Abstract

The calibration of thermochromic liquid crystals (TLC) used for measuring surface temperatures is required to develop a correlation between the surface temperature and reflected color. The few commercially available calibration systems tend to be very costly and are usually sold as complete packages containing a computer, camera, and thermocouples. The project objective is to produce an inexpensive and portable calibration system. The following report describes the development of a final design concept for the system, including the previously available information, concepts considered, and the final design. The liquid crystal, adhered to a copper plate, is heated using two Kapton heaters that are controlled by Hewlett Packard Virtual Environment (HP VEE). When the TLC reaches specified temperatures, monitored by thermocouples using HP VEE, color images of the TLC are recorded using a digital camera connected to the computer. The hue values of the colors are then analyzed using Matlab. From this series of images and the subsequent hue values, a calibration curve of the TLC is constructed.
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97/100
Mechanical, Industrial, and Manufacturing Engineering Department

Northeastern University
Snell Engineering Center
360 Huntington Ave
Boston, MA 02115

Re: Transmittal Letter

March 6, 2000
To whom it may concern,

This report is being submitted in partial fulfillment of the requirements for the Capstone Design Class, MIM1501. The development of a calibration system for polymer-dispersed thermochromic liquid crystals (TLCs) is discussed. This project was authorized at the start of the winter quarter by Professor Mohammed Taslim, representing the Department of Mechanical Engineering at Northeastern University.

Certain types of liquid crystals reflect a range of visible light over a specific portion of the liquid crystal phase, an intermediary phase between the liquid and solid states. The reflected color of the liquid crystal can be calibrated with its corresponding temperature, making the liquid crystal a very effective thermometer for complex temperature contours or geometric surfaces. The goal of this project is to construct a simple yet effective calibration system, to determine the temperature corresponding to a single color.

This report describes the development of the calibration system design. The design is composed of a heating assembly, an image acquisition system, and a computer control system. Concepts for each component are developed and designs are finalized. From here the components will be assembled, the computer control system program will be written, and the design will be tested.

The design team can provide answers to any reader questions.

D. Colanto, B. McCarthy, T. Roberts, M. Wotzak

Liquid Crystal Calibration Design Team
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EXECUTIVE SUMMARY

Project Need

Prof. Taslim needs a device that quickly and accurately calibrates the temperature to color relationship of a sheet of thermochromic liquid crystal.

Thermochromic liquid crystal (TLC) is often used in laboratory experiments to measure temperature. In order for the user to know exactly what color of the TLC corresponds to what particular temperature, a calibration must be performed. Currently, the calibration process Prof. Taslim uses is difficult to use and there are many uncertainties. Commercial calibration devices available are extremely expensive, and usually include many more components than Prof. Taslim needs. Therefore, there is a need for a calibration device that is fast, accurate, user-friendly, and low cost.

Design Objectives and Requirements

Design Objectives

The objective of this project is to design an inexpensive and easy to use temperature calibration device for a TLC sheet.

Design Requirements

This project is focused on the design of an imaging system, which will calibrate TLC sheets between 30-40°C. The temperatures corresponding to the green/yellow color state need to be determined. During calibration, a picture of the liquid crystal will be simultaneously recorded with the corresponding thermocouple temperature measurement.

Design Concepts Considered

Concepts were considered for ways to heat the TLC, acquire temperature data and images, and process the data.

The project was divided into three main parts, heating the TLC, temperature and image acquisition, and data processing. Concepts were developed for each of these components.

When evaluating the heating concept, two components need be determined. The first is the heating method and the other is the heating medium through which the heat would travel. A concept used electric resistance heat strips attached to a thin copper plate. Another concept uses a hot plate to heat either water or air. Microwave and ultrasound heating methods were considered, again using air or water as the heating medium. A design matrix was developed to evaluate the heater concepts. This matrix concentrated on heating/cooling time, price, transparency (clear view to take picture of TLC), cleanup time, and isothermicity.

A number of data acquisition and process control methods are available on the market. Amazon Electronics PC Data Acquisition Unit, Eagle Technologies PC-73C, Labtech, LabVIEW, and Data Translation/HP VEE were the different packages considered. The system must read thermocouple data, have programmable outputs, and be within the project cost constraints.

A Mustek VDC-3500 digital camera, and a Nikon film loaded camera and a web camera were considered for image acquisition. The key
features needed for the project were to view and capture real-time images, imported into a PC, and the price be within the specified budget.

**Recommended Design Concepts**

A design matrix was used to determine the most suitable heating concept. Electric resistance heaters attached to a copper plate will be implemented. This concept offered good visibility, quick heating, minimal cleanup and maintenance, and is cost efficient. Prof. Taslim provided the two Kapton heaters. Machining three thermocouple port near the surface of the copper plate is required. A block of polyurethane will be used to insulate the heating assembly.

HP VEE, provided by Northeastern University, will be used as the data acquisition and control system. Data Translation is the company that provides the data acquisition hardware, which consists of a PCMCIA card, and HP VEE is the programming language used to control the inputs and outputs. This system can read thermocouple data, be programmed to send output signals, and it can be used at no cost.

The Mustek VDC-3500 digital camera has all the features necessary for the project. The images captured by the camera can then be downloaded to a PC through an RS-232 serial port. The camera was provided at no cost.

**Design Description**

The apparatus will be placed on a portable lab cart. The apparatus consists of an adjustable camera mount onto which the lighting will be attached. The insulation will be made of machineable plastic, and a copper plate with Kapton heaters attached to act as the heat source. The TLC sheet will be adhered to the copper plate and heated. The temperature will be measured by three thermocouples placed inside the copper plate and monitored by HP VEE. When a designated temperature is reached the control system sends an output signal to turn off the heaters. With the heaters off, the copper plate and TLC sample will slowly cool. Pictures will be taken at specified temperatures and examined using Matlab to measure the TLC RGB color values. A Matlab function then converts the RGB values into hue values. The hue values and their corresponding temperatures form a calibration table.

**Financial Issues**

Due to the fact that many components were provided by Northeastern University and Prof. Taslim, the project is within budget constraints. The camera software and manual, lab cart, lighting fixtures and assembly, machineable plastic, and copper plate have been purchased. $230.00 has been spent. The project is ready for fabrication, assembly and testing. In the future some additional small electrical components may be purchased for use with the data acquisition system. These are expected to be relatively inexpensive.

**Future Work**

The polyurethane and copper plate need to be machined before the apparatus can be assembled. The HP VEE control program needs to be written and the Matlab color quantification program needs to be refined. The total time of the calibration process will be measured. The accuracy of the thermocouples must be determined. Due to possible adverse effects from lighting on the liquid crystal, special filters may be needed.
1. Introduction

This report presents the existing methods and equipment for calibrating thermochromic liquid crystals. The calibration system is used to correlate the color of liquid crystals with temperature. This report gives background information for understanding how and why this project arose. A state-of-the-art survey describing current patents, existing products and technical literature is included. Finally, the report documents the development of concepts for the calibration system and the finalized design.

Liquid crystals are used when it is desirable to know the continuous temperature distribution on a surface and not be limited by finite temperature acquisition systems, such as thermocouples. Thermochromic liquid crystals are commonly used to measure surface temperatures for fluid flow over heated and adiabatic surfaces. In an existing experiment, air flows over a flat-heated surface with ribs perpendicular to the flow. A sheet of thermochromic liquid crystals is adhered to the surface. The power applied across the surface is increased until a section of the liquid crystal changes color. The power and color are recorded. The corresponding temperature is determined and the overall heat transfer coefficient is calculated. This procedure is repeated at different power levels, changing the temperature at different locations on the surface. The subsequent local heat transfer coefficients are calculated and used to determine the average \( h \) for the plate. Given that the surface temperature directly influences the calculated heat transfer coefficient value, it is critical to make an accurate measurement. The correlation between the color of the liquid crystal and temperature must be precisely calibrated.

The purpose of this project is to design a thermal imaging system, which will calibrate a sheet of thermochromic liquid crystal (TLC). The calibrated temperature must correspond to a point in the green/yellow color range, which occurs over an approximately 1 °C range somewhere between 30-40 °C. During the calibration, a photographic image of the liquid crystal will be synchronized with a temperature measurement so the color can be matched to a temperature value. The measured value must have an accuracy of 0.5 degrees Fahrenheit. The environment in which the TLC sheet is placed must have lighting that is similar to experimental conditions.
Concepts have been developed for the heating of the TLC, the overall process control, and the recording and analysis of the image. From these concepts, a final design was developed. It consists of a circular 2” diameter liquid crystal sample adhered to a 3”X3” copper plate that is heated using two 2.50”X1.25” Kapton heaters. A block of polyurethane is used for insulation. HP VEE, a virtual programming environment, controls the activation of the heaters and monitors the temperature readings from the thermocouples. When the TLC reaches specified temperatures, color images are recorded using a Mustek VDC-3500 digital camera connected to the computer via the serial port. The red, green and blue (RGB), values of the colors are then analyzed. Matlab calculates the corresponding hue values from the RGB values. A calibration curve of the TLC is constructed from the designated temperatures and the subsequent hue values.

1.1. Requirements

The list of design requirements was compiled from the initial project description, an examination of the currently available commercial calibration systems, and a review of the relevant literature

- The system should be automated to ensure the ease of operation as well as accurate timing of image acquisition.
- The lighting of the sample should emulate the experimental setup to safeguard the observed color of the LC.
- The lights should only be turned on long enough to take the picture, to conserve the bulb life.
- The sample should be appropriately sized and shaped to avoid “edge effects.”
- A punch should be made to cut consistent sample sizes.
- The device should be portable.
- The design of the sample holder should allow for quick and easy setup.
- Total calibration time should not exceed 30 minutes.
1.2. Specifications

The specifications are more quantitative versions of the Requirements section. They define a series of specific goals to be met by the final design.

1.2.1. Project Statement Specifications

These specifications were culled from the initial project description and the resulting project statement. They are the most well defined and concrete requirements for the calibration system.

- Calibration accuracy of 0.5 °F (0.28 °C)
- Temperature calibration range of 30 – 40 °C
- Allow for calibration of green-yellow TLC color
- Tungsten light bulbs used for illumination

1.2.2. Developmental Specifications

These specifications were created during the concept development. They are not as critical to the design as the Project Statement Specifications, but are highly desirable for the final calibration process.

