CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

DEPARMTENT OF PROCESS ENGINEERING

THERMOCHROMIC LIQUID CRYSTALS AS A TEMPERATURE INDICATOR

BACHELOR THESIS

2019

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I confirm that the diploma (bachelor's) work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of the documents and literature.

In Prague Name and Surname

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DEDICATION

I dedicate this research work to my unborn child, my mother, the mother of my unborn child, and to my uncle, Hamzat.

ACKNOWLEDGEMENT

With profound gratitude, I acknowledge the assistance of my thesis supervisor Stanislav Solnar, in various aspect of the research work.

I would like to thank my mother Dupeola Suleiman for her unalloyed and untiring love. I would like to extend my appreciation to my father and members of my family; Suleiman, Idris, Ishaq, Memunat, and Muhammad Jamiu.

Annotation sheet

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Annotation - Czech: Byl proveden stručný přehled termochromních kapalných krystalů pro měření povrchové teploty. Praktický aspekt se zaměřil na získání a kalibraci křivky barevného odstínu a teploty pro různé úhly osvětlení a vertikální vzdálenosti osvětlení.

Annotation - English: A concise review of the application of thermochromic liquid crystals for surface temperature measurement was conducted. The practical aspect focused on obtaining a hue-temperature calibration curve for different angles of illumination and vertical distances of illumination, in order to evaluate of illumination source on accuracy of measurement.

Keywords: Temperature, Liquid crystals, thermochromic liquid crystals, hue, calibration curve, angle of illumination

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CHAPTER ONE

INTRODUCTION

1.1 Temperature and Heat

Temperature, a physical quantity is a convenient and most widely used expression of the degree of hotness or coldness. Oxford dictionary defines temperature as ***"The state of a substance or body with regard to sensible warmth or coldness, referred to some standard of comparison; spec. that quality or condition of a body which in degree varies directly with the amount of heat contained in the body, and inversely with its heat-capacity; commonly manifested by its imparting heat to, or receiving it from, contiguous bodies, and usually measured by means of a thermometer or similar instrument."*** (Oxford Dictionary 2019).

Temperature is a **measure** of the heat or thermal energy associated with the microscopic motion, average kinetic energy**,** of all the particles, atoms or molecules in a substance or matter. The molecules in a cup of hot coffee will move faster than the molecules in a cup of cold milk, thus possessing higher temperature and consequently higher average kinetic energy.

The interrelationship between temperature and heat is stated simply as follow, "***temperature refers to the average kinetic energy per molecule of a substance; it is measured in degrees Celsius (C), degrees Fahrenheit (F) or, in scientific articles, temperature is given in degrees Kelvin (K). Hence, simply stated, temperature is how hot or cold an object is, while heat is the energy that flows from the hotter substrate to the cooler substrate, measured in Joules or calories"*** (Horikoshi et al. 2018).

According to Reif (1965) ***"***The transfer of energy from one system to another can occur as a result of purely thermal interaction. The mean of this energy that is transferred as result of purely thermal interaction necessitated by temperature difference between systems is what is known as heat. This energy can be denoted as positive if it absorbed into the system and denoted as negative if it's given off by the system."

The energy in transit nature of heat is further stated by Blundell and Blundell (2006) in their definition of heat as some sort of energy transferred from a hot substance to a cold substance when these those substances are in contact.

The importance of temperature is not only strengthened by its interrelationship with heat or thermal energy but the interdependency and convertibility of thermal energy and other forms of energy.

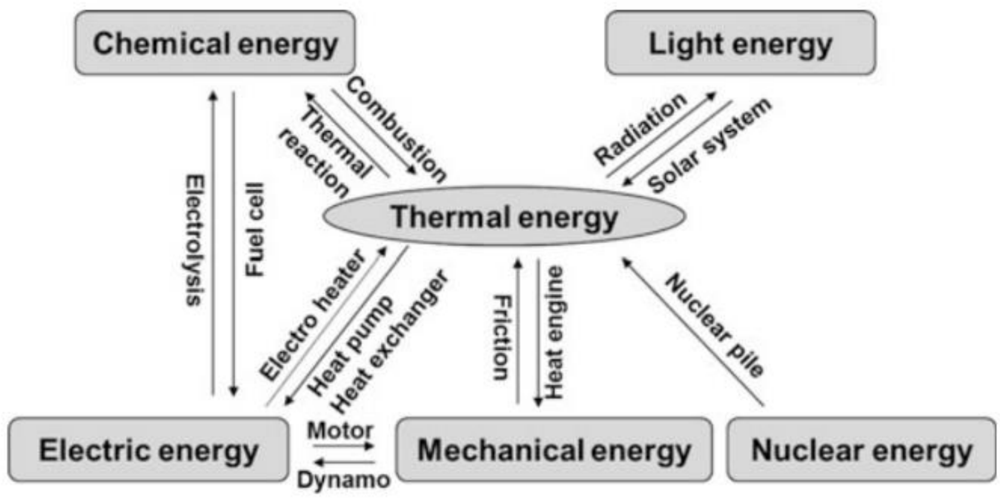


Figure 1.1 Possible changes of forms of energy (Horikoshi et al. 2018).

Having mentioned heat as a form of energy which is transit between two systems or bodies, the mechanisms of this transit include conduction, convection, and radiation. Conduction mechanism is in play when there is a direct contact between the source and the receiving system or body, radiation on the other hand occurs between remote systems or bodies. The combination of these mechanism is also seen in many cases (Chandrasekhar 1961).

From the definitions of temperature and heat given, the interdependency and relationship between the two is crystal clear, however they need not be confused with each other and can't be used interchangeably. This is laid bare by Horikoshi et al. (2018), "***heat refers to a quantity of energy transferred between two bodies, it is not a function of the state of either of the bodies, in contrast to temperature and internal energy. Instead, according to the first law of thermodynamics, heat exchanged during some process contributes to the change in the internal energy, and the amount of heat can be quantified by the equivalent amount of work that would bring about the same change."*** While temperature is an intrinsic property of matter, system, substance, heat is not a property or a function of the body or matter (Leland 2001).

The relevance and role of temperature in our daily lives, the immediate world around us and the universe at large can't be overemphasized. The physical state (i.e. solid, liquid, gaseous) of a substance and the phase change between these states of matter, the internal energy of a substance, several physical processes such as melting, boiling, evaporation, sublimation, the physical properties of a substance such as color, texture, viscosity, density, volume, solubility, electrical conductivity or electrical resistivity, chemical properties of matter such as reactivity, flammability, and several mechanical properties, thermal properties of matter and thermodynamics processes are all either dependent on temperature or a direct or indirect function of temperature.

1.2 Methods of Temperature Measurement

The term thermometry refers to any procedure or process used for measuring temperature and thermometric properties are properties of matter such as physical, electrical or magnetic properties, that changes considerably and measurably with temperature change. Hence, the measurement of temperature is anchored to a certain change in the property or characteristics of the system, body or substance of interest that can be directly linked or correlated with the change of its temperature. Two major classification of thermometry is based on thermometric properties or principle and based on the mode of operation.

Based on the measuring principle or thermometric properties, there are four types of temperature measuring devices (Pdhonline.com, 2019):

1. Mechanical (liquid-in-glass thermometers, bimetallic strips, bulb & capillary, pressure type etc.)
2. Thermojunctive (thermocouples)
3. Thermoresistive (RTDs and thermistors)
4. Radiative (infrared and optical pyrometers)

A general classification based on the mode of operation is as follows:

1. Thermometers
2. Probes
3. Non-contact

1.3 Liquid Crystals

The history of liquid crystals perhaps can be said to bring with the curious observation of Prague scientist Friedrich Reinitzer in 1888 with double melting points of cholesterol benzoate. This observation gave way to what is now known as liquid crystals (Lagerwall and Scalia, 2012).

As implied by the name, liquid crystals have some properties or characteristics of both liquids and solid crystals**.** The degree of order of molecules of liquid crystals is in-between the molecular order of three dimensionally ordered solids and the molecular order of isotropic liquids. The typical characteristics of liquid possessed by the liquid crystalline mesophases includes fluidity and inability to withstand shear stress, formation and coalescence of droplets. Liquid crystalline mesophase also have crystalline properties such as periodic arrangement of molecules in defined spatial directions, anisotropy of electrical, optical and magnetic properties. (Andrienko, 2018). In essence, a liquid crystal can have the fluidity similar to an ordinary liquid while possessing properties of a crystalline phase such as birefringence.

The tendency of the molecules to point along a common axis called the director is hallmark of liquid crystalline state, which is different from liquid phase which has not intrinsic order and in between the solid state which has highly ordered molecules which has little translational freedom. Hence, their characteristic orientation and order is between solid and liquid phases.

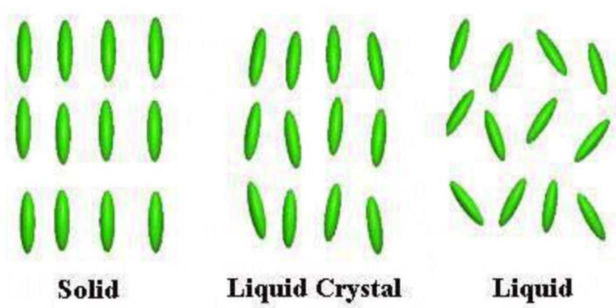


Figure 1.2 Difference in the order and orientation of molecules of solid, liquid and liquid crystals.

Based on whether the liquid crystal mesophases is obtained mainly by variation of temperature of the individual molecules without the addition of further molecular specie, or by the addition of a solvent to a molecular specie, or whether the constituent molecular specie is inorganic or organic, liquid crystals are broadly classified into:

1. Thermotropic liquid crystals
2. Lyotropic liquid crystals
3. Metallotropic liquid crystals

1.Thermotropic liquid crystals: are temperature dependent liquid crystals. As described by (Lagerwall and Scalia, 2012) they are individual molecules that requires no solvent molecules or any other molecular specie to form a liquid crystalline mesophase. Temperature is the only fundamental thermodynamic parameter that controls and determine their liquid crystalline mesophase order and formation. They have two key temperature values, the temperature that signifies the start and end of the liquid crystalline order, that's the melting point temperature from crystalline solid and the clearing point into an isotropic liquid.

Thermotropic phases exists in a certain temperature range and doesn't depend on concentration or presence of other species, hence thermal motion will destroy the delicate cooperative ordering of the liquid crystal phase is destroyed by thermal motion from high temperature, pushing the material into a conventional isotropic liquid phase. At a temperature very much lower than the range for the existence of the thermotropic phase, most LC materials will form a conventional crystal. Hence, the temperature dependence of thermotropic liquid crystals enables them to have a range of phases that varies with temperature.

