to attain natural-looking colour appearance and good colour discrimination. The use of UV and IR cut-off filters further helps to minimize degradation of TLCs.

3. The use of an on-axis illumination-viewing arrangement coupled with in-house correction algorithms helps to minimize illumination disturbance arising from variations in illumination-viewing angles, illumination intensity and background reflection, and is particularly useful for calibrations of wideband TLCs. Most of the recent works were focused on the development of correction algorithms, with an achievable accuracy in temperature measurement of ±0.1 °C. Consistency in TLC coating and surface preparation, illumination source, illumination-viewing arrangement and imaging system settings further helps to minimize illumination disturbance effects, particularly for non-in situ calibrations.

4. Hysteresis in TLCs can be avoided by ensuring that the TLCs are cooled from temperatures below the clearing point temperatures of the TCLs, and ensuring that actual tests are carried out in the same direction of temperature change as that for calibrations, and from the same initial temperatures.

5. A consistent film thickness between calibration and actual test surfaces should be maintained in order to minimize film thickness effects. Aging effects can be minimized by using thick film thicknesses between 20 and 50 μm, minimizing exposure of the coated surfaces to UV and IR radiation, and by storing the coated surfaces at temperatures well below the red start temperatures of the TCLs.

6. Finally, it is emphasized that there is not a single excellent calibration method applicable for all temperature measurements. The suitability of a calibration method, be it steady-state or transient, in situ or non-in situ, hue-based or intensity-based, generally depends on the experimental conditions, available apparatus, desired accuracy in temperature measurement and the reader’s experience. The current trend shows an increasing improvement in the development of calibration methods such as calibrations based on light transmission and neural networks, and it can be expected that more novel methods will emerge in the near future to produce robust calibrations with broader useful calibration range and reduced uncertainty in temperature measurement.

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