- Major Dimension of Sample: 1- 2”
- System Size: Small enough to fit on a 3’ X 4’ lab cart for portability
- Quantification of observed color
- Conversion of RGB values to single scales
- Automated calibration process
- Insulated sample enclosure
- Digital imaging
- Calibration time of 30 minutes
- Calibration temperature cooling rate of less than 0.2 °C/min
- Price of $500, which excludes digital camera, computer, and software as these are already available

The above specifications describe a calibration system that will quickly and accurately determine the color associated with a specified temperature in the range of 30 - 40 °C.

1.3. Background

The use of liquid crystal materials for accurate temperature measurement is a relatively recent technology, although the general liquid crystal color response to temperature is common knowledge. The presented background material first describes how the liquid crystal structure allows the reflected color to change with temperature. The method of color quantification that allows the temperature/color curve to be accurately determined is then discussed.

1.3.1. Liquid Crystal Background

Liquid crystal materials are moderately sized organic compounds that have an elongated, cigar-type shape. The typical molecule is 20-30 Angstroms long, but only about 5 Angstroms wide [1]. The name comes from the fact that these materials go through an intermediate phase between the liquid and solid states. In this phase, the molecules do not have the positional order of a solid, but they do retain orientational order uncharacteristic of liquids. For certain liquid crystals, this orientational order varies in a known fashion across a plane of molecules such that a director, \( n \), describing the average molecular orientation at a point in the plane, traces a helical path [2]. The distance spanned by the helix is the crystal’s pitch. As Bragg’s Law states that incident light normal to a surface causes selective reflection, the liquid crystal takes on a visible color when the pitch of the crystal orientation matches the wavelength of a given color [2]. Since the pitch is strongly dependent on temperature over a well-defined range in the liquid crystal phase, the reflected light can be correlated with a temperature scale.

The liquid crystal phase can be subdivided into smectic and nematic sub-phases. The smectic phase occurs on the cooler side of the liquid crystal phase, closer to the solid phase of the material. In this phase, the molecules are arranged in layers with the long axes of the molecules perpendicular to the plane of the layer [2]. Figure 1 [1] shows a schematic of how the smectic phase molecules are arranged.
This phase is fairly rigid and the molecules are highly constrained in their movement. Although, as Figure 1 shows, there are small variations in the orientation of the molecules with respect to each other, there is no pattern to the variation. The average molecular orientation is always perpendicular to the plane of the layer and parallel to the neighboring molecules. In the nematic phase, the molecules are no longer restricted to layers, but they still retain most of the orientational order, with the long axes generally parallel to each other. An illustration of the molecular arrangement in this phase is shown in Figure 2.

Nematic liquid crystal molecules can also be divided into chiral and achiral subcategories. Achiral molecules are symmetric about their long axes, meaning the intermolecular forces that hold them together are somewhat weaker than in the chiral molecules. The asymmetry of the chiral molecules allows inter-molecular forces to rotate the molecules slightly with respect to each other. The directional vector, n, shown in Figure 2, represents the average molecular direction at a point in the plane. However, n rotates, following a helical path, over a section of molecules. The distance required for a complete 360° rotation is termed the pitch of the liquid crystal [2]. It is this orientational pitch that determines whether the liquid
crystal reflects visible light. An illustration of the pitch and molecular rotation is shown in Figure 3.

![Liquid Crystal Orientational Variation](image)

**Figure 3 – Liquid Crystal Orientational Variation** [2]

Bragg’s Law states that the orientational pattern of a crystal, separated by half the wavelength of incident light that is normal to the crystal surface, results in constructive interference, or selective reflection [2]. Because a liquid crystal molecule, rotated 180°, is essentially the same as a molecule with 0° rotation, light with a wavelength equal to the pitch of the liquid crystal is reflected [2]. Thus, chiral nematic liquid crystals (CNLCs) are the only ones with the possibility of reflecting visible color.

The angle of incidence for the illuminating light is important because it can affect the observed color. When the angle of incidence is something other than 90°, or not normal to the surface of the liquid crystal, the reflected wavelength is no longer equal to the pitch of the crystal. Instead it is \( p \sin \tau \) where \( p \) is the pitch of the crystal and \( \tau \) is the angle of incidence [2]. This means that the observed color can changed based on lighting, and any calibration or experimental setup must take this into account.

CNLCs reflect a certain light if their pitch matches the wavelength of the given light. Typical CNLCs reflects a range of colors that can be calibrated to a temperature range because there are large changes in pitch as chiral liquid crystals make the transition from the nematic to smectic phase. As the smectic phase approaches, smectic-type groups begin to form, limiting orientational rotation within them [2]. As these groups increase in size, the effective pitch of the liquid crystal increases, reaching infinity once the smectic phase is fully formed. Thus, as the
pitch increases it passes through the visible spectrum at some point and reflects the complete range of visible light. Due the inverse relationship between liquid crystal pitch and temperature, blue is representative of the warmer side of the temperature scale and red is representative of the cool side.

1.3.2. Color Quantification Background

For a specified illumination, any color can be defined in terms of three primary light sources. The color observed is a combination of both the chromaticity (wavelength) of each of the sources and the intensity of the light. There is not a unique set of primary colors, however the RGB system developed by the National Television Systems Committee [2] is used in the vast majority of commercially available imaging equipment. R, G, and B are the color intensities of red, green, and blue light, respectively, that make up an image.

The three primary color intensities can be converted to chromaticity coordinates by dividing each by the overall intensity, which is proportional to the sum of the individual color intensities. For the RGB system, the chromaticity coordinates, r, g, and b, are defined in this manner [2]. The coordinates can then be plotted in the form of a triangle on an x-y plane with the vertices positioned at the unity values on the x and y axes. The white light point, which is the equal combination of each of the color intensities, is at the triangle’s center. A new set of x-y axes can then be defined using the white light point as the origin [2]. The chromaticity coordinates, r, g, and b can then be related to the x-y coordinates [2] using

\[
x = \frac{2}{\sqrt{3}} \left( r - \frac{g}{2} - \frac{b}{2} \right)
\]

\[
y = \frac{g - b}{\sqrt{2}}
\]

(1)

Finally, the RGB triangle can be described in terms of polar coordinates, hue and saturation. The hue, h, is the angular coordinate and represents the dominant wavelength of the color being defined. The other coordinate, the saturation, provides the radial distance from the white light point. For a thermochromic liquid crystal, the saturation value is determined mainly by the lighting conditions. Thus, the temperature calibration can then be performed solely in terms of the hue, making a simple calibration curve possible. The hue is related to the RGB values in the following manner [2]
In (2), RGB values can be substituted for RGB values because the chromaticity coordinates are simply the individual RGB values divided by the intensity. For calibration tests, the RGB values from the acquired image can be converted to a single hue value. This value can then easily be compared to the temperature to develop an appropriate calibration curve. Thus, the structure of a liquid crystal material between the liquid and solid states allows it to reflect a visible color that is a function of the material temperature. The color can then be quantified and related to the temperature, creating an accurate and efficient thermometer.

\[ h = \arctan \frac{\sqrt{3}(G - B)}{2R - G - B} \]  \hspace{1cm} (2)

2. Available Information

Most of the available liquid crystal calibration system information describes complex methods of calibrating liquid crystals that are beyond the scope and cost of the current project. Several simpler methods of calibrating liquid crystals and a complex color quantification method are also described.

2.1. Patents

There are two patents that related to the current design project. The first is a complete calibration system that calibrates the full range of visible color reflected by a given liquid crystal material. This patent has resulted in a commercially available system, but the product is far too complex and expensive for the stated design requirements and specifications. The second patent describes a method of quantifying color and relating it to temperature that was developed for calibrating liquid crystals. This method is far more complicated that what is required by the current design, however.

2.1.1. Calibration System

Patent #5,526148 [3] describes a calibration system for microencapsulated liquid crystals. The system captures color images of the liquid crystal at controlled temperatures. Experimental images are then calibrated by comparison to the analyzed control images.

The full-field color response of thermochromic liquid crystals is accurately calibrated. The technique and tools used are the claims of the patent. The thermochromic liquid crystals are
coated on a thermally conductive substrate. The substrate is heated by using heating bars located at the ends of the substrate material. The bars are heated using thermal elements, which direct a known temperature gradient across the substrate and therefore the thermochromic liquid crystal. A transparent material holds the thermochromic liquid crystal against the heated substrate under pressure. The color response associated with the temperature gradient is recorded with a color camera by means of reflected light through the transparent material and translucent insulation plates. Figure 4 is an exploded view of the thermochromic liquid crystal holding fixture.

The illuminating light is a ring-shaped light source located concentrically around the camera lens and has the capability to be positioned at different angles. The intention of the light is to approximate a spot source. The light travels through both infrared and ultraviolet filters before reaching the camera to remove unpolarized light. These filters also aim to remove thermal energy and stop degradation. Further, to insulate the substrate and liquid crystal, two translucent plates are arranged on top of the transparent material. A thin layer of air separates the transparent material and each of the plates. Figure 5 is a side view of the entire apparatus.

The gradient obtained from the heating elements is a concentric pattern. The lower temperature is located in the center of the thermochromic liquid crystal and the highest located at the edge of the thermochromic liquid crystal. The temperature of the substrate is held at approximately steady state. The temperature is constantly monitored by thermocouples. This enables the process of continuous calibration of the color-to-temperature reaction of the thermochromic liquid crystal.

There are several design requirements that are not met. The calibration process can take up to forty-five minutes, which is fifteen minutes longer than the design specifications. An isothermal process is desirable for simplicity and ease of development. The system is beyond the design scope, which boasts a full-temperature and color range calibration. It does not have the desired maximum uncertainty of 0.25 degrees Celsius. This is due to the uncertainty of 0.5 degrees Celsius of each thermocouple. It is difficult to change liquid crystal samples in the apparatus. The system is not designed for sheets of liquid crystals as specified.