Thermotropic liquid crystals can be further grouped, on the basis of the symmetry of the molecules in a mesophase, or the arrangement of the molecules, into into nematics, cholesterics, smectics, and columnar mesophases. (Andrienko, 2018).

Generally, the difference between nematics and smectics, according to (Vertogen and Jeu, 1988) lies in the degree of freedom of the centres of mass of the molecules**.** Since the centre of mass of nematic liquid crystalline mesophase has three translational degrees of freedom, they are randomly distributed. They are more closely related to anisotropic liquids. Smectic liquid crystalline mesophases have positional order in at least one dimension of their molecular arrangement. The centres of the molecules are arranged in equidistance positions on average.

In a nematic phase, positional order is lacking in the arrangement of the *calamitic* or rod-shaped organic molecules, but there exists self-alignment in the form of long-range directional order with their long axes roughly parallel (Rego et al. 2010).

The lack of positional order makes the nematics the simplest liquid crystal phase, and they are characterized by their spontaneous long-range orientation order with the molecules on average, oriented parallel to a mean direction referred to as the director, which is generally signified by the symbol ***n***. Their alignment arrangement gives rise to optical properties of uniaxial crystals and this makes them extremely useful in liquid crystal displays.

The smectic phases, are found at a temperature lower than the temperature range of the nematiccs. They differ primarily from nematics and cholesteric mesophases due to their positional order along one direction and well-defined layered structure which can slide freely over one another, they have both positional and orientational ordering. In addition to the similar classification as nematics, smetics can also be characterized based on layered ordering of the molecules e.g. in a smectic A, molecules are aligned perpendicular to the layers, without long-range crystalline ordering within them.

The chiral nematic and cholesteric mesophase are interrelated, and sometimes used interchangeably. As implied by the name, chiral nematics are distinguished by their chirality (handedness). Chloesteric mesophase is a name derived from the class of chiral nematics that were first observed in chelostrol derivatives (Lagerwall and Scalia, 2012). Since nematic liquid crystal is a form of cholesteric liquid crystal having an infinite pitch, there is no phase transition between nematic and cholesteric mesophases. This cholesteric mesophase, which is exhibited by materials composed of optically active molecules that have no internal planes of symmetry, is essentially of the nematic type except that the structure has a screw axis which is superimposed normal to the director. The molecules are twisted perpendicularly to the director with the axis of the molecules parallel to the director. They also have longer range chiral order (Andrienko, 2018).

While the nematics liquid crystals have very useful property that is employed in liquid crystal displays, chiral liquid crystals have promising potential in thermometry. ***Chiral nematic or cholesteric liquid crystals reflect light with a wavelength equal to their pitch. As the pitch is sensitive to temperature variations, the color of the reflected light depends on temperature. It is therefore possible to determine temperature just by looking at the color of the thermometer. By mixing different compounds, devices for practically any temperature range can be built.*** (Andrienko, 2018). Other optical properties exhibited by cholesteric liquid crystals due their helical structure include selective reflection of circularly polarized light, very high optical rotatory power, etc. Another main difference is that unlike the nemetic mesophase, the director (***n***) varies throughout the medium in a regular way even in an unstrained state. The director distribution can be seen as a twist of a nematic aligned along the *y* axis about the *x* axis.
The columnar mesophase are distinguished by the arrangement of the molecules into a cylindrical structure. Due to their columnar structure which is composed of stacked flat-shaped discotic molecules (e.g. triphenylene derivatives) or bowl-shaped molecules, they were known as discotic liquid crystals or blowlic liquid crystals. (Andrienko, 2018) (Lam, 1987).

The position of the molecule of columnar liquid crystals is fixed with respect to the plane perpendicular to the column axis, the packing of the molecule along the axis of the column is irregular, and the position of the molecule along that axis is not defined with respect to its neighbors in adjacent columns (Bock, 2001).

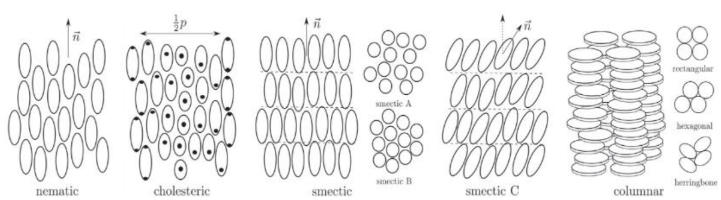


Figure 1.3 Arrangement of molecules in the liquid crystalline mesophases. (Andrienko, 2018).

Figure 1.4 Schematics of molecular alignment in the nematicsm sematics, chiral and columnar phases respectively. (Andrienko, 2018).

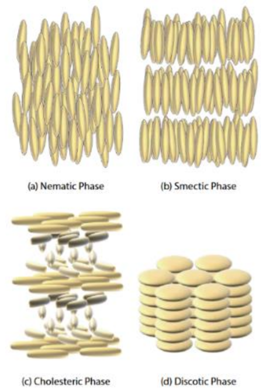


Figure 1.5 Illustration of thermotropic liquid crystals. (Andrienko, 2018).

2. Lyotropic liquid crystals: The fundamental difference between the thermotropic liquid crystals and the lyotropic liquid crystals is in the dependence of the later on concentration while the former depends on temperature. The formation of lyotriopic liquid crystal phase is only on the addition of a solvent which is most often water. The building block of the lyotropic liquid crystal is often not one but many molecules regardless of the addition of the solvent (typically on the order of 100), organized into an aggregate called a micelle**.** The formation of micelle is a due to the amphiphilic (A compound that has two immiscible hydrophilic and hydrophobic parts within the same molecule is called an amphiphilic molecule.) nature of the constituent molecules, generally surfactants. Lyotropic liquid crystals can form also by anisometric nonamphiphilic macromolecules or particles such as viruses or inorganic rods or discs in colloidal suspension. The volume balance between the hydrophilic part and hydrophobic part of amphiphilic molecules determines their tendency to form lyotropic liquid crystal phase. The micro-phase segregation of two incompatible components on a nanometer scale is the mechanism by which the liquid-crystalline phases are formed.

For lyotropic liquid crystals the important controllable parameter is the concentration, rather than temperature or pressure. Most of the theories presented below are equally valid for thermotropic and lyotropic liquid crystals. In contrast to thermotropic liquid crystals, lyotropic liquid crystals have another degree of freedom of concentration that enables them to induce a variety of different phases.

This generalization of the lyotropic liquid crystals is established as their defining characteristics. ***"A liquid crystalline mesophase is called lyotropic (a portmanteau of lyo- "dissolve" and -***

tropic "change") if formed by dissolving an amphiphilic mesogen in a suitable solvent, under appropriate conditions of concentration, temperature and pressure." (Baron 2003)
A lyotropic liquid crystal consists of two or more components that exhibit liquid-crystalline properties in certain concentration ranges. In the lyotropic phases, solvent molecules fill the space around the compounds to provide fluidity to the system. (Liang et al. 2005)

A generic progression of phases, going from low to high amphiphile concentration, is:

- Discontinuous cubic phase (micellar cubic phase)
- Hexagonal phase (hexagonal columnar phase) (middle phase)
- Lamellar phase
- Bicontinuous cubic phase
- Reverse hexagonal columnar phase
- Inverse cubic phase (Inverse micellar phase)

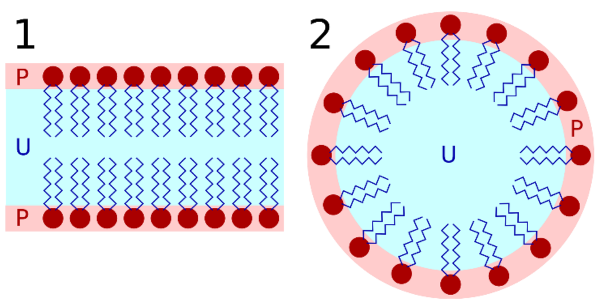


Figure 1.6 Structure of lyotropic liquid crystal. The red heads of surfactant molecules are in contact with water, whereas the tails are immersed in oil (blue): bilayer (left) and micelle (right). (Liang et. al 2003)

3. Metallotropic liquid crystals: Most liquid crystals are organic molecular units with anisotropic properties, however the addition of inorganic metallic components to create metallotropic liquid crystals or metallomesogens has been shown to be possible. The key to this transformation is stated by (Martin et al., 2006) **"Achieving liquid-crystalline behaviour in inorganic fluids should be possible if the anisotropic structure can be retained or designed into the molten phase."** The INTERNATIONAL UNION OF PURE AND APPLIED CHEMlSTRY (IUPAC) recommendation of 2010 defines metallotropic mesophases of liquid crystals as ***"a mesogen composed of molecules incorporating one or more metal atoms and may be either calamitic or discotic."*** (Barón, 2001)

While the mesophase formation for thermotropic liquid crystals is influenced only temperature, and the phase transition for lyotropic liquid crystals is influenced by both temperature, concentration and presence of a solvent or other molecular specie, the metallotropic liquid crystals are influenced by temperature, concentration and organic-inorganic composition ratio (Rau et.al., 2015).

1.4 Thermochromic Liquid Crystals

1.4.1 Principle of Thermochromism

According to Somani (2010), **"*'Chromism' means 'color change' and the materials that show color change are known as Chromic Materials. The phenomena of color change are known as Chromism. Such color change in materials can be as a result of some external stimuli such as an electric field, temperature, pressure, solvent, light, humidity, vapor etc. Accordingly, the phenomena are known as Electrochromism (color change due to application of electric field), Thermochromism (color change due to change in temperature), Piezochromism (due to pressure), Solvatochromism (due to solvent), Photochromism (due to light), Humidochromism (due to humidity), Vapochromism (due to vapors or gas), Bio-chromism and so on."***

Thermochromism is a phenomenal link between the color of a substance, a physical property, and the temperature of the substance. The greek word "*thermo"* means heat and the greek word "chromic" means color. Generally, this link between color and temperature can be regarded as thermochromism is the color change is reversible on cooling or heating, noticeable, and occurring over a sharp temperature interval. (Day, 1968)

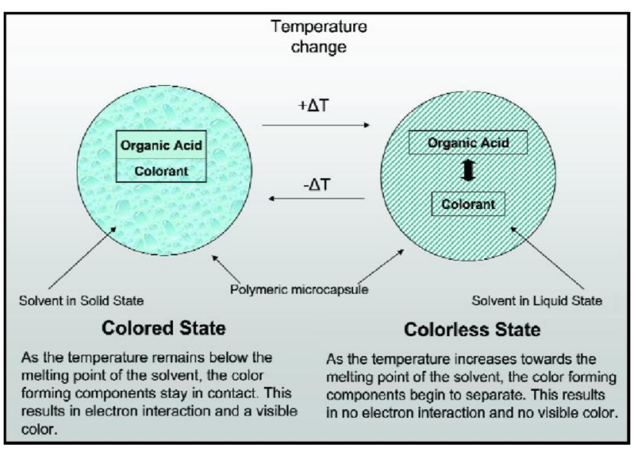


Figure 1.7 Pictorial depiction of the thermochromic principle. (Day, 1968)

There are two main types of materials that are widely used to produce thermochromic effects. Some use liquid crystals; others use organic (carbon-based) dyes known as leucodyes (sometimes written leuco dyes). The focus of this research is on the class of liquid crystals which exhibits thermochromic properties.