This patent already meets many of the previously discussed design specifications. The high-resolution camera used to record the color image assimilated with filtered and polarized light specifications meets the design criteria. The apparatus has the ability to calibrate a wide
Details:

10. Substrate Material
12. Thermochromic Liquid Crystal
14. Thermal Element
16. Thermocouples
20. Bed
22. Channel
28,30. Thermal Elements
32,34. Leads
36. Transparent Material
38. Spring Racking
40. Frame
42,44. Translucent Plates
46. Air Gap

Figure 4 - Exploded View of Fixture for Holding the Thermochromic Liquid Crystal [3]

Details:

β. Angle of Camera
d. Height of Camera
h. Air Gap Width
50. Camera
52. Objective
54. Light Source
56. Infrared Filter
58. Ultraviolet Filter
60. Duct
62. Primary Light Source
64, 66. Polarizers
100. Incident Light
101. Reflected Light

Figure 5 - Side View of Entire Apparatus [3]
range of temperatures. The temperature gradient can be varied from one to forty degrees Celsius. The device calibrates thermochromic liquid crystals recording a high-resolution color image. It has the ability to perform continuous calibration eliminating the need to interpolate. These concepts will be incorporated into the development of the design. The full text of the patent is available in Appendix A for reference.


Patent #5953449 [4] describes a method of calculating a three-dimensional curve used in calibrating a coloring member. This method uses existing hardware to control and measure a physical quantity of the coloring member. Simultaneously, the subsequent image is recorded to form a three-dimensional color space for that physical quantity. From a series of three-dimensional points, a best-fit curve is interpolated. An image of an experimental sample is then compared to the known curve and the corresponding temperature is noted.

The preferred physical quantity measured is temperature. A thermo-sensible liquid crystal member is preferred for the coloring member. The color change of the thermo-sensible liquid crystal member is recorded using a charge-coupled device (CCD) camera. The photographed images are processed and calculated in terms of either RGB or L*a*b*. From these three values a three-dimensional color-space is graphed. From sets of calculated values based on a series of images recorded at known temperatures, a color-temperature calibration curve is interpolated.

Figure 6 shows a sample three-dimensional RGB color space. The spheres represent data points recorded from the calibration at set temperatures. The line connecting the individual spheres is a curve interpolated using a quadratic function and the recorded data values.
Figure 6 - Illustration of RGB Values Plotted in Three-Dimensional Color Space [4]

Figure 7 is a flow chart showing the process for calibrating the crystal liquid is below.

In Figure 8, RGB values are graphed versus temperature. The temperature was recorded at the same time as the image of the liquid crystal was recorded and analyzed.
Using a three-dimensional color space is an effective means of documenting the appearance of the liquid crystal at a known temperature. However, this is only a method of relating the colored image to a numerical value not a method for the entire process of controlling and recording the temperature of the liquid crystal. Additional controls and equipment are needed to complete this procedure. This method of color analysis is designed for a large color band and will not be implemented into the processing of data. The full text of the above patent is available in Appendix A for reference.

Although, the first patent does what is required by design specifications, it would be too costly due to its unnecessary complexity. The second patent describes an advanced method of quantifying color. However, it exceeds the specifications in complexity and difficulty of implementation. Thus, it cannot be used and will not affect the current design.

2.2. Available Products

There are two calibration systems commercially available based on the calibration patent described in Section 5.1.
2.2.1. TempVIEW Calibration System

The TempVIEW calibration system, shown in Figure 9, is manufactured by Image Therm Engineering Inc., 159 Summer Street, Waltham, MA 02452.

Figure 9 – TempVIEW TLC Calibration System


TempVIEW is a complete thermal imaging system which includes a CCD color camera, a PC (Hewlett-Packard Vectra) or National Instruments PXI mainframe, plug-in color image acquisition board, computer controlled color-temperature calibration hardware, thermochromic liquid crystal materials, white light source, and corresponding software. Image Therm only offers their product as a complete package costing around $5000. This package fits into the expected space limitation in terms of product portability, it can be transported via a cart. Image Therm obtained a patent based on the calibration hardware, which is described in Section 5.1.

The calibration unit is controlled through the computer and produces a color-temperature scheme based on temperature readings from thermocouples embedded in a heated plate that is insulated from the environment and illuminated by fiber optic lighting. The calibration can be performed either by creating a temperature gradient across the plate or using a series of isothermal states. Color images are taken of the liquid crystals, which come in a sprayable medium, with the CCD camera and sent to the PC via the color image acquisition board. Images used for actual surface temperature measurement are converted to temperatures based on previously created color schemes by the software. Images can then be filtered, saved, exported, compared with one another, and individually analyzed.
The manufacturer claims that TempVIEW has a temperature measurement range of 10-140 °C and accuracy’s of 0.1 °C and 1 μm spatial resolution [5], which is within the design specification. This product also allows for our temperature operation range of 30-40 °C. The stated accuracy of this product is based on differentiation between colors. The proposed system will only analyze one color at a time.

The TempVIEW software and data acquisition system was developed with National Instruments LabVIEW and IMAQ Vision for windows 95/98/NT platforms. LabVIEW allows users to create virtual control interfaces instead of writing scripted programs to control instrumentation, acquire data and images, and file input and output. IMAQ Vision accompanies LabVIEW to add image-processing capabilities, which include multi-media functions for color images. TempVIEW combines these technologies to allow for live image acquisition storage and retrieval, automatic image conversion of color to temperature, multiple images to be shown at once, and cursor interaction with the images.

TempVIEW was designed to perform all of the temperature measurement tasks and offer the instrumentation control capabilities described in the project statement, however it also adds a number of image-processing operations that are not necessary. The cost of this product is ten times higher than desired, mainly due to the fact that it can only be purchased with a PC. The implementation of liquid crystal sheets (polymer-dispersed liquid crystals) instead of as a sprayable medium is necessary to meet the design specifications. The calibration hardware setup used with TempVIEW is patented but the use of data acquisition and image processing software such as LabVIEW and fiber optic lighting will be integrated into the design if they fit within the cost limitations.

2.2.2. LCI (Liquid Crystal Imaging) Calibration System

The LCI calibration system, shown in Figure 10, is made by Advanced Thermal Solution, 89-27 Access RD, Norwood MA 02062.
The Advanced Thermal Solutions thermal imaging system, LCI, is similar to the patent described in Section 6.1 and the TempVIEW calibration system. The system consists of a CCD color camera and optical system which is illuminated with fiber optics, a software package, data and image acquisition boards, and a calibration rig. This package fits into the expected space limitation in terms of product portability; i.e. it could be placed on a rolling table or cart.

Similar to the TempVIEW product offered by Image Therm, the calibration unit is controlled via the computer to obtain a color-temperature scheme. The calibration system is integrated for in-situ temperature calibration of the liquid crystals. A fiber optic ring light supplies the lighting for the optical system. This lighting is IR free, eliminating IR absorption interference with the temperature measurement. Images used for actual surface temperature measurement are converted to temperatures based on previously created color-temperature schemes. The software that is included can then manipulate the images. LCI runs off of LCImage, a Windows based software package for data acquisition and image processing. LCImage offers a variety of image-processing functions that allow customization of the control and image windows.

The manufacturer claims that LCI has a temperature measurement range of 10°C to 160°C and accuracy’s of ±0.1 % and 1 μm spatial resolution [6]. Highly polarized optics are used to increase the accuracy of the temperature measurements. LCI was designed to perform all of the temperature measurement tasks and offer the instrumentation control capabilities described in the project statement, however it also adds a number of image-processing operations...
that are not necessary. The cost of this product is much higher than desired. The use of data acquisition and image processing software similar to LCImage, enhanced optics, and fiber optic lighting will be integrated into the design if they fit within the cost limitations.

The products listed above are very similar in design and offer comparable performance capabilities. These TLC thermal imaging systems were designed to provide a cost reductive solution to determining thermal gradients across complicated surfaces to compete with much more expensive infrared imaging systems. TempVIEW and LCI also provide an abundance of image processing tools that are not necessary for calibrating a single color. Both of these observations add to the notion that these systems offer an excess of functions in relation to the project statement, which leads to them being much too expensive. Both of these systems are geared towards microencapsulated rather than polymer-dispersed liquid crystals.

2.3. Available Literature

The relevant literature falls into two general categories. The first category is comprised of systems analogous to those described in the Available Products section. These calibration methods are accurate, but on the complex and expensive side. The second category describes inexpensive methods that are typically used in the course of heat transfer experiments. These methods sacrifice some accuracy and repeatability for simplicity.

2.3.1. Complex Methods

Hay and Hollingsworth describe the modern standard for calibrating a liquid crystal thermometer across its entire temperature range in [2] and [7]. The entire process is laid out in [2] for polymer dispersed liquid crystal thermometers and a specific lighting setup. The calibration’s usefulness is then expanded in [7] by including microencapsulated liquid crystals and a variety of lighting conditions.

The basis of any calibration system is the heater setup that controls the temperature of the liquid crystal. For this setup, the authors use a combination of a 0.254cm thick aluminum plate and a circulating water system. The plate forms one side of a Plexiglas box, and the liquid crystal is affixed to the plate. It does not provide heating by itself, but maintains the entire liquid crystal at a constant temperature. The heating is provided by hot water, which is forced to circulate through the box in a serpentine flow, providing a more even heat flux to the plate. A
1.5 mm air gap and a 3 mm thick sheet of Plexiglas separate the plate from the water. The temperature of the water is measured with a 0.1 °C resolution RTD and is taken to be the liquid crystal temperature.

The calibration is completed by recording the color of the liquid crystal with a digital video camera and passing the image to a PC by way of an image grabbing board. The camera records the image in terms of the RGB values for each pixel. These values are then converted to a scalar hue matrix using custom software, and the hue values are compared to the recorded temperatures to get a calibration curve. Finally, a dimensionless temperature method of calibration is developed that could allow for the full temperature-hue calibration curve to be developed with only six hue-temperature pairs.

This calibration system satisfies all of the stated design specifications except for the cost, which is most important. It essentially describes the methods employed by the commercial systems already available that cost in the neighborhood of $5000 with all the equipment included. The system described also goes above and beyond the stated design specifications in one area. For the design, the calibration of only a single well-defined color is necessary, whereas, the above system determines the calibration for the entire range of colors. Concentrating on a single color could significantly reduce the cost of the system by eliminating the need for a video camera. It would also eliminate the need for completely integrated data collection and image processing in one unified software product.