1.4.2 Thermochromic Liquid Crystals

Thermochromic Liquid Crystals (TLC) are liquid crystals, most especially nematics, smetics, and cholesterics liquid crystals whose reflected colors (light at different visible wavelengths) when illuminated by white light depends on their temperature**. "*Liquid crystals are temperature indicators that modify incident white light and display colour whose wavelength is proportional to temperature"*** (Stasiek and Kowalewski, 2002). In essence, they are liquid crystals with thermochromic properties.

The application of liquid crystals response to temperature, by selective reflection of the incident light, to measure surface temperature and other heat related measurement is known as Liquid crystal thermograph. The selective reflection of incident light as function of their temperature results from the alignment of the crystals at relative angles to form helical structures. Hence, the pitch of the formed helix as a result of temperature change determines the wavelength of light that is reflected. The angle between the crystals is relatively small at lower temperature, resulting in a longer pitch and the crystals reflect wavelengths close to red. The angle between the crystals is relatively large at higher temperature and resulting in a shorter pitch that corresponds to the wavelengths close to blue color. (Bakrania and Anderson (2019)

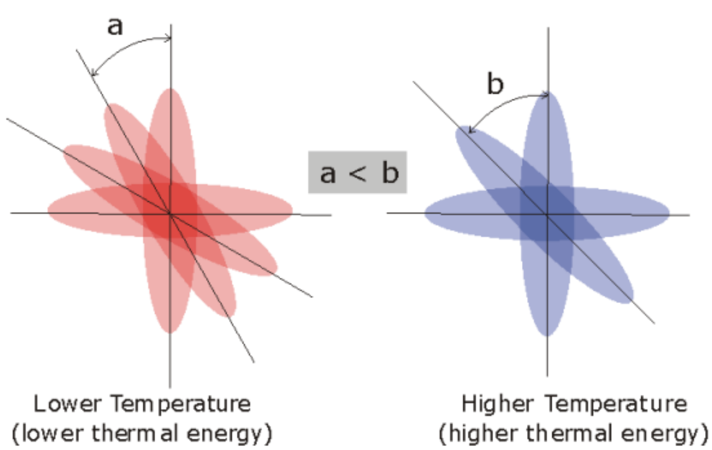


Figure 1.8 Relative angles between the molecules as a function of temperature and the consequent of which is the reflected color change. (Bakrania and Anderson, 2019)

It is imperative to state that while thermochromic liquid crystals is a general name for LC that changes their color as a function of temperature, this term says nothing about their molecular structure**.** In particular, cholesteric LCs have a smaller usable temperature range and longer time response compared to chiral nematic LCs. For example, the color change time constant of chiral nematic LCs is typically reported to be 3-5ms, while the cholesteric LCs are 100ms. (Smith, Sabatino and Praisner, 2012)

Liquid crystals used in thermometry applications can either be encapsulated in a sphere of up to 5-10 micro size suspended in a binder material for protection against UV radiation and chemicals and other contaminant or they can be unencapsulated which produces brilliant color however they are unprotected from contamination from the surface or environment. Table below shows some few examples of commercial TLC.

Company	**Symbol**	T_{start} **(°C)**	ΔT **(°C)**	**Form**	**Comments**
Hallcrest	BM 250/R0C 10W /S33	0	10	Encapsulated	$\Delta T \approx 5\,°C$, heavy tracers
Hallcrest	BM 100/R90F 2W /S33	32.5	2	Encapsulated	
Hallcrest	BM 100/R90F10W /S33	32.5	10	Encapsulated	
Hallcrest	BM R29C 4W /S33	29	4	Encapsulated	
Hallcrest	BM 100/R20C10W /S33	20	10	Encapsulated	
Hallcrest	BM 100/R6C12W /S33	6	12	Encapsulated	
Hallcrest	BM 100/R29C4W /S33	29	4	Encapsulated	
Hallcrest	BM /R96C6W	96	6	Liquid	
Hallcrest	BM /R60C6W	59.8	6	Encapsulated	
Hallcrest	BN /R70C6W	69.5	6	Liquid	
BDH	TM 445 (R17 C6W)	17	6	Liquid	Strong colors, $\Delta T \approx 4\,°C$
BDH	TM 446 (R37 C6W)	37	6	Liquid	Strong colors, $\Delta T \approx 4\,°C$
BDH	TM 317	21	20	Liquid	Strong colors, $\Delta T \approx 4\,°C$
BDH	TM 107 (R27 C6W)	27	8	Liquid	Strong colors, $\Delta T \approx 3\,°C$
Merck	TM 912	−2	10	Liquid	Strong colors
Merck	TCC 1001 (27C-31C)	27	4	Encapsulated	Very stable suspension

Table 1.1 Commercially available TLC, their nominal red clearing point *T*start and temperature range ΔT according to catalog. (Tropea, Yarin and Foss, 2007)

A TLC thermometer is one of the simplest implementations of LC for thermometry, shown below:

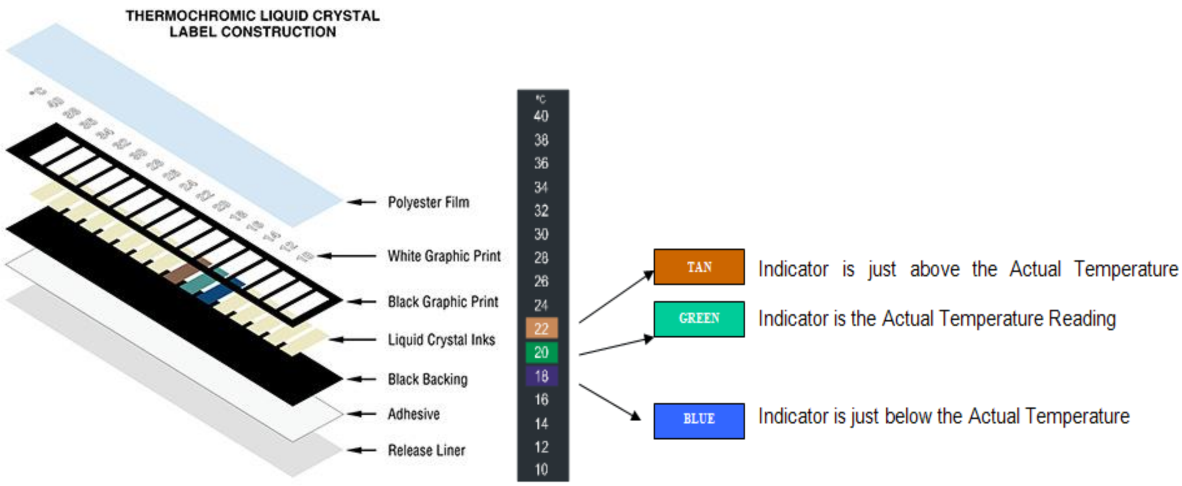


Fig 1.9 A simple construction of liquid crystal thermometer**.** (Hallcrest.com, 2019)

1.4.3 Principle of Temperature Measurement Using Thermochromic Liquid Crystals

The simplicity of TLC thermometry is a significant attribute of the technique. In their simplest thermometry setup, they can either be implemented directly by spraying on the test surface or by the use of prefabricated LC sheets, however, as stated by Smith, Sabatino and Praisner (2001) Both methods have their strength and weakness. While prefabricated LC sheets which are laid on black backing materials and covered with protective covering are the simplest form of LCs to employ for thermography their limitation is their slower thermal response characteristics and increases thermal contact resistance compared with sprayed TLC applications. A sprayable form of TLCs has been generally shown to be choice option for surface thermography. This is the choice of application for this research purpose.

The thermochromic effect of LC and its direct measurable correlation with temperature is the backbone of LC thermography. Hence the calibration of test surface temperature against the displayed color (hue) is an integral part of the TLC thermography. (Smith, Sabatino and Praisner, 2001)

TLC changes their clear or milk appearance over a narrow range of temperature known as the color-play interval. The color-play interval is the reflected color change from red (at the lowest applied temperature) to blue (highest applied temperature) as a function of temperature change over this interval, the blue color is also known as the clearing-point temperature.

For accurate visualization of this temperature change, a bright and stable white light is required for the removal of infrared and ultraviolet radiation from the output spectrum. Present IR energy in the incident light spectrum will cause unwanted heating of the test surface while TLC color-temperature dependency is negatively affected by UV radiation. Bright white light also ensures the accuracy of the reflected light intensity from the TLC-coated surface.

The case for the importance of the stability of the white light during measurement is also stated by (Vejrazka and Marty, 2007). Instability of the white light might lead to change of color-temperature assignment between the two stages or points of TLC thermochromism.

For the specification of thermochromic liquid crystals, two temperatures or color are used. The first temperature and color signify the activation color and temperature. For example, R40C5W implies, activation color which is red color temperature at 40^{o}C, a 5W signified the start of blue color at 45^{o}C, i.e. 5^{o}C from activation. Beyond the rated range the material will not exhibit any color change to the naked eye. 25C2W implies a 25 to 27^{o}C temperature range compound, with activation color of red starting at 25^{o}C and blue starting at 27^{o}C. Narrow band is a common designation when liquid crystal formulation is below 2^{o}C, while wide-band TLC range between 5-20°C with resolution of 0.1°C range.

As earlier stated, calibration is the key reference to the application of LC in thermometry. Calibration of TLC is similar to the process of calibrating voltage-temperature response of a thermocouple. The color change or response of the TLC coated surface as a result of known temperature variation is recorded on a color-sensitive camera or other imaging system. This methods of capturing with the digital camera has become a standard for TLC calibration. Linear relation of the camera output to the intensity of the red, green and blue (RGB) components of the incident light gives the highest accuracy. (Smith, Sabatino and Praisner, 2001). This is the image capturing technique employed in this research.

According to (Bakrania and Anderson, 2019), the steady state calibration technique in which liquid crystal test surface is set to a known determined temperature within the interplay range of

the crystals and an image of the surface obtained upon reaching a steady state is the most favor and general calibration technique of LCs. The average hue of the images obtained over the interplay range of the LC is then calculated to obtain a hue-temperature curve.
The steady state calibration technique, which is also reported as standard by (Camci, Kim and Hippensteele (1992) and also by (Hay and Hollingsworth ,1996) is the calibrating technique employed in this research. Another term for the calibration technique or method, whether steady state method or transient method, that is frequently used in several literature is the heat transfer method. (Chan, Ashforth-Frost, amd Jambunathan, 2010, Ghorbani, Sunden, and Tanda 2011) The advantage of this method calibration using the hue is also reference by Smith, Sabatino and Praisner, (2001*),* ***"Regardless of the method employed to obtain digital images in RGB color space, the hue component (from HSB color space) of the color is extracted and used as the calibration parameter. Hue physically represents the dominant wavelength of the light being displaced by the LCs and is determined by establishing the angle between the orthogonal red, green and blue components in RGB space. Using hue from HSB color space reduces possible sources of uncertainty, such as variations in the brightness of the light source."*** The calibration curve is the relationship between the temperature of the crystal and the measured Hue of the reflected light. Hence the practical result of the calibration process is a curve relating the Hue of the reflected light to the surface temperature.

Invariant of calibration methods, each TLC has its own calibration curve and a temperature-color relationship of a particular TLC can't usually be generalized for all surfaces, this is clearly presented from Abdullah et al. (2010). The calibration is the only technique for obtaining the TLC color temperature correlation. The color-temperature relationship for a particular TLC can't be the same for all conditions since the several factors affect such as test surface, illumination, imaging system e.t.c. affects the color-temperature relationship. Hence, the TLC calibration curve even when supplied by manufacturers on request can only act as a reference and TLC has to be always calibrated according to the specific demand and condition of the user.

In addition to stating that the steady state calibration technique is the preferred method for this research, it's also pertinent to clarify that the "***uniform surface temperature method***" of stead state technique is used. This method is one of the calibration techniques stated and preferred by many researches including by Abdullah et al. (2010), "***The uniform surface temperature method is a variant of steadystate method for calibrating TLCs. In this method, the calibration surface is heated at predefined temperatures between the colour 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.***"

The uncertainty of temperature measuring using the TLC technique can't be ignored because of various constraints, from human error, individual interpretation of color, surface preparation, light source, e.t.c., associated with either the temperature or heat transfer measuring technique. The table below according to Smith, Sabatino and Praisner, (2001) gives a summary of uncertainty estimates associated with TLC measurement or calibration cited by a number of literatures.

Author(s)	Measured quantity	Uncertainty (mean)	Uncertainty a function of T?
Hippensteele and Russell (1988)	h	6.2%	[a]
Hollingsworth et al. (1989)	T	7.1–14.3 (9.1)% of ΔT	yes
Camci et al. (1993)	h	5.9%	no
Farina et al. (1994)	T	5.0% of ΔT	no
Babinsky and Edwards (1996)	h	7.0%	no
Wang et al. (1996)	T	2% of ΔT	no
Wang et al. (1996)	h	7.5–8.5%	yes
Giel et al. (1998)	h	6.0–11.0%	[a]
Hay and Hollingsworth (1998)	T	6.5–8.0% ΔT	yes
Baughn et al. (1999)	T	3.9% of ΔT	yes
Sabatino et al. (2000)	T	0.7–8.7 (2.4)% of ΔT	yes
Praisner et al. (2000)	h	3.6–7.9 (4.7)%	yes

[a] These studies were conducted employing a narrow-band technique

Table 1.2 Summary of uncertainties of measurement associated with temperature T and convective heat transfer measurement *h.* (Smith, Sabatino and Praisner, 2001).

As stated by Kaveh Azar in the article for Advanced Thermal Solution Inc, The following steps are taken when measuring surface temperature with an LCT system

a. Select the optics suitable for the spatial resolution required.

b. Select the appropriate liquid crystal and calibrate it.

c. Coat the test specimen with black paint.

d. Spray the test specimen with liquid crystal.

e. Apply power to the test specimen and start the measurement.

1.4.4 Applications:

The first commercial applications of liquid crystalline materials were in the area of thermographic or thermochromism (Bahadur, 1992). The versatility and applicability of TLC as a thermal imaging and visualization tool has been demonstrated by several research works and industrial applications including but not limited to its employment as thermal imaging tools in applications such heat transfer investigations in gas turbines (Esposito and Ekkad 2006, Vogel and Boelcs, 2001, Ireland and Jones 2000), several visualization of flow research (Kowalewski et. al. 2007, Smith, Sabatino and Praisner,2001, Dabiri and Gharib 1999), electronics thermal management (Farina, 1995, Azar and Farina 1995) microfluidic devices, (Fung et. al. 2006, Chaudari et. al. 1998) and medical research and diagnostics such as low-back pain monitoring (Stasiek et. al. 2006, Bharara, Cobb and Claremont, 2006). Thermochromic liquid crystals has proven to be an excellent visualization and quantitative thermographic tool which has been variously employed in determination of field-wise surface temperature measurement, convective heat transfer and flow-field temperature measurement (Smith, Sabatino and Praisner, 2001).

The thermometric application of thermochromic liquid crystals can be both qualitative and quantitative measurements, as a result of either conduction, convection, and radiation. While the quantitative measurement is very much less complicated, qualitative measurements do require a complete system more than just the light source and the application of the TLC (Vejrazka and Marty, 2007)

Stasiek and Kowalewski (2002) also demonstrated the application of encapsulated TLC as a tracer for heat transfer research, **"*Thin coatings of TLC's at surfaces are utilized to obtain detailed heat transfer data of steady or transient process. Application of TLC tracers allows instantaneous measurement of temperature and velocity fields for two-dimensional cross-section of flow."***

The simplest application of liquid crystal thermometry is household surface temperature implementation, TLC thermography medical devices, forehead TLC thermometers, fish-tank thermometer, mood rings, color sensitive coffee cups. They have also found applicability in devices such as propane tank gas level indicator, thermal mapping and other industrial applications where custom inexpensive temperature monitoring is warranted.

The use of TLC is not only limited to direct temperature visualization as stated by (Smith, Sabatino and Praisner, 2012) "***While LC thermography can be employed to directly measure temperature, it is very often used to determine convective heat transfer properties in fluid flows over solid boundaries. Liquid crystal thermography, when combined with known boundary conditions, can yield detailed convective heat transfer information in complex flow configurations. Examples of these flows, both laminar and turbulent, include boundary layers, transitional flows, three-dimensional separation, and bluff-body flows. Time-mean convective heat transfer coefficients are generally determined using one of two experimental approaches coupled with LC thermography."***

1.4.5 Advantages and Limitations:

All physical measurement techniques have their limitations, challenges and advantages which determines their suitability for a specific application. The semi-invasive nature of TLC thermography is an advantage that ensures its applicability and flexibility of application in virtually any thermometric need from small sized electronic circuits to large scale gas turbine blades. (Kaveh A., 2010) (Ghorbani, Sunden, and Tanda 2011). The simplicity of the method is also very important advantage as stated by (Vejrazka and Marty, 2007), "***The main advantage of liquid crystals is that they provide a simple visualization of the temperature field immediately after spraying the TLC paint or gluing a TLC film."*** Temperature measurement using sensors such as thermocouples and resistance thermometers are most suitable for individual locations. Hence, a large number of sensors or a large number of repeated measurements maybe be required for complete mapping of a large surface. Liquid crystal thermography has proven to be a useful alternative in such applications (Perry, 2019).

The ultra-high (<1 micron) spatial resolution of TLC thermography, non-destructive application for the device under test, ability to easily use common color video cameras and recorders as input devices to the system, customized and cost-effective solution for many demanding applications; two or three multiples less expensive than IR systems that offer poorer spatial resolution, are among several advantages of note (Smith, Sabatino and Praisner, 2001).

The advantage of TLC thermography over infrared camera thermometry was put succinctly as "***When the measurement of a few discrete points is insufficient, the infrared camera (IRC) is usually used. However, IRCs cannot be employed in certain cases, especially when the surface of interest is submerged in a liquid, which is generally opaque for infrared rays. Another limitation of the IRC is the cost of this technology, which remains expensive. The thermochromic liquid crystals (TLC) and the laser-induced fluorescence can be suitable alternatives."*** (Vejrazka and Marty, 2007)

The main drawback of TLC thermometry is the need for pre-treatment of the specimen with TLC in the case than an already prepared TLC thermometer can't be used directly.
A very important drawback of TLC thermometry and calibration is the dependence of the accuracy of the result on the relative position of the TLC coated layer, light source and the camera. (Smith, Sabatino and Praisner, 2012) "***A problematic feature of TLCs is the dependence of the hue value of reflected light on the angle between the light source, TLCs, and camera. [..]This angular dependence will make the temperature measurements difficult (or even impossible) on curved surfaces."*** (Vejrazka and Marty, 2007). This dependency is one of the main focus of this research.

1.5 Aim of the Research

The aim of this research is to provide a concise research of the thermochromic effect of liquid crystals and their application in surface thermography. Issues related the application of TLC for thermography such as the effect of several measuring condition and parameters on the accuracy of the measurement is concisely discussed. The practical aspect of the research focuses on obtaining a TLC hue-temperature calibration curve with focus on establishing a relationship between the effect change of distance and angle of illumination on the curve.

CHAPTER TWO

LITERATURE REVIEW

Rao and Zang (2009) examined the effects of the use of an image noise reduction technique, the lighting angle, the TLC coating thickness and the coating quality on the hue–temperature curve and the measurement uncertainty through experimental results obtained from the calibration and the measurement uncertainty for a thermochromic liquid crystal (TLC) with a bandwidth of 20 °C**.** They found that the image reduction technique of 5X5 median filter helped to improve the accuracy of the measurement. Most notably they also concluded that the lighting angle which is also known as the illumination angle has distinctive effects on the hue curve and the measurement uncertainty of the TLC, and a smaller lighting angle provides a smaller measurement uncertainty. It was also noted that the coating thickness has a profound effect on the TLC hue-temperature curve but has a non-distinctive effect on the measurement uncertainty if the coating thickness is over 20 μm. However, the coating quality was found to have a distinctive effect on the TLC hue curve and the measurement of uncertainty.

The effects of lighting and viewing angles on liquid crystal thermography was investigated by (Kodzwa and Eaton, 2007), they presented a theoretical basis to the quantification and elimination of the effects of lighting and viewing angles on TLC thermography. Using analytical relationships that describe the perceived color shift, a systematic manner of improving the performance of a TLC system was outlined. As part of other important conclusions, the relationship between the bandwidth of TLCs and angle of illumination was established that if intensity is used in analysis of narrow-band TLC, the effect of lighting and viewing angle are considered irrelevant. Their analysis also show that point-wise calibration is no guarantee of accurate measurement.

The time response of a thin film of encapsulated thermochromic liquid crystal (chiral nematic thermochromic liquid crystal) applied to the surface was investigated by rapidly increasing surface temperature. Ireland and Jones (1987) concluded that the delay between the time at which the surfaces reaches the steady-state colour display temperature and the occurrence of the colour display is no more than a few milliseconds.