The calibration system described provides an excellent starting point for the required design as it essentially does what is needed on a more elaborate scale. Sub-sections of the system, such as the method of heating and maintaining the temperature of the liquid crystal could theoretically be transferred directly to the design. Improvements would mainly involve simplifying the system to reduce costs and eliminate the unnecessary complexity of the existing system. For instance, the circulating water flow could probably be eliminated with a properly designed electric heater in an isolated environment. The video camera and custom software could also be reduced to a still camera and several unintegrated packaged software programs that are already available.
2.3.2. Simple Methods

The simpler methods are described in two papers. Cooper, Field, and Meyer describe their calibration system in terms of the heat transfer experiment for which it was used. In this case, the heating system is comprised of a stationary water bath that is capable of establishing and maintaining a temperature of 0.01°C [8]. The liquid crystals are placed in clear plastic bags and suspended in the bath. The color analysis of the liquid crystals is then done by eye, both during heating and cooling. Due to human variation in color characterization, only the calibration of the onset of the blue, green, and red colors is done. The authors claim an accuracy of 0.1°C for the three aforementioned points in the temperature range when the same observer is used [8].

The system is much simpler than the commercially available systems and still technically meets the stated design specifications. It could most likely be constructed within the available budget. However, the use of a human observer introduces some cause for concern. With human color analysis involved, there is no way to ensure that the experimental uncertainty can be transferred from person to person. Thus, every time a new person gets involved in the experiment for which the calibration is performed, the calibration, and possibly the experiment itself, must be restarted. This may not be an issue for short-range experiments, but for longer ranges and as far as addressing reproducibility issues, it could be a significant problem. Thus, while the heating and temperature control system could technically be directly transferred to our design, the reliability of the system could be improved upon. The best way to make it more reliable is to substitute the qualitative color analysis with a quantitative one.

The calibration system described by Simonich and Moffat in the second paper, [9], is analogous to that in the first. Once again, the liquid crystal is suspended in a water bath with transparent sides so that it remains visible. The main difference involves the lighting of the system. Instead of using typical white lighting, a mercury-vapor lamp is employed. This type of light emits three separate spectral lines that can be filtered independently. The authors claim that this reduces any bandwidth ambiguity and results in a calibration system accuracy of ±0.25°C [9].

Like the Cooper, Field, and Meyer system, this setup meets the stated design requirements and is far simpler than the commercial systems available. Unfortunately it also
relies on human interpretation of color. In this way, the potential reliability is reduced. The mercury-vapor lamp is the only possible addition to the current design project. However, this would mean that this lamp would also be needed for the experiments themselves, as uniformity must be preserved. Therefore, the simple approach described by Cooper, Field, and Meyer [8], should prove more useful. The use of standard white light bulbs for the actual experiment along with safety considerations makes the applicability of the mercury-vapor lamp to the calibration process somewhat dubious.

The complex systems described in the literature, like those described in the Patent and Available Products sections are overkill in the case of the present design. Their complexity means that they cost too much. The simpler systems, on the other hand, leave too much room for human error. None of them employ the quantification of the observed color, so human judgement is needed. This is unacceptable for the present design as multiple operators could use it.

3. Concept Development

Concept development for the calibration system can be divided into four sections. The heater assembly is made up of the heating element itself, the attachment mechanism for the liquid crystal, and the control system for the heater. The image acquisition component involves the selection of camera, and the method of actuation for picture taking. Finally, data acquisition and translation deals with the collection of thermocouple and image data, using the thermocouple data to control output signals, and converting the image data to scalar hue values.

3.1. Heater Assembly Concept Development

Initial brainstorming produced several unique heating concepts. One concept employs a thin copper plate as the heating medium, shown in Figure 11. A resistance type electrical heat strip would be placed underneath the copper plate to heat the liquid crystal sample by conduction. Thermocouples would be placed in various locations to measure the temperature.
Another concept uses air or water for the heating medium as shown below in Figure 12. A hot plate would be placed beneath the enclosure to heat the liquid crystal sample by convection. To create turbulence and an isothermal temperature in the medium, a fan would be used for the air concept, and a mixer would have to be used for the water version. Again, thermocouples would be placed in various locations to measure the temperature.

The three ideas presented above all employ electrical resistance heaters to bring the liquid crystal sample up to the desired temperature, meaning they can all be placed in one general category. Two other categories were also investigated. The first involves using microwave technology to heat the liquid crystal, and the second uses ultrasound waves to heat the sample. These methods are less common, so they are not subdivided. The difference in the choice of heating mediums can be sorted out in the electrical resistance category. The merits of the individual designs can be compared efficiently using a design matrix.

In the matrix, each concept is evaluated against a number of criteria. In order of importance, they are:
- Isothermicity of the liquid crystal sample
- Transparency of any material between the liquid crystal sample and the camera
- Heating and cooling time of the sample
- Price and availability of parts
- Setup/cleanup time for the calibration procedure
- Build time for the concept

The isothermicity of the sample is of utmost importance because it directly affects the accuracy of the calibration. The sample must be at a uniform temperature when the picture is taken, so the camera will see a unified color. A variation in color will make it difficult to determine which temperature the thermocouples are reading as well as creating problems in the color quantification process. The transparency of the material between the sample and the camera is also critical because it is necessary to get a clear picture of the sample so that distortions can be avoided.

The next level of importance involves the cost and calibration time of the system. The cost of any heating concept is important due to the limited budget of the project. The heating system will most likely represent the largest percentage of the cost as most of the process control and image acquisition hardware will come from the available stock. However, money must be leftover for unforeseen expenses in case the available hardware does not perform satisfactorily. The heating and cooling time of the sample is also important as one of the goals of the project is to design a process that can be completed in a timely manner. Finally, the build time must be considered, because the system has to be built within the time constraints of the project. The resulting design matrix is shown in Table 1.

<table>
<thead>
<tr>
<th>Value</th>
<th>Isothermicity</th>
<th>Transparency</th>
<th>Heating/Cooling Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value</th>
<th>8</th>
<th>8</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Heater</td>
<td>Copper</td>
<td>Water</td>
<td>Air</td>
</tr>
<tr>
<td>Microwave</td>
<td>7</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>7</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
The design matrix is evaluated by multiplying each rank in the body of the matrix by its value on the left-hand side. The products for each concept are then summed to get a total, and the highest total is the best concept. Using this method, the copper plate idea is a clear winner, with the air bath a distant second. The copper plate should be easier to setup and build because it will not require a completely enclosed space. The air bath would require some type of cover to enclose the heated air, which would increase setup time and introduce the possibility of image distortions when the picture is taken. The microwave and ultrasound concepts cost more and require more build time due to the steeper learning curve, and the water bath would be too messy during setup and cleanup. Thus, the copper plate will be implemented in the final design.

Concepts for the heater circuit were also developed. Ideally, the heaters and their associated electrical power circuit would be fully automated and controlled by the computer. This way, the circuit could be incorporated into the overall program, and the data collection part of the calibration process would be a one step procedure for the human operator. Once the program was started it would control the necessary processes. Initially it would provide a high voltage across the heaters, allowing the liquid crystal to heat up quickly. At the desired temperature, the voltage would then be reduced to steady state levels, the isothermality of the copper plate could be verified, and the picture could be taken. Unfortunately, due to difficulties in obtaining working control software and equipment, as well as the time constraints of the project, this is probably not possible. A simpler method that incorporates a transistor into the circuit to control the heater could be employed. Using the computer, the heater could be turned on at the start of the program by way of the transistor. Once the liquid crystal had been heated past the temperature being analyzed, the computer could then turn the heater off. The pictures could be taken as the sample cooled and matched to the specified thermocouple temperature.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Price/Availability</th>
<th>8</th>
<th>6</th>
<th>7</th>
<th>3</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Sample Setup Time</td>
<td>8</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Sample Cleanup Time</td>
<td>10</td>
<td>2</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>System Build Time</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>421</td>
<td>250</td>
<td>337</td>
<td>290</td>
<td>275</td>
</tr>
</tbody>
</table>

Table 1 – Heater Concept Design Matrix
This simplified control system would introduce a source of error not seen in the more complex method, as the sample is not at steady state when the pictures are taken. This extra error may not be significant, however. A further simplification would be to make the process completely manual, ruling out the computer entirely. While this type of system would be the easiest to construct, it would most likely not be a significant improvement over the current one in terms of required human time and calibration accuracy. Thus, the simplified automated system will be used.

3.2. Image Acquisition

The implementation of a camera into the design of the system will eliminate the human factor of differentiating between colors. Two camera models were immediately available from Professor Taslim, a digital camera and a film loaded camera. The digital camera was chosen as the mechanism for acquiring images of the liquid crystal being calibrated. It is preferred over the conventional film-loaded camera due to its ability to obtain images instantly and save them as image files. The colors of the image files obtained from the digital camera can then be quantified into their respective red, green, and blue (RGB) components easily using a Matlab program. A web camera was also considered a possibility for acquiring images but the software that came with the digital camera allows the user to view and capture real-time images, making it almost equivalent to web camera in terms of streaming capabilities.

Methods of activating the camera were also evaluated. The user could manually push the button, but the project specifies that the system be automated. One way to automate this procedure would be to mount an actuator inline with the trigger and activate the actuator with the control software. A digital scale was used to determine the amount of force needed to depress the camera trigger. A pencil was mounted vertically on the adjustable camera base, the camera was placed on the scale, and the pencil was lowered until it depressed the camera release. By subtracting the weight of the camera from the scale reading, it was found that a force of 1.77 Newtons would be necessary to depress the camera button. A solenoid was found in the McMaster-Carr catalog that met this force requirement. Push style model 70155K61 cost $13.02 and has a maximum stroke of 0.75” [11]. Another alternative is to wire a relay switch in the camera, which would be actuated by the control software. The last alternative is to find a camera with software that allows pictures to be taken using software. This is the easiest of all the
methods because it requires fewer parts, thus saving money and time. As the digital camera and associated software provided by Professor Taslim already has these capabilities, camera actuation through the camera software will be used in the final design.