Baughn et al. (1999) examined the behavior of a particular microencapsulated TLC for hysteresis, the influence of thermal lag or nonuniform temperature in the calibration block on the result of measurements involving thermochromic liquid crystals. It was found that the hue-temperature behavior contains a significant hysteresis if the TLC was heated above its useful color-play range (i.e. the hue-temperature behavior during cooling is significantly different from during heating). Also, the resetting of the TLC after cooling below the useful color-play was observed. The hysteresis was also found to have a greater effect than the effect of thermal lag or nonuniform temperature on the uncertainties of the measurement.

Schulz et al., 2016 investigated the effect of coating thickness on the evaluation of heat transfer coefficients using the transient liquid crystal technique. The TLC hue-temperature calibration was the backbone of the technique**.** The result of the experiment showed that if a black paint is sprayed above the liquid crystal layer in order to provide high intensity signals or multiple liquid crystal layers are used, and the paint thicknesses are not considered, the heat transfer coefficients can be significantly underestimated.

Smith, Sabatino and Praisner, (2001) researched a review of recent developments in the application of liquid crystals to fluid flow measurement. This research focused on application, illumination, recording, and calibration of liquid crystals on solid surfaces, as well as in fluid suspensions among others. Part of the important conclusion is that it was concluded that on-axis lighting/viewing arrangements, combined with in-situ calibration techniques, generally provide the most accurate temperature assessments. By comparison it was concluded that the wide-band technique while more complicated to implement required simpler post-processing and can yield temporal behavior. While the narrow-band calibration technique is simpler to implement but requires complicated post-processing and yield only time-averaged information.

Experimental investigation and assessment of the errors that are related to hue-based thermochromic liquid crystal calibration methods was carried out by Wiberg and Lior (2004). Some of other sources of errors enumerated were response time, hysteresis, aging, surrounding illumination disturbance, direct illumination and viewing angle, amount of light into the camera, TLC thickness, digital resolution of the image conversion system, and measurement noise. On the effect of light intensity on the observed hue, an irregular variation of hue with light intensity was noticed with a maximal change in hue due to the 88% decrease in the light quantity was found to be 0.025, which is 4% of the useful hue range for the typical TLC films studied in this work. The temperature dependence of on TLC film thickness was also established to be not significant, and thicker films are were found to be less susceptible to aging and thickness nonuniformities.

Using transient state calibration technique, Bakrania and Anderson (2019), investigated the effect of surface preparation, lighting and heat on the accuracy of the result. An important conclusion was made that the transient technique compares well to steady state techniques for cooling and heating rates of 0.03 ^{o}C/s. Hysteresis was also noted when the surface was heated above the play range of the TLC. It was also found that a poorly prepared liquid crystal surface yielded a "steep" calibration curve, was subject to light 'warm up' effects and the hysteresis effect was severe upon overheating.

Since the limitation of temperature range in which TLC can be used for thermometry application is limited, perhaps the research work of (Toriyama et al., 2016) is of passing interest. The extension of the measurable range of temperature measurement using thermochromic liquid crystals (TLCs) was conducted. In the proposed method, the temperature is uniquely determined by measuring only a single optical parameter: the spectrum intensity of the scattered light at a specific wavelength. In the first stage of the study, the relationship between the spectrum intensity of the scattered light at the TLC and temperature of the heat transfer surface was investigated. It was found that a white LED had more favorable features than a halogen lamp, and thus was suitable as a light source for the proposed method. Using the white LED, the range of the measurable temperature achieved by the proposed method, 27–60 ^{o}C, was approximately three times as broad as that by conventional methods that use mapping of the color change of TLCs, 32–42 ^{o}C. In the second stage, the proposed method was applied to measurement of the two-dimensional temperature distribution over a planar heat-transfer solid surface. The range of the measurable temperature with a temperature resolution of 0.1 ^{o}C was found to be 28–46 ^{o}C, which is approximately twice as broad as that by conventional methods using TLCs, 32–42 ^{o}C.

CHAPTER THREE

EXPERIMENTALS: MATERIALS AND METHODS

As reported by numerous research works including (Hay and Hollingsworth 1996) and (Camci et al, 1992), the steady state technique is the standard method for calibrating liquid crystals, however as shown by (Bakrania and Anderson, 2019), the transient state shows the almost totally same result of calibration curve as the steady state calibration method.

In the steady state technique, a heat source is used to set a test surface which is made up of liquid crystal to a predetermined temperature within the play range of specific liquid crystal. When a steady state condition is achieved, an imaging system which is usually a camera is used to acquire the image. The image is captured repeatedly over the play range of the liquid crystal to obtain the data for calibration. Most often, the average hue of the images obtained over the play range of the interval is calculated and the hue temperature calibration curve is obtained.

3.1 Experimental Materials

3.1.1 Test Surface Preparation

The test surface is the primary component of the experiment. For the purpose of this research, a thermochromic liquid crystal ("12 Color Liquid Crystal, temperature range between 15.5 °C to 32.0 °C) purchased from Solar Color Dust was used. Black matter color (RAL 9005M) was sprayed in single layer on a galvanized metal sheet of dimension 100 mm diameter and thickness of 1 mm (see fig 3.1 for detail of cross section).

As stated by Smith, Sabatino and Praisner (2001) the black backing is required to absorb impinging light which are not reflected by the LC layer from the test surface. After drying of the black matter, 7 layers (app. 2.5 ml) of the TLC color was sprayed over the black coated surface, the direction of spraying was also changed (one horizontal layer and one vertical layer).
There was drying times about 30 minutes between layers to ensure adhesion to the surface. No overlayer for protection. Provided on the test surface is the hole for connection to the heating system for heating and convenience of setting the temperature.

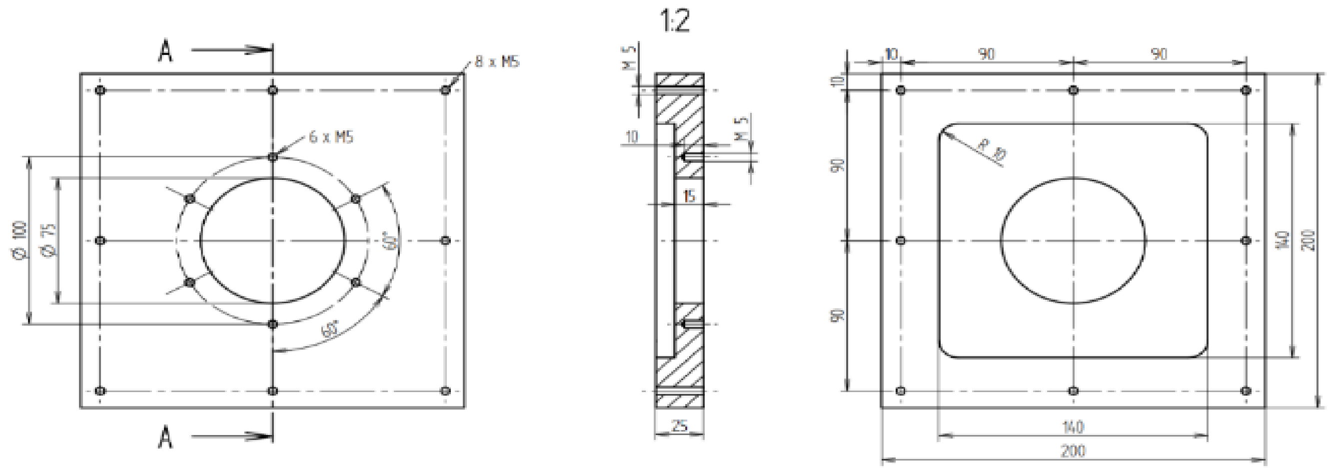


Fig. 3.1 Schematics drawing of the test surface

3.1.2 Source of Illumination and Dark Enclosure

According to (Vejrazka and Marty, 2007) the source and condition illumination is an important factor that determines the accuracy of the result from TLC thermometry. The illumination source and disturbances associated with it affects the shape of the hue-temperature calibration curve and this may lead to higher or lower temperature uncertainties over the applicable range. Apart from the importance of the angle illumination, which is of investigative interest of this current study, the light source is recommended to be strong and uniform enough to enable the proper capture of the color change. The heating up of the test surface by the light source and reflection towards the imaging system should be avoided. These conditions were considered in the experimental setup and choice of the illumination source. The need for white light as source of illumination is already discussed in detail in Chapter one.

Continuous white light source obtained using **Osram Ledvance Floodlight 20W 4000K** was used as the illumination source at three different angles and vertical distance of illumination from the test surface in order to investigate the effect of the angle of illumination on the result. The essence of the dark enclosure is to act as a shield for filtering out unwanted sources of light from the experimental setup. A dark fabric cloth with metal stands was used as a dark enclosure. Since the observed color is both a function of temperature and illumination, heating system is needed to provide the needed set of regulated temperature. For this purpose, Lauda E100 Thermostat was used.

3.1.3 Imaging System

Several researches have shown that the advances in resolution and color sensitivity of CCD cameras have made them more favorable over photographic film for TLC thermography. Hacker and Eaton (1995) demonstrated that when employing CCD camera to capture images from LC gives highest accuracy when the camera output is linearly related to the intensity of the red, green, and blue (RGB) component of the incident light, this has been the principle of many steady-state LC thermography studies and this is the method of calibration favored by this research. Hence, the imaging system play a crucial role in the experiment since the hue component of the digital images in RGB color space is the raw data obtained in the experiment as the calibration parameter. Below is the picture of the digital camera GoPro Hero 5 Black as imaging system. The choice of the camera also is based on its great resolution, full options of remote controlling white balance. The camera settings are as follows: focus of view-linear; white balance-400K; color settings-flat; ISO-900/fix; shitter-1/250.

Figure 3.2 GoPro Hero 5 Black

3.2 Setup and Measurement Procedure

The experimental setup is shown in Figure 3.3, comprising of the imaging system, the test surface, the thermostat for heating, and illumination source. The design of the set up is such that the flat board is fitted with screws for changing the angle and distance of the illumination source. The digital camera is mounted directly facing the middle of the test surface. Successively, the TLC coated test surface was set within temperature range of $21^{\circ} - 31^{\circ}\mathrm{C}$ with a step of $^{\circ}0.5\ ^{\circ}\mathrm{C}$. For each temperature step, the image of the TLC coated test surface was captured remotely using the digital camera. As shown in the experimental setup schematics, the off-axis setup was used (i.e. the camera and the illumination not in the same axis).

For three vertical distances of 100mm,200mm, 300mm and three angles of illumination 65.60, 47.70, 36.30 degrees, the experimental setup with steady state measurement was repeated over the temperature range. The RGB pixel pictures captured by the digital camera was recorded against the set temperature.

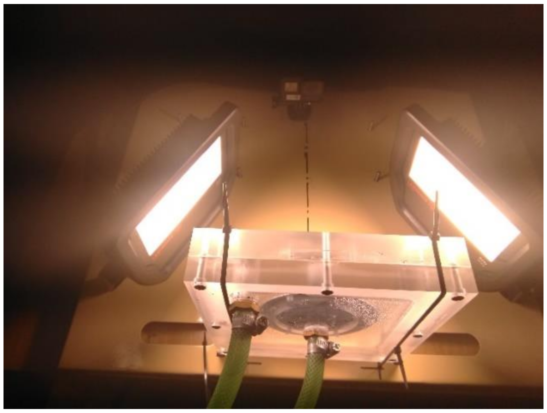


Figure 3.3 Experimental setup comprising of the test surface, image system and illumination source.

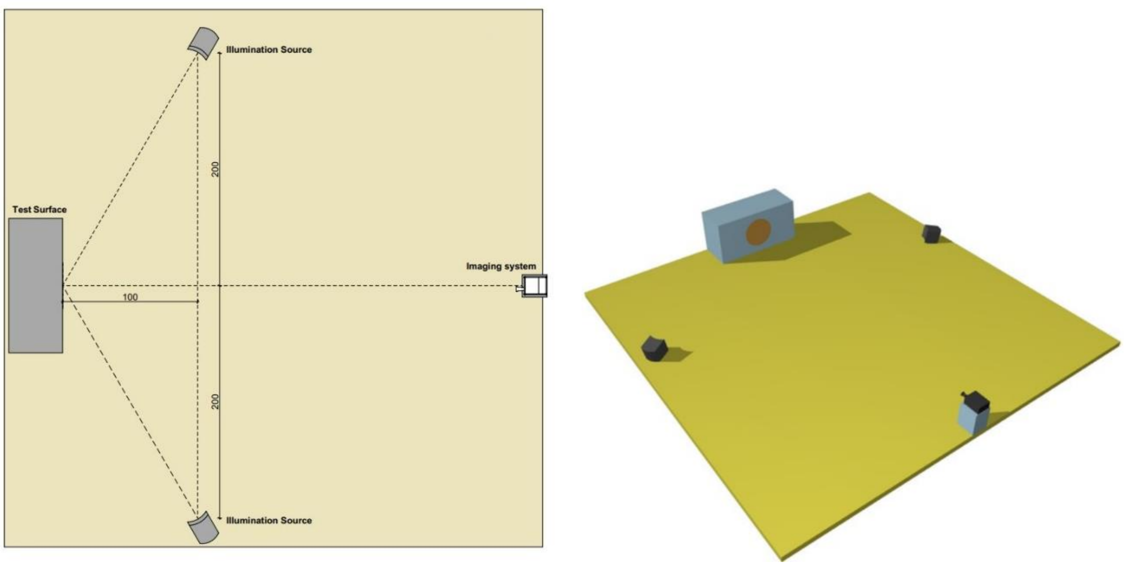


Figure 3.3. 2D and 3D schematics of the experimental setup.

Since the imaging system is arranged directly opposite to the to the test surface and at some angle away from the illumination source, it can be seen from the pictorial definition of illumination viewing angle below that the off-axis illumination was used in the calibration technique.

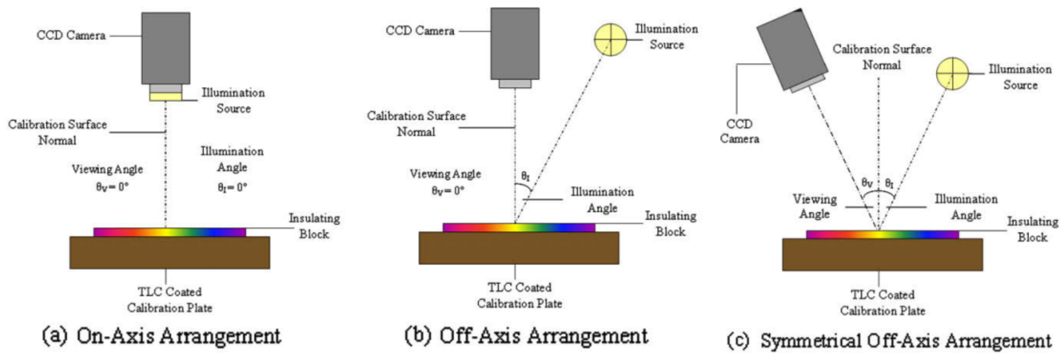


Figure 3.4 Definition of angle of illumination. Abdullah et al. (2010)

3.3 Hue-Temperature Calibration Curve

The dependent relationship between the captured images of TLC color changes and the known set temperatures of the TLC coated surface is established by the calibration curve for a specific distance and angle of illumination.

The Hue–Saturation–Value (HSV) colour space is mapped to the surface temperature to obtain what is known as the hue–temperature curve of the TLC. This curve is 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 easiest and most common calibration technique for correlating the color change of LCs with temperature change is the hue-temperature curve and it has been very widely used by researchers as a standard. Abdullah et al. (2010).

Analysis of the image was done using MATLAB and the MATLAB rgb2hsv function was used to convert pixel by pixel RGB values to HSV. Also, dominant color for each image was identified using MATLAB to obtain the RGB start temperature for the sets of images of the three angular variation of the illumination source. In plotting the calibration curve, for each image, the mean hue value was computed and plotted against the temperature. Below is the MATLAB code used in the analysis of the images and plotting of the calibration curve.

```
clear all; format compact; clc
number = dir('*.jpg');
number=length(number);
a=dir('*.jpg');
for i=2:number
    file=a(i).name;
    [name,ext]=fileparts(file);
    temp(i)=str2num(ext)/10;
    foto = imread(file);
    field=foto(1262:1754,1810:2314,:);    % x1:x2, y1:y2
    color=rgb2hsv(field);
    hue=color(:,:,1);
    huem(i)=mean(mean(hue))*360;
end
plot(temp,huem,'k.')
xlabel('temperature (^o C)');
ylabel('hue value (deg)');
table(transpose(temp), transpose (huem))
```

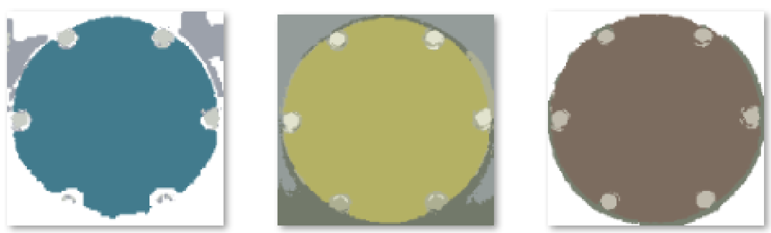
CHAPTER FOUR

RESULT AND DISCUSSION

Figures 4.1-3Shows the dominant RGB startup temperature images obtained during the experiment, for vertical distances 100mm, 200mm, and 300mm and angles of illuminations 65.60º, 47.70º, and 36.30º respectively. Also, Figures 4.4, 4.5, and 4.6, shows the calibration curve, which is a plot of the HSV (hue, saturation, value) of the defined region (sampling location x1:x2,y1:y2(1262:1754,1810:2314,:) which is at the centre of the circular profile.) of the RGB picture against the temperature set within the bandwidth range of the TLC during the experiment. An image histogram is a chart that shows the distribution of intensities in an indexed or grayscale image. Fig 4.8 shows the image historam of the test surface and it shows dominance of one single color.

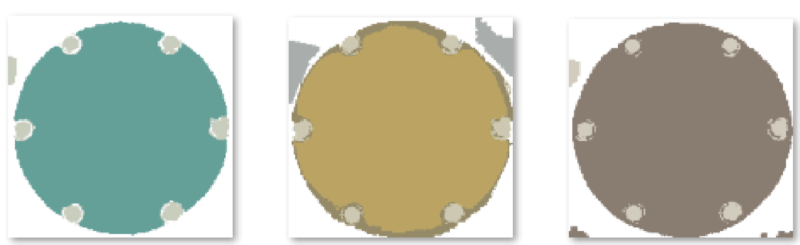
blue green red

Figure 4.1 Dominant RGB startup temperature images for vertical distance 100mm



blue green red

Figure 4.2 Dominant RGB startup temperature images for vertical distance 200mm



blue green red

Figure 4.3 Dominant RGB startup temperature images for vertical distance 300mm

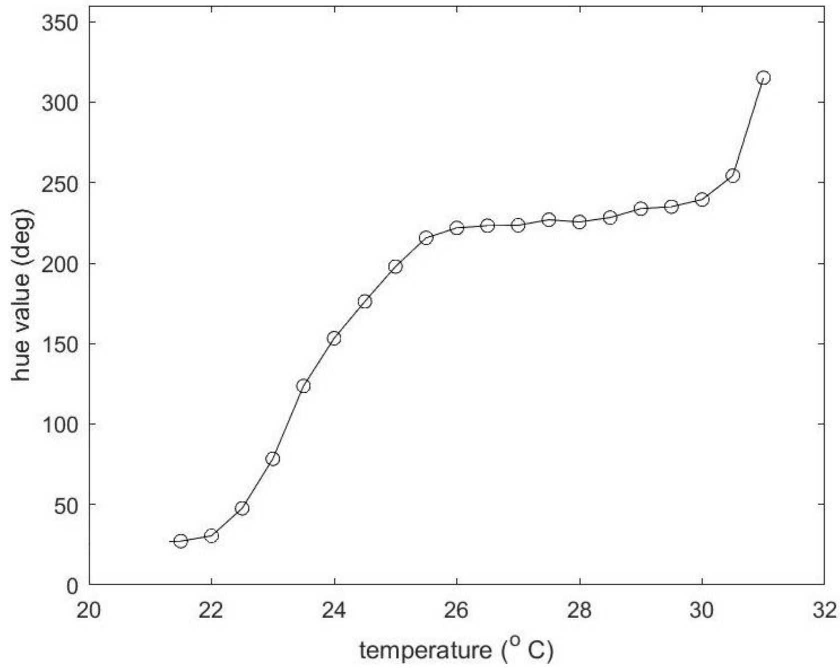


Figure 4.4 Hue- temperature calibration curve for vertical distance 100mm and angle of illumination 65.60º