3.3. Data Acquisition and Translation

A number of potential solutions to obtain the color of a liquid crystal at a corresponding temperature have been analyzed. The heating rig consisting of a copper plate, Kapton heaters, insulation, and thermocouples has been established. The imaging system consisting of digital camera, stand, and 100-Watt halogen lights has also been defined. The control system that coordinates the two subsystems and automates the process must now be developed. It is crucial that the images obtained correspond with a known temperature.

The simplest method available consists of placing a digital panel meter that is connected to a thermocouple in the view of the camera when taking pictures of the liquid crystal. This method ensures that the temperature recorded corresponds with the color observed. This approach limits the viewing area of the liquid crystal, incorporates only one thermocouple reading, and is dependent upon the operator to take pictures at given temperatures. The manual component is the least desirable part of this system, as it would violate one of design specifications.

The ideal method of obtaining images of the liquid crystal at the same time that the liquid crystal temperature is recorded involves the use of a computer. A number of processing operations could be designated as computer operations. The images and the temperature readings are to be stored in a file accessible by a computer. The quantification of the colors at a specific temperature is performed with software on the computer. The use of a computer to perform as many tasks as possible allows the system to be more automated by eliminating steps required for the transfer of data, which are prone to transposition errors. The cost of a data acquisition system is dependent upon the number of inputs and outputs and the depth of the software capabilities. Five data acquisition systems have been analyzed for use.
3.3.1. **Amazon Electronics PC Data Acquisition Unit**

![Image of Amazon Electronics Data Acquisition Unit](http://electronics123.com/amazon/pictures/cps93_box%20open.jpg)

**Figure 13 – Amazon Electronics Data Acquisition Unit[12]**

Amazon Electronics PC Data Acquisition Unit is an example of an inexpensive data acquisition system. The hardware consists of a small plastic box with eight digital outputs (open collector, 500mA, 33V max.), sixteen digital inputs (0.20V max. Protection 1K in series, 5.1V to ground), eleven analog inputs (0-5V), and one analog output. 0.2.5V or 0-10V. 8 bit (20mV/step). The hardware is connected to the PC by a 25 pin straight through cable. The unit comes with software utilities that can be used in Virtual Basic and Borland C. An example of a program that processes thermocouple inputs is also included. This system is limited to data acquisition and control utilities [12].
3.3.2. Eagle Technologies PC-73C

An example of a basic plug-in-board designed specifically for thermocouple and RTDs is Eagle Technologies PC-73C. The PC-73C offers 8 input channels for thermocouple inputs and 8 digital outputs for control applications. The software included with all Eagle Technologies boards is not defined for use with one specific operating language, but comes with a software developer program. Drivers for Delphi, Borland C, Microsoft C, Pascal, Qbasic, Visual Basic, and Windows are supplied along with example programs in each language. Eagle Technologies claims that type J thermocouple readings with an accuracy of 0.5°C or less (without averaging) have been achieved with the PC-73C [13].

A pre-packaged data acquisition system that contains hardware and adjoining software is preferred over writing software to control hardware. The typical hardware for a pre-packaged data acquisition system consists of a plug-in board or a PCMCIA card. The data acquisition system is required to obtain temperature measurements from thermocouples and to activate the digital camera to acquire images of the liquid crystal at specific temperatures. A number of data acquisition systems are sold as complete hardware and software packages, but are expensive.

3.3.3. Labtech and National Instruments LabVIEW

Labtech is almost exclusively used throughout the Northeastern MIME department for laboratory applications and would be able to fulfill all of the input and output needs for the
calibration system. There are not any available licenses for the permanent incorporation of Labtech into the system. LabVIEW is the ideal data acquisition candidate because it offers a wide variety of functions including an optional image acquisition package. The basic LabVIEW system costs $600 alone and $1200 with the image acquisition board and software. The cost of purchasing LabVIEW or Labtech alone does not conform to the budget for the development of the total liquid crystal calibration system.

3.3.4. HP VEE Data Translation System

The HP VEE Data Translation data acquisition system is available for use by the MIME department. HP VEE is programming language created by Hewlett-Packard, which provides a visual environment for the control and observation of inputs and outputs. Data Translation produces a number of data acquisition systems that are used in conjunction with HP VEE. The two systems have been combined to create a pre-packaged fully developed data acquisition system.

The hardware consists of a DT 7102 PCMCIA card, which connects to a DT 784 terminal Port. Personal Computer Memory Card International Association (PCMCIA) cards are primarily used in conjunction with laptop computers but PCMCIA ports are available for personal desktop computers. The screw terminal port is fitted with a series of clap spring connectors that accept the input and output leads. The analog input section of the system consists of a total of sixteen single-ended or eight double-ended analog inputs with a range of 0-5 Volts and a maximum throughput of 100 kHz. The two analog outputs have 12-bit resolution, a range of +/-5 Volts, and a maximum throughput of 50 kHz. An amplifier is required to be able to take accurate
temperature measurements with thermocouples because they output only a few milli-volts and the resolution of the system without an amplified signal would not be sufficient. Two digital inputs (DIN) and four digital outputs (DOUT) are also included [14].

The software included with the system includes a device driver for the DT 7102 card and DT VPI, which allows the Data Translation hardware to be accessed by HP VEE. HP VEE provides a virtual environment for the programming of the control and processing of inputs and outputs. A relatively simple directory of devices and functions are connected in block diagram format on a pallet to form programs. Each individual channel that is used on the DT 784 terminal port can be configured and controlled separately. The data obtained from each channel can be written to a single file or the system can be configured to allow data acquired from multiple channels to be written to a single file. The ActiveX feature included with HP VEE acts as an automation controller that allows the user to control other Windows applications such as Word, Excel, or Matlab [15].

The Data Translation system has been chosen to control the calibration system due to its availability and vast array of functions that are included. It is the only well defined data acquisition system that can be considered due to the cost and availability of the other pre-packaged systems evaluated.

4. Final Design Description

As described in Section 3, the heater assembly for the final design will consist of the liquid crystal sample fixed to a copper plate, which is heated by electrical resistance heaters. The image acquisition system will consist of the camera, an adjustable stand, and a lighting system. Finally, the control system will consist of a computer, HP VEE data control software and data acquisition system, and a Matlab program to analyze the images. The detailed discussion of the final design is divided up into five sections. First, the overall calibration process is described. Then the heater assembly design, including the electrical power circuit is detailed. Next, the computer controlled data acquisition and processing for the thermocouples and camera is presented. Finally, peripheral design considerations are discussed. The design concept is then proven with three thermal analyses. A complete bill of materials is given in Appendix B.
4.1. Overall Calibration Process

The path that the overall system follows to acquire the appropriate data is listed below in sequential order.

1. The appropriate Ixla Explorer, Matlab, and HP VEE programs are opened in Windows. The lighting system and digital camera are plugged into their respective power outlets and turned on. The maximum temperature and temperatures that the digital camera is to be activated at are manually inputed.

2. 120 V AC from a standard wall outlet is converted to 24V DC by a power converter.

3. 24 V DC flows through a MOSFET transistor to the Kapton heaters, which are placed on the bottom of a 3”x 3” x 0.5” copper plate.

4. The temperature of the copper plate is measured with three thermocouples and processed by a HP VEE program. The measurements from the three thermocouples are averaged to decrease the expected uncertainty of the temperature measurement.

5. At a designated temperature, an alarm in HP VEE is triggered and an output signal is transferred to the MOSFET transistor, cutting off power to the Kapton heaters.

6. The HP VEE program tracks the cooling of the copper plate. At specified temperatures or temperature intervals, the ActiveX feature of HP VEE is used to manipulate the Ixla Explorer software, activating the digital camera and taking a picture of the liquid crystal.

7. The thermocouple data recorded with HP VEE is transferred to Matlab as an array with the ActiveX feature.

8. Matlab grabs the images of the liquid crystal that are stored in files with designated names. The post processing of the data collected during the events described in the automation flow diagram is performed in Matlab. Ixla Explorer saves the images into files with a designated prefix number and a suffix number that corresponds with the order that the pictures are taken.

Prefix number   Suffix number

650001 - image 1 in set 65
A Matlab program recognizes the image files and places the images in a figure. The hue values and corresponding temperature values are processed and displayed in a chart. A graph of the hue value as a function of temperature is also included in Figure 16.
4.2. Heater Design

The final heater design consists of the heater assembly and the electrical circuit that powers the heater. The heater assembly is made up of the liquid crystal sample, the copper plate it is mounted on, the resistance heaters, the insulation used to isolate the liquid crystal from the environment, and the thermocouples used to record the temperature. The electrical circuit links the heaters to their power supply and to the computer control system.

4.2.1. Heater Assembly Design

The copper plate, chosen as the heating medium, will be 3” X 3” X 0.5” and was purchased for $8.91 from Onlinesteel [16]. The copper has a thermal conductivity of 388 W/m²K. The temperature of the copper will be measured using three Omega quick disconnect grounded thermocouple assemblies that are going to be provided by Prof. Taslim. The thermocouples are 12” long, Type J, iron-Constantine with a 304 SS sheath that is 1/16” diameter. Three holes will be drilled in the copper so that the thermocouples can be mounted inside the plate.