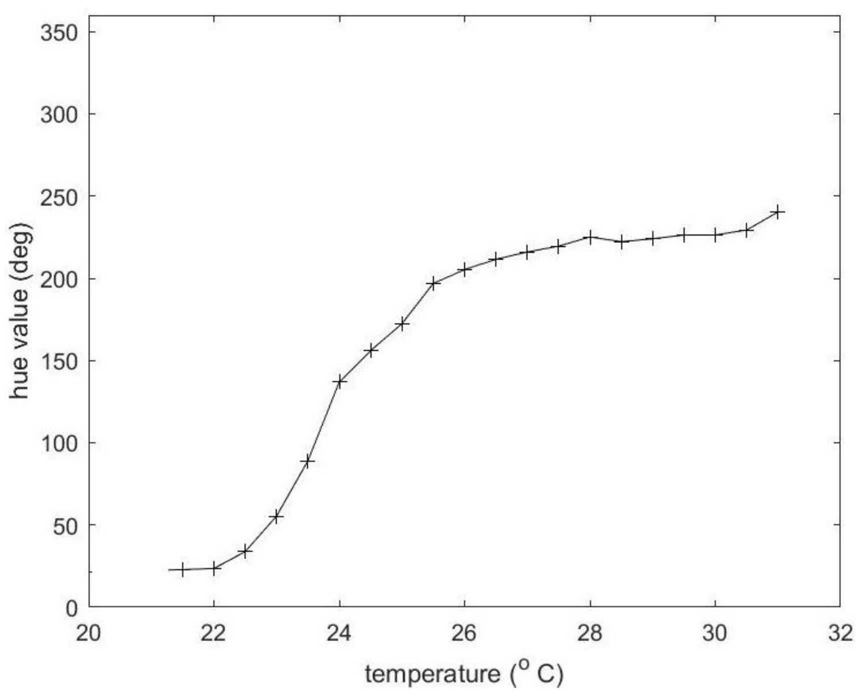


Figure 4.5 Hue- temperature calibration curve for vertical distance 200mm and angle of illumination 47.70º

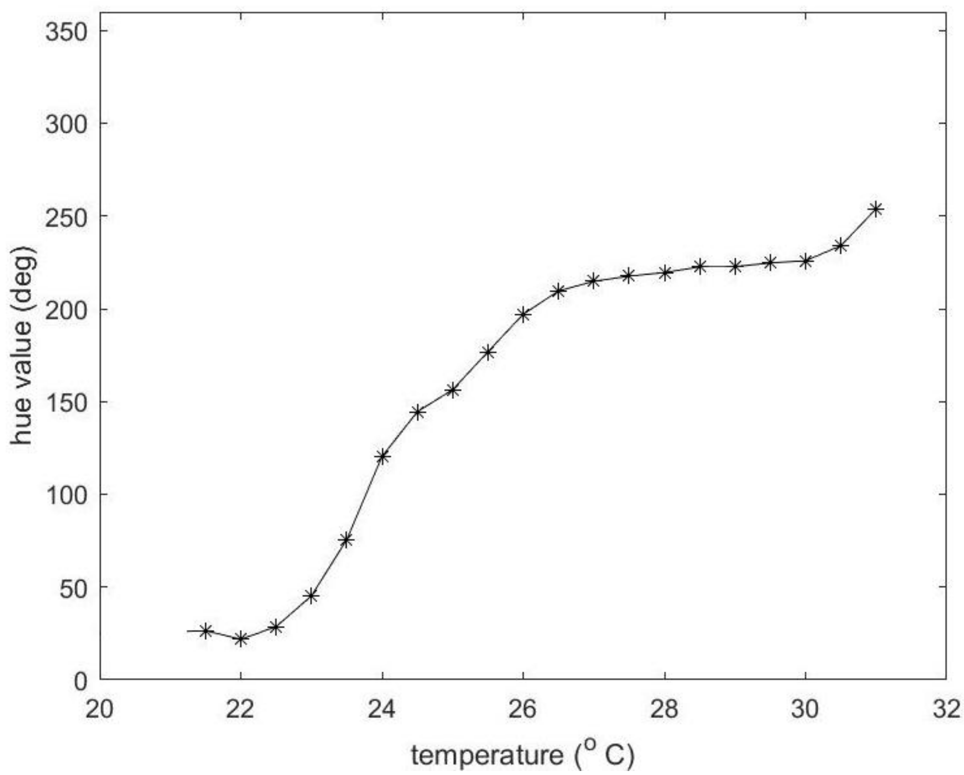


Figure 4.6 Hue- temperature calibration curve for vertical distance 300mm and angle of illumination 36.30º

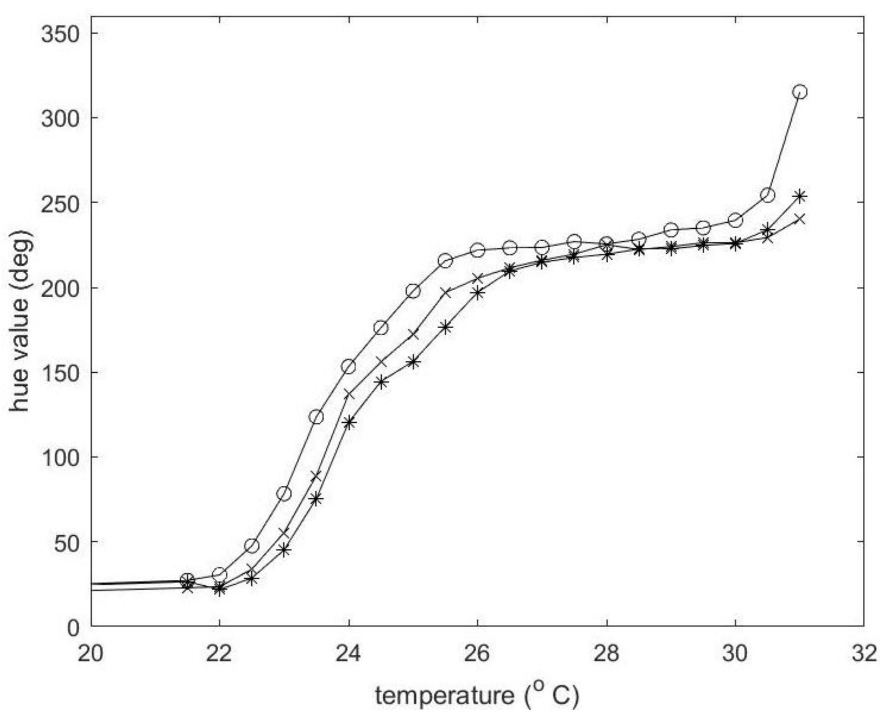


Figure 4.7 Combined Hue- temperature calibration curve for all variation of vertical distances and angles.

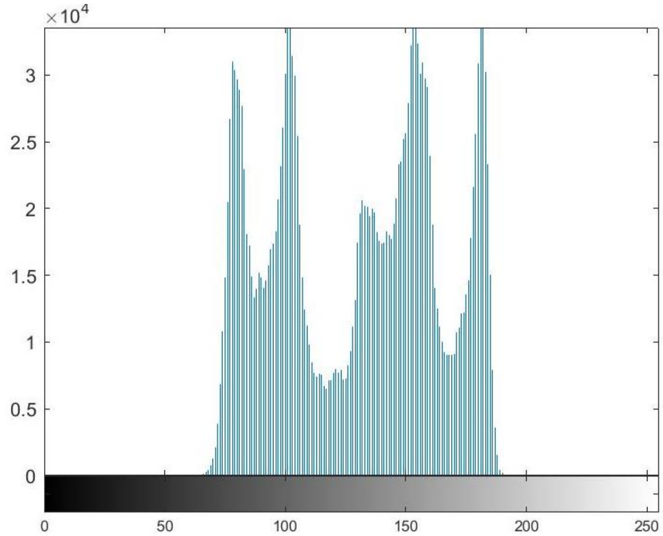


Figure 4.8 Image histogram for the temperature 25ºC and vertical distance 300mm and angle 36.30º

While it is necessary to state that every thermochromic liquid crystal has its own distinct hue-temperature calibration curve that is dependent on several parameters and conditions, however the calibration curves of TLC tend to conform to a general shape described by several experimental results. Typically, the hue-temperature calibration curves are non-linear, monotonically increasing curve. The area of monotonical increase of hue with temperature is known as useful calibration range or the effective temperature range.

For the sake of brevity, comparison of the shape of the hue-temperature curves obtained shall brief. The shape of the hue-temperature calibration curve obtained compares very well with several typical hue-temperature TLC calibration curve from several research works, most especially the hue-temperature calibration curve of Hallcrest Inc. type C17-10 micro-encapsulated chiral-nematic obtained by Sabatino, Smith, and Praisner, (2000) shown below in figure 4.7. The hue-temperature calibration curve also conforms with the shape of the calibration curve from Wang et al. (1996) for calibration of two TLCs namely, M/R25C 1 5W/S-40 and BM/R30Cl5W/S-3, for different illumination strength and different location on a flat plate.

A defining characteristic, that is easily observable from almost all cited hue-temperature calibration curve for TLCs is the monotonical increase of the hue between the green-blue transition region. The result of the calibration curve of this experiment also agree with these characteristics for the three different angles of illumination. For the 100mm vertical distance and angle of illumination 65.60°, the hue value increases from about 50 degrees to about 220 degrees with just a temperature change of 4°C. The same property can be attributed to the curves for 200mm and 300mm. However, this monotonical increase is somewhat more decreased and less steep for 200mm and 300mm, this can be attributed to the corresponding change of angle of illumination. The result shows that the TLC is more sensitive at higher temperature range of about and has a wide useful calibration range of about 5°C given the length of the region where the curve is monotonically increasing.