Two printed-circuit resistance heaters will be adhered to the copper plate to insure even heat distribution across the total surface area. The heaters are shown below in Figure 17. Each covers an area of 2.48” X 1.24” and has a resistance of 108.2 Ω. The heaters are comprised of five layers. The outside layers are Kapton and have a thermal conductivity of 0.0942 Btu/ hr ft °F. The inner layers are adhesive, which has a thermal conductivity of 0.1272 Btu/ hr ft °F. The middle layer is Inconel and has a thermal conductivity of 9.0152 Btu/ hr ft °F. Kapton laminated circuits are to be used because they are designed to evenly distribute precise levels of heat at specific locations, and they were taken from Professor Taslim’s current supply. The heating element is constructed of etched Inconel foil. Welded lead wire connections are completely embedded within the laminate structure to withstand tensile loads.
The copper plate and liquid crystal sample must be insulated from the surrounding environment to reduce the power required to heat them up and ensure that the heat transfer from the heater assembly is constant. To accomplish this, a 7” X 7” X 4” block of R1/BB Butter-Board polyurethane was purchased from Goldenwest Mfg. Inc. for $25.62 after a 10% student discount. The Butter-Board has a thermal conductivity of 1.9 Btu/hr ft °F, which makes it a good insulator. The heaters, copper plate, and liquid crystal sample will be placed in a machined-out section of the Butter-Board, and holes will be drilled in it for the thermocouple and heater wires. The entire heater assembly is shown in Figure 18, and engineering drawings for copper plate and the insulation block are available in Appendix - C.
4.2.2. Heater Electrical Circuit

The electrical circuit for the heaters is fairly simple, containing only the pair of electrical heaters, a transistor linked to the computer, a 1-ohm resistor to provide for current measurement with an ammeter, and a DC power supply. The major decision that must be made in wiring the circuit is whether the pair of heaters should be wired in series or parallel. A quick calculation shows that, for a given heater power output, \(Q\), the only difference between two setups is the magnitude of the circuit current, \(i\). To get a specified power output from the heaters, the parallel circuit requires twice the current of the series. Because of this, the parallel circuit will be used, so that the current can be easily measured during testing. Diagrams of the series and parallel circuits, in Figure 19 and Figure 20 respectively, show why the current in the parallel circuit is twice that of the series version.
In the figures, the resistance, R, is the same everywhere because the resistance of the heaters is fixed, at 108.20 ohms each. For any electrical circuit, there are two relevant laws relating the power, current, resistance, and voltage, V \[10\].

\[ V = iR \]  \hspace{1cm} (3)

\[ Q = \frac{V^2}{R} \]  \hspace{1cm} (4)

Applying (3) to the series circuit in Figure 19, shows that both \( V_1 \) and \( V_2 \) are equal to \( i_1R \), so \( V_1 = V_2 \). Thus, according to (4), the voltage required to get a desired power output is

\[ V_1 = \sqrt{\frac{QR}{2}} \]  \hspace{1cm} (5)

For the parallel circuit, an equivalent resistance is used to replace the two separate resistances \[10\].
\[ \frac{1}{R_{eq}} = \frac{1}{R} + \frac{1}{R} \]
\[ R_{eq} = \frac{R}{2} \tag{6} \]

The voltage necessary to get a specified power output can then be easily found using (4).

\[ V_3 = \sqrt{\frac{QR}{2}} \tag{7} \]

Because (5) and (7) are equivalent, \( V_1 = V_3 = V \) and a given applied voltage produces the same power output in both circuits. The currents are different though, as shown using (3) for the series circuit in Figure 19, and (3) and (6) for the parallel circuit in Figure 20.

\[ i_1 = \frac{V}{R} \]
\[ i_2 = \frac{2V}{R} \tag{8} \]

Thus, \( i_2 \) is twice as large as \( i_1 \).

Ideally, the current in the heater circuit should be close to 1 A without exceeding it, so that it can be measured with an available multimeter. A thermal analysis in Section 4.5.2 shows that when 24 V is applied across the heater circuit, the liquid crystal will heat up to 35 °C in a reasonably quick 6 minutes. As 24 V corresponds to a current of 0.44 A in the parallel circuit, this circuit provides a more measurable current, and thus is the more desirable setup.

With the parallel heater setup, the final heater electrical circuit design is shown in Figure 21.
Figure 21 – Heater Electrical Circuit Schematic

The design provides a DC power source for the heaters from an AC/DC converter that will plug into a wall outlet. Such a converter, that provides 24 V and 0.5 A, is available in the Allied Signal catalog for $36.00. The two V symbols represent the placement of a multimeter to measure the voltage and current in the circuit. The voltage measurement is straightforward, but the current measurement requires a quick calculation. To determine the current, the voltage across the 1-ohm resistance is measured. The current can then be found using (3). The transistor is a MOSFET type that allows the computer to turn the heater power on and off. Using this circuit, the liquid crystal can be quickly heated to the desired temperature with the only manual input being program initiation.

4.3. Data Acquisition and Processing

The final design for the image acquisition process can be divided into four components. The camera itself is a digital one that allows the images to be easily transferred to the controlling computer and analyzed. The camera setup consists of a mounting stand for the camera and a lighting system for liquid crystal illumination. It allows the camera to be positioned directly over the liquid crystal sample and provides sufficient and correctly oriented illumination to create an accurate image. The camera activation process allows the picture taking to be controlled by the computer, ensuring that pictures are taken at the desired temperatures. Finally, the image processing component converts the pictures into quantitative hue values and correlates those values with the corresponding temperatures.
4.3.1. Camera

Professor Taslim provided a MUSTEK VCD-3500 digital camera with corresponding software for downloading and viewing images. The VDC-3500 is a very basic digital camera with a manual viewfinder and flash. A DC power supply was purchased because the 3-volt lithium batteries that the camera requires are expensive and the camera does not have to be used in an external environment where a 120 VAC outlet is not accessible. The images obtained from the camera can be downloaded to a PC through an RS-232 serial port. An internal 2-MB memory card can hold 8 fine (640 x 480 pixels) or 26 standard (320 x 240 pixel) images.

![Mustek Digital Camera for Image Acquisition](http://v.rd.rVw.mustek.com/images/vdc3500brochure.jpg)

4.3.2. Camera Setup

The positioning of the camera relative to the liquid crystal must be consistent throughout a test series, and the sample must be correctly illuminated at the same time. Incorrect or varying amounts of light will affect the reflected color of the liquid crystal and, as a result, the calibration accuracy. The basis of the camera and lighting setup is a Benchmate Copymate stand that Professor Taslim provided. The Copymate consists of a 20” x 19” x 1” laminate baseboard, a three-foot aluminum column, and a head that slides vertically along the column. A knob on the head allows the operator to finely adjust the height of the camera and lock it in place. The plate that connects the camera to the head slides forward and back to control the horizontal position of the camera and has five ¼-20 fastening screw holes, the industry standard size screw hole on 35 mm cameras and tripods. Thus, the camera can be easily mounted to the plate with a connecting screw. The camera position can then be adjusted both vertically and horizontally as well as...
being locked into place. In this way, the best possible images can be obtained. The lighting assembly is also attached to the movable portion of the stand to provide maximum adjustability.

The illumination is provided by a subassembly that attaches to the stand. The base of the subsystem is a 24” long piece of aluminum angle (1.5” X 1.5’’), costing $5.71, that is bolted to movable head on the stand. The rest of the components are then bolted to the base. The setup is illustrated in Figure 23.

![Figure 23 – Light Assembly Design](image)

The boxes, cover plates, switch, wire, connectors, and lock nuts for the light fixtures cost a total of $10.57. An 8’ power cord leading and flood light, cost $7.50 and $6.97 respectively. The light bulbs themselves are tungsten Sylvania MU1 Superflood BBA, 115-120V, provided by Prof. Taslim. These components are assembled into two light fixtures on either end of the base. The angle of each fixture can be adjusted to a desired angle and then fixed in place using a tightening bolt. The nature of the light fixture allows the supplied light to be adjusted to match the experimental setup and provide the correct angle of illumination. The entire camera setup assembly is shown in Figure 24.
4.3.3. Camera Activation

In accordance with the specifications to automate the system and to capture images at the designated temperatures, the computer will control the picture taking process. Two software packages, the Ixla Digital Camera Suite and Ixla Explorer, were included with the VDC–3500, which is also TWAIN compliant. The Ixla Digital Camera Suite allows for the computer-automated acquisition and editing of images. TWAIN is a standard that allows digital cameras to interact with other computer applications. Thus, the HP VEE control program can be used to access the camera through the Ixla software. The program will have the camera take a picture when the desired temperature is reached and import the image into a specified folder on the computer hard drive. Image processing can then be accomplished quickly and efficiently.
4.3.4. Image Translation and Processing

Quantification of the color that corresponds with a specific temperature is needed to eliminate the human judgement factor that is implemented in the existing calibration process. A Matlab program has been developed to convert the RGB values of a chosen pixel at the center of an image to a single hue value. The program grabs a stored image with a known filename and places it at specific coordinates in a figure. A Matlab function is used to observe a pixel at a known location within the image and separate it into its RGB values. The RGB values are then stored into an array. A number of pixels on a single image can be evaluated and then averaged to determine the mean red, green, and blue component values. The mean RGB value is converted to a hue value by a Matlab calculation. A number of images can be displayed in one figure and the RGB values of any pixel can be displayed by moving a crosshair over an image with the movement of a mouse. The basic calculation described in Section 1.3.2 can then be used to convert the averaged RGB values to a single hue value. The conversion will allow the temperatures to be compared to scalar color values. The Matlab program discussed in this section is available in Appendix D. The Matlab user interface is displayed in Figure 25.
Color Quantification Program

Welcome to the TLC Color Processing and Calibration Program. Please enter the file prefix value and then press run.

File Prefix: 65

---

<table>
<thead>
<tr>
<th>File</th>
<th>Value</th>
<th>Hue Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>65001</td>
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<td>0.6316</td>
</tr>
<tr>
<td>65002</td>
<td>39</td>
<td>0.6152</td>
</tr>
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<td>65003</td>
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<tr>
<td>65004</td>
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<td>0.1139</td>
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<tr>
<td>65008</td>
<td>36</td>
<td>0.0707</td>
</tr>
<tr>
<td>65009</td>
<td>35</td>
<td>0.0543</td>
</tr>
</tbody>
</table>

---

Figure 25 - Matlab User Interface
4.4. System Portability

A lab cart has been selected to conform to the specification that the calibration system be portable. The selected cart is made out of structural polypropylene with a 400 pound capacity. The cart is 36-1/4"(W) x 22-1/4"(L) x 33-3/8"(H), meaning it can fit the 20” wide stand and computer monitor. A flat top shelf, a lower shelf, two rigid casters, and two swivel casters make up the geometry of the assembled seamless polypropylene foam cart. The cart is available in the McMaster-Carr catalog under part number 2602T66 and is shown in Figure 26.

![Lab Cart Picture](http://www.mcmaster.com/)

4.5. Proof of Concept

Three types of thermal analysis are used to prove that the design will meet the requirements and specifications set for it. First, a steady-state analysis verifies that only a miniscule amount of power is needed to keep the liquid crystal at a constant temperature and that temperature gradients across the thickness of the copper plate are insignificant. It also allows simplifying assumptions to be made for the other two transient analyses. The second analysis is a transient heating analysis. This shows the amount of time required to heat the liquid crystal to the desired temperature when a given power level is used. This analysis is necessary to show that reasonably low power levels will still give relatively quick heating times, minimizing the time required for each calibration. Finally, a transient cooling analysis is done to approximate how long each calibration run will take and to show that taking measurements while the sample is cooling is an effective calibration method. All of these analyses are done using a single dimension, neglecting any heat flow through the sides of the heater assembly and assuming isothermal conditions across each of the components. The one-dimensional approach is not the
most accurate, but it is all that is necessary for this design. Once the calibration system is constructed, physical tests can be easily run, to determine the exact times and heat loads required for each stage in the process. These calculations are only necessary to bracket the appropriate values.

4.5.1. Steady State Analysis

A thermal circuit is used to set up the steady state analysis. The circuit is a series type and is made up of all the layers in the heater assembly. Figure 27 describes each of the layers that contribute to the overall thermal resistance. In the figure, \( t \) is the layer thickness. Only the liquid crystal itself is not included because its thermal conductivity is not known, and would be rather difficult to determine. As will be shown for the glue, Kapton, and Inconel layers, however, it can most likely be neglected based on its very small thickness, even if it did have a low thermal conductivity.

For the thermal model, each component is described as a one-dimensional plane wall to simplify the analysis. Doing this neglects any heat transfer from the sides of the assembly, but because this is only intended to be an approximation, the results should be good enough. The area, \( A \), of each plane wall section is taken to be the surface area of the copper plate, 9 in\(^2\).

![Figure 27 - Thermal Model Schematic](image)

Figure 27 can then be translated into the thermal circuit shown in Figure 28 by replacing each plane wall with an equivalent thermal resistance. The convective thermal resistances at the top
and bottom of the assembly and the heat flow into the Inconel are also added to complete the circuit.

\[ R_{sb} T_{sb} T_{4b} J_{b} \]

Figure 28 – Steady State Thermal Circuit

The subscript, \( b \), denotes the lower side of the heater assembly, below the Inconel heater element, while the subscript, \( a \), is given to the layers above the heater element. The R-values are the resistances of each layer and the T values are the temperature values at the edge of each layer. \( T_{4a} \) is the temperature at the top surface of the copper plate and corresponds to the temperature of the liquid crystal. This temperature is the focus of the analysis and will be calculated for a series of heat flows. For the calculations, \( T_{o} \), the ambient temperature is assumed to be 20 °C.

For a given heat flow, \( Q_{a} \), the temperature, \( T_{start} \), can be determined using [11]

\[
T_{start} = T_{o} + Q_{a} R_{a} \\
R_{a} = \sum_{i=1}^{5} R_{i\alpha}
\]  \hspace{1cm} (9)

The temperature at the top surface of the liquid crystal, \( T_{4a} \), can then be calculated using the same method.

\[
T_{4a} = T_{start} - Q_{a} (R_{1\alpha} + R_{2\alpha} + R_{3\alpha} + R_{4\alpha})
\]  \hspace{1cm} (10)

Finally, the bottom-side heat flow, \( Q_{b} \), and thus the total heat flow can be found using the calculated value of \( T_{start} \).
The total heat flow, $Q$, is the sum of $Q_a$ and $Q_b$.

Before (9), (10), and (11) can be used, each of the individual resistances must be calculated though. For the conductive resistances, the calculation is straightforward, but the convective resistances depend on the temperature at the top and bottom surfaces of the heater assembly. Since these surface temperatures can only be found using variations on (3), which involves the convective resistances, a double iteration is necessary to get the correct values of the two heat transfer coefficients, the calculated temperatures, and the calculated heat flows.

For the first iteration, each of the conductive resistances, $R_{1b} - R_{5b}$ and $R_{1a} - R_{4a}$, is calculated using the general form

$$R = \frac{t}{kA}$$

(12)

where $k$ is the thermal conductivity of the material [11]. The thermal conductivity for each material in the heater assembly is listed in Table 2 for reference.

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Glue</th>
<th>Kapton</th>
<th>Inconel</th>
<th>Butterboard</th>
<th>Wood Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$ (W/m*K)</td>
<td>388</td>
<td>0.220</td>
<td>0.0942</td>
<td>9.02</td>
<td>3.29</td>
<td>0.170</td>
</tr>
</tbody>
</table>

Table 2 – Thermal Conductivities of Heater Assembly Materials

Next, the temperature at the upper surface of the assembly, $T_{4a}$, is given an assumed value that is used to calculate an initial heat transfer coefficient for that surface, $h_a$. As there is no air movement around the heater assembly, the heat is dissipated through free convection, so the Nusselt number depends on the Raleigh number, $Ra$ [11].

$$Ra_a = \frac{gT_{\alpha(obs)}^{\frac{1}{3}}(T_{4a} - T_o)L^4}{\nu \alpha}$$

(13)

The variable, $g$ is the gravitational constant and is taken as 9.81 m²/s, $L$ is the length of the surface, 0.0762 m, $\nu$ is the kinematic viscosity, which is $15.89E-6$ m²/s for air at 300 K, and $\alpha$ is
22.6E-6 m²/s for air at 300 K. The relationship of the heat transfer coefficient to the Raleigh number for the top surface of a heated plate is then used to calculate $h_a$ [17].

$$h_a = \frac{k_a}{L} \left[ 0.5R_{aa}^{0.25} \right] 10^4 \leq R_{aa} \leq 10^7$$

$$h_a = \frac{k_a}{L} \left[ 0.15R_{aa}^{0.25} \right] 10^7 \leq R_{aa} \leq 10^{11}$$

The variable, $k_a$, is the thermal conductivity of air at 300 K, 0.0263 W/m*K. The convective resistance, $R_{5a}$, is then of general form [11]

$$R = \frac{1}{hA}$$

The initial value from (15) is used to calculate an initial $T_{start}$ and $T_{4a}$ using the given heat flow, $Q_a$, along with (9) and (10). The difference between the new value of $T_{4a}$ and the initial value is compared to a tolerance, which is set at 0.0005°C. The new value of $T_{4a}$ is substituted for the old if the difference in temperatures is greater than the tolerance. The iteration is then repeated until the difference between the new and old temperatures is within the tolerance value.

With the first iteration complete, the temperature of the heater element, $T_{start}$, is known and can be used to calculate the heat flow through the bottom of the heater assembly, $Q_b$. However, since the convective resistance on the bottom of the heater assembly depends on the temperature of the bottom surface, a second iteration is needed here. To perform this iteration, an initial $Q_b$ is calculated using (11) with the initial convective resistance, $R_{6b}$, set equal to the convective resistance on the top of the assembly, $R_{5a}$. With $Q_b$, an initial bottom surface temperature, $T_{5b}$, is then calculated using

$$T_{5b} = T_{start} - Q_b (R_{1b} + R_{2b} + R_{3b} + R_{4b} + R_{5b})$$

With the initial value of $T_{5b}$, the new value of $h_b$ can be determined using the associated Raleigh number, $Ra_b$. $Ra_b$ is calculated in the same manner as $Ra_a$, using (13), except $T_{4a}$ is replaced with $T_{5b}$. The relationship between the heat transfer coefficient, $h_b$, and the Raleigh number is different than (14), though, because the bottom surface of a heated plate is used in this case. Because the heated surface is on the bottom of the assembly, it interferes with the upward flow of the warmer air, making the convection less efficient and lowering the value of $h_b$. For the bottom surface of a heated plate, $h_b$ is [11].
Using $h_b$, the convective resistance, $R_{6b}$, can be calculated with (15) and new values for $Q_b$ and $T_{5b}$ can then be calculated using (11) and (16). As in the first iteration, the difference between the new and old values of $T_{5b}$ are compared to a tolerance value of 0.0005 °C. If the difference is greater than the tolerance, the new temperature value is substituted for the old and the iteration is repeated as many times as necessary. The Matlab program written to implement these iterations is available in Appendix – E.

Once the calculations are completed, three comparisons are made. First, the voltage required to maintain a specific liquid crystal temperature is plotted. The voltage is directly related to the total heat flow calculated above as shown in Section 0, and it should be miniscule because a much higher voltage will be needed to heat the sample up in a reasonable amount of time. The heat flow out the bottom of the heater assembly, $Q_b$, is also compared to the heat flow out the top, $Q_a$. This comparison shows that $Q_b$ is much smaller than $Q_a$. As a result, it can be neglected in the two following transient analyses, simplifying them somewhat. Finally, the temperature gradient across the copper plate is examined to ensure that it is negligible. The high conductivity of the copper makes the possibility of a significant gradient rather slim, but any difference between the top and bottom temperatures will mean that the thermocouples and liquid crystal in the heater assembly will not be recording the same values.

A plot of the applied voltage against the temperature of the liquid crystal is shown in Figure 29. The total heat flow, $Q$, is converted to a voltage using the method described in Section 4.2.2.
As Figure 29 shows, only about 4.8 V are needed to keep the sample at a temperature of 35 °C. This small magnitude of required voltage is an encouraging sign because it suggests that the voltage required to heat the liquid crystal quickly will be reasonable in size. Thus, the design looks good in this regard.

Next, the magnitude of $Q_a$ can be compared to $Q_b$. As the critical performance range of the design is in the vicinity of 35 °C, the comparison is made there. Table 3 shows the value of $Q_a$ and $Q_b$ for a series of temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$Q_a$ (W)</th>
<th>$Q_b$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.06</td>
<td>0.389</td>
<td>0.012</td>
</tr>
<tr>
<td>34.56</td>
<td>0.406</td>
<td>0.013</td>
</tr>
<tr>
<td>35.06</td>
<td>0.424</td>
<td>0.013</td>
</tr>
<tr>
<td>35.55</td>
<td>0.441</td>
<td>0.013</td>
</tr>
<tr>
<td>36.04</td>
<td>0.459</td>
<td>0.014</td>
</tr>
<tr>
<td>36.52</td>
<td>0.476</td>
<td>0.014</td>
</tr>
<tr>
<td>37.02</td>
<td>0.494</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 3 – Comparison of Upper and Lower Steady State Heat Flows
Q_a is more than thirty times greater than Q_b in the vicinity of 35 °C, meaning the heat flow through the bottom of the heater assembly can most likely be neglected from the transient heating analysis without any noticeable effects. Removing the extra heat flow and half the thermal resistances greatly simplifies those processes.