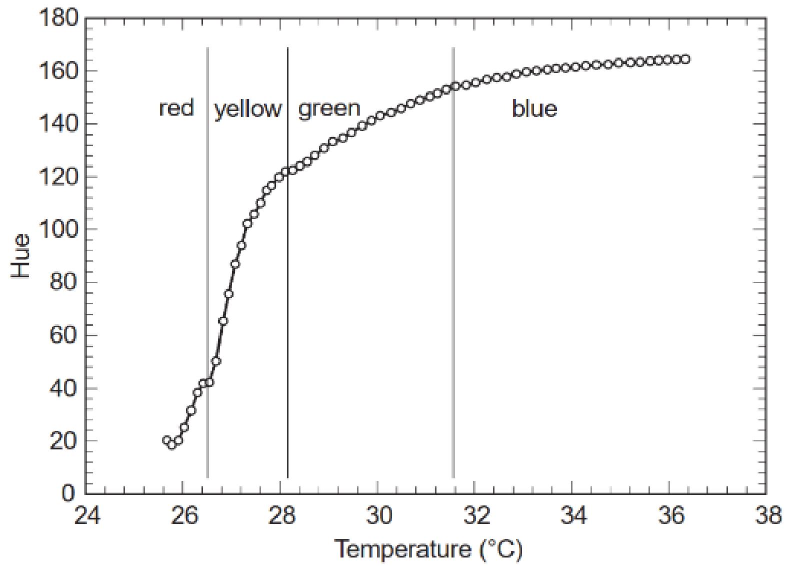
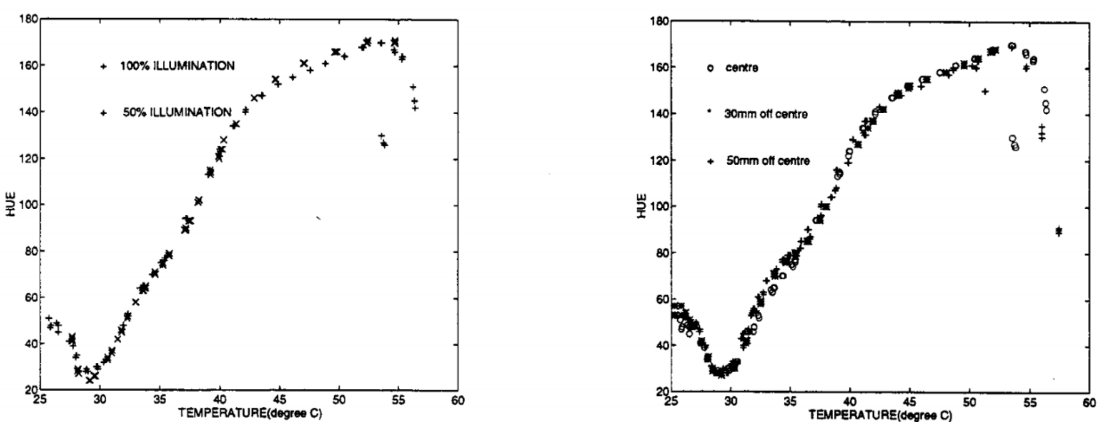


Figure 4.9 Typical calibration curve showing the relationship between the displayed hue and surface temperature. (Sabatino, Smith, and Praisner, 2000)



Figures 4.10 a Hue calibration for different illumination strengths. b. Hue calibration at different locations on a flat plate (Wang et al. 1996).

The angle of illumination has been shown to be a major source of errors regarding TLC thermography. As stated by Abdullah et al. (2010), there are mainly three disturbances associated with source of illumination, namely angle of illumination, illumination intensity, background reflection. Researches have shown that the accuracy of TLC thermography is negligibly affected by illumination intensity, Wang et al. (1996), Sabatino, Smith, and Praisner, (2000), Kakade et al. (2009). Also, the use of dark enclosure or other methods to filter out unwanted source of illumination, helps to reduce the influence on accuracy of background reflection. However, as concluded by various cited research works, an unfavorable and inherent feature of TLCs is the dependence of the hue value of reflected light on the angle of illumination.

The narrowband TLC (bandwidths within the range of 0.5–3 ºC) are known to be less susceptible to illumination disturbances and in particular their hue-temperature relationship is less affected by the angle of illumination. The table below shows the red start and blue start temperature for three different TLCs, two of which are wide-band TLCs with bandwidth of 5ºC and 10 ºC respectively. It can be observed that new blue start temperature as a result of change of illumination angle by 20º from the calibration surface normal causes a 30% narrowing of the bandwidths, leading to a reduction of the blue start temperature. This infers that the so called narrowing of bandwidth effect is larger for wideband TLCs.

Sample	TLC	Bandwidth (°C)	T_{RS} (°C)	T_{BS} (°C)	$T_{BS,new}$ (°C)	ΔT (°C)
A	R35C1W	1	35	36	35.7	0.3
B	R35C5W	5	35	40	38.5	1.5
C	R35C10W	10	35	45	42.0	3.0

Table 4.1 Narrowing bandwidth effect in three samples of TLCs due to change in illumination-viewing angle of 20º from the calibration surface normal. Abdullah et al. (2010)

Since the TLCs used in this research is a wide bandwidth TLC, similar result can be expected. This effect consequential, since the resulting calibration curve is a function of both temperature and hue of the colored picture obtained from TLC coated test surface. This is a notable and profound result of the change of illumination angle during the experiment. In order to identify the RGB start temperature for each set of the three variation of angle of illumination, MATLAB and (Labs.tineye.com, 2019) was used to extract the dominant RGB color from the pictures of test surface obtained during the experiment, see figure 4.1-3. The result is presented below.

Vertical Distance	Angle of Illumination	Red Start Temperature	Green Start Temperature	Blue Start Temperature
100	65.50º	21.0ºC	23.0ºC	25.0ºC
200	47.70º	21.0ºC	23.0ºC	25.50ºC
300	36.30º	21.0ºC	23.0ºC	25.50ºC

Tab 4.2 Experimental result showing the narrowing effect as a result of change of angle of illumination

As observable from the calibration curves and also the raw image data of the calibration, there is no change in the red start and green start temperatures respectively. However, there was a change of 0.5ºC for change of angle of illumination of 17.90 degrees and change of vertical distance of 100mm. This also can be easily inferred from the shift of the range of the hue from 0-300 degrees for angle of illumination of 65.60º to about 0-250 degrees for angle of illumination of 47.70º. This result of significant effect of angle of illumination on the green-blue transition region is consistent with the finding of (Kakade et al. 2009). Further confirming the finding of the result of this current study, the result of calibration curves of R30C1W TLC and R30C5W TLC concluded by (Kakade et al. 2009) also shows that effect of angles of illumination angles were more prominent for R30C5W TLC (wide bandwidth TLC) compared with R30C1W TLC (narrow bandwidth). Their results indicate that illumination angle effects are negligible in the red and green regions of hue–temperature calibrations.

The off-axis arrangement used in the experimental setup contributed to the illumination disturbance as shown by Farina et al (1994) in the calibration of R35C5W TLC. A 0.6 ºC shit in hue-temperature was reported when the illumination source was deviated at an angle above 20 degrees from the calibration surface which is in off-axis arrangement. However, only about ±0.25 C shift in hue-temperature calibration when on-axis arrangement was implemented.

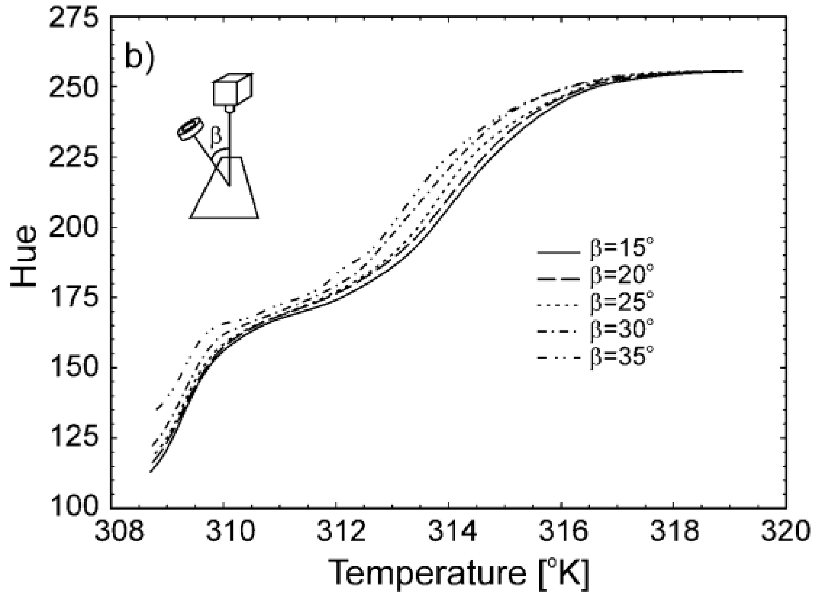


Fig 4.11 Variation in calibration curve with angle of illumination. (Farina et al. 1994)

Cami et al. 1993 and Giel et al. 1998, concluded that the micro-encapsulated chiral nematic LCs are the least sensitive to the variation in the angle of illumination. Also, sprayable liquid crystals are less sensitive to lighting and viewing geometry than pure liquid crystals as shown by Farina et al.1994, hence these are factors that might have positively affect dependency of the hue-temperature curve on the angle of illumination.

CHAPTER FIVE

SUMMARY AND CONCLUSION

The necessity and application of temperature in our domestic, research and industrial environment is of very diverse scope. To meet these requirements, innumerable advances have been made in the development of sensors, techniques, and devices for temperature measurement. The strength of thermochromic liquid crystal thermography lies in being a noncontact, relatively simple and inexpensive measurement technique. Particularly outstanding of its numerous advantages is that the reflected light by TLC is within the visible spectrum which allows easy visibility and imaging. Hence, in the absence of the need for accurate quantitative application, visual observation of the colors provides fast and easy useful information about the temperature field of the surface being considered. Numerous studies have also shown that liquid crystals have proven to be a powerful and promising tool for vast studies relating to heat transfer, fluid-flow experiments, and other heat research.

However, since the human eye is susceptible to color bias, the use of TLC for precise and accurate quantitative measurement of temperature very much depends on its calibration. Numerous studies have concluded that the liquid crystal color change can be calibrated accurately to temperature with high resolution. Steady-state hue-temperature calibration of TLC is the most common method of TLC calibration.

Several factors such as image noise, illumination disturbances, TLC coating thickness and, hysteresis, are known to influence the accuracy of the hue-temperature relationship. The experimental aspect of this present study focused on the establishing the bandwidth of the used TLC and investigating the effect of angle of illumination on the hue-temperature calibration curve using the steady state calibration technique.

The result of the experiment agrees well with established characteristics of the TLC hue-temperature curve and the narrowing-effect observed from the variation of angle of illumination which is about 0.5ºC for 17.9 degrees change in the angle of illumination corroborates other research work on the bandwidth shift for wide-band liquid crystals. The narrowing effect was not observed for lower angular change of illumination of 11.4 degrees. This also agrees with cited studies which concluded that the dependency of the narrowing effect is more profound for high change of angle of illumination.

The result of the experiment suggests the need for calibration of TLCs each time before use to improve the accuracy of data. If the settings of a calibration have changed or need to be changed then recalibration is necessary. The glare effect doesn't have considerable effect on the hue calue. Furthermore, the scope of the study can be expanded to investigate and compare the effect of the angle of illumination based upon on-axis experimental setup and over a wider variation of the angle of illumination. Also, it is very important to consider the effect of hysteresis on the repeatability of the calibration curve. The hue-temperature calibration curve dependence on angle of illumination also suggests that the repeating the study on non-flat or curved surfaces.

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LIST OF ABBREVIATIONS

LC Liquid crystal

TLC Thermochromic liquid crystal

HSV Hue saturation value

RGB Red green and blue component

RTD Resistance temperature detector

LED Light emitting diode

CCD charge-coupled device

NOMENCLATURE

T Temperature (K)

h Convective heat transfer coefficient ($Wm^{-2}K^{-1}$)