Finally, the temperature gradient throughout the top half of the heater assembly can be examined.

<table>
<thead>
<tr>
<th>T_{start} (°C) (Heater Element)</th>
<th>T_{3a} (°C) (Bottom of Copper Plate)</th>
<th>T_{4a} (°C) (Top of Copper Plate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.09</td>
<td>34.06</td>
<td>34.06</td>
</tr>
<tr>
<td>34.59</td>
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<td>36.52</td>
</tr>
<tr>
<td>37.04</td>
<td>37.02</td>
<td>37.00</td>
</tr>
</tbody>
</table>

Table 4 – Steady State Temperature Gradients

Table 4 shows not only the temperature gradient across the copper plate, but also the gradient between the Inconel heater and the top surface of the copper to be insignificant, at least for the purposes of these calculations. The temperature difference between the two sides of the copper plate is less than one one-hundredth of a degree Celsius at 35 °C and only grows to 0.02 °C at about 37 °C. As our accuracy goal is an error of less than 0.28 °C, there is no cause for concern here. Also the difference of only 0.04 °C between the Inconel and top of the copper plate means the glue and Kapton thermal resistances can be eliminated from the transient analyses without a significant loss in accuracy.

4.5.2. Transient Heating Analysis

The transient heating analysis is based on a simplified version of the thermal circuit used for the steady state analysis. Because Table 3 shows Q_b to be significantly smaller than Q_a, the b side of the steady state circuit is neglected, meaning the heat flow through that side is assumed to
be zero. Also, because the resistances of the glue and Kapton layers between the heater element and the copper plate are negligible and the resulting temperature difference between $T_{\text{start}}$ and $T_{4a}$ is almost non-existent, these layers are also neglected in the circuit. The resistances for the two glue layers and the Kapton layer between the Inconel heater element and the copper plate are all less than 0.054 K/W while the convective resistance between the copper plate is about 30 K/W, depending on the temperature of the copper surface. The elimination of these resistances is also a necessary assumption as the density and specific heat data for the glue and Kapton layers are not available. Thus, the applied heat flow is assumed to enter directly into the copper plate for the purposes of calculation. The resulting circuit is shown in Figure 30.

![Figure 30 – Transient Heating Thermal Circuit]

Using the thermal circuit, a lumped capacitance analysis can be developed for the copper plate. The equation relating the temperature of the copper plate to the elapsed time for a given heat flux can be formed by starting with an energy balance on the copper plate.

$$Q_a - \frac{\theta_1}{R_{5a}} = \rho V_0 c \frac{d\theta_1}{dt}$$

$$\theta_1 = T_{\text{start}} - T_a$$

The variable, $\rho$ is the density of the copper plate, 8933 kg/m$^3$, $V_0$ is the volume of the copper plate, 7.37E-5 m$^3$, and $c$ is the specific heat of copper, 385 J/kg*K. (10) is a first order, non-separable differential equation, meaning it is of the form [18]

$$\frac{d\theta_1}{dt} + \alpha \theta = b(t)$$

$$\alpha = \left[\rho V_0 c R_{5a}\right]^{-1}$$

$$b(t) = \frac{Q_a}{\rho V_0 c}$$

(19)

For these types of equations, the solution is of the form [18]
\[ \theta_1 = \frac{\int_a^t a(t)b(t)\,dt}{a(t)} \]  
\[ a(t) = \exp\left[ \int_a^t \alpha \,dt \right] \]  

This can be converted back to the known parameters,

\[ T_{\text{start}} = T_o + Q_{a} R_{sa} \left[ 1 - \frac{1}{\exp\left( \frac{t}{R_{sa} \rho V_{o} c} \right)} \right] \]

and the results can then be plotted for given values of $Q_a$. This plot is displayed in Figure 31.

**Figure 31 – Liquid Crystal Heating Time for a Variety of Voltages**
The results of the transient heating calculations show that the liquid crystal can be heated from an ambient temperature of 20 °C to 35 °C in as little as 6 minutes when 24 V is applied to the heating circuit. The quick heating time at a relatively low voltage means that the heater assembly design falls well within the time efficiency requirements set for it.

4.5.3. Transient Cooling Analysis

The goal of the transient cooling analysis is to show that the heater assembly design allows the liquid crystal to cool at an appropriate rate in the absence of heating. An appropriate rate will not allow any time delay between sensing the desired temperature and snapping a picture to decrease the accuracy of the results. It will also be quick enough that the entire process will not take an exorbitant amount of time. For the analysis, the lumped capacitance method is used with the full thermal circuit, described in Figure 27. The full circuit is used because the extra resistances are relatively easy to add without changing the overall form of the solution, and their use provides increased accuracy. There are two minor changes to the circuit that are necessary, though. Because the lumped capacitance method assumes the object of interest is isothermal, the copper plate resistance, $R_{4a}$, is removed from the circuit and the conductive resistance, $R_0$, for the Inconel heater is added as it is now impeding heat flow rather than supplying it.

The solution to the cooling analysis comes from an energy balance on the copper plate, just as in the heating analysis [3].

$$-\frac{\theta}{R_{4a}} - \frac{\theta}{R_0 + R_{1a} + R_{2a} + R_{3a} + R_0} = \rho V_o c \frac{d\theta}{dt}$$

Unlike the heating balance, this first order differential equation is separable and yields

$$T_{4a} = T_o + \theta, \text{EXP} \left[ \frac{t}{\rho V_o c R_{tot}} \right]$$

$$\theta_t = T_{4a, initial} - T_o$$

$$R_{tot} = \frac{R_{4a} (R_0 + R_{1a} + R_{2a} + R_{3a} + R_0)}{R_0 + R_{1a} + R_{2a} + R_{3a} + R_{5a} + R_0}$$

With (23), the temperature of the copper after a given amount of time has elapsed can be plotted. The plot is shown as Figure 32.
The results of the transient cooling calculations show that the liquid crystal will cool from an initial post-heating temperature of 40 °C to 35 °C in about 32 minutes. Depending on the precision and accuracy of the heating cut-off system, the 5 °C difference between the initial post-heating temperature and the desired measurement temperature is probably on the high side. Heating the liquid crystal only 1 or 2 °C above the measurement range would speed the process up somewhat. Even so, 32 minutes is an adequately short amount of time for the cooling process, as the operator does not have to be present during this time.

Also, for the cooling curve that starts at 40 °C, the sample is cooling at approximately 0.0023 °C/s. The numerical value of the cooling rate is significant, because there will be some delay between the time the thermocouples record the temperature and the time the camera snaps a picture. The small magnitude of the cooling rate means that even if the delay is 30 s long, the difference between the temperature read by the thermocouple and that recorded by the camera will only be 0.07 °C, which is well within our experimental error goal. Thus, the design seems to meet the requirements in this respect as well.
5. Conclusions and Future Work

The final concept and analysis is complete. The system will be placed on a lab cart. The apparatus consists of an adjustable camera mount onto which the lighting will be attached. The insulation will be made of polyurethane. A copper plate is heated with Kapton heaters attached to the bottom of the copper plate. The liquid crystal will be adhered to the copper plate. The temperature will be measured by three thermocouples imbedded in the copper plate near the surface. The Data Translation system will read the thermocouple inputs. A program will be written using HP VEE to output a signal that will cut power to the Kapton heaters via a transistor, when the temperature reaches 40°C. With the heaters off, the copper plate and liquid crystal sample will slowly cool, thus allowing for pictures to be taken at the temperatures specified in the HP VEE program. These pictures will then be examined using Matlab to quantify the liquid crystal color into RGB values. Hue values will be calculated from the RGB values. Using these hue values and the corresponding temperatures, a calibration table will be constructed.

The project is on schedule. The project Gantt Chart is available in Appendix - F. Financially, the total cost is a little under half of the specified budget of $500, due to the fact that Northeastern and Prof. Taslim provided many components. All parts have been purchased, however some additional electrical parts may be needed. These parts would include transistors, which are inexpensive relative to the budget. The final design is complete and no problems are predicted for the future. The entire apparatus can be assembled after the polyurethane and copper plate are machined.

After assembly, testing and debugging of the HP VEE control program and the color quantifying Matlab program can begin. The thermocouple and overall system accuracy will need to be determined. The time of the calibration process will be measured.

6. References


Appendices

Appendix – A

Patents

Calibration System

United States Patent 5,953,449
Matsuda, et al. September 14, 1999
Measuring apparatus and measuring method

Abstract

The disclosed measuring apparatus can measure a predetermined physical quantity (e.g., temperature) of a coloring member (e.g., liquid crystal) whose color condition changes according to change of the physical quantity. The measuring apparatus comprises: a coloring member (2) whose color condition changes according to change of a predetermined physical quantity; a color detecting section (5) for detecting the color condition of the coloring member; a data base section (8) for constructing a three-dimensional color space (10) having three coordinate axes each corresponding to each of tristimulus values of color of the coloring member, relationship between the predetermined physical quantity and the tristimulus values being represented in the three-dimensional color space; and a physical quantity calculating section (9) for calculating the physical quantity of an object (1) to be measured on the basis of the tristimulus values of color of the coloring member detected by the color detecting section (5) and with reference to the data base section (8).

Inventors: Matsuda; Hisashi (Yokohama, JP); Watanabe; Takeshi (Naka-gun, JP); Otomo; Fumio (Zama, JP)
Assignee: Kabushiki Kaisha Toshiba (Kawasaki, JP)
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Intern'l Class: G06K 009/00
Field of Search: 382/162,167
References Cited [Referenced By]

U.S. Foreign Patent Documents 61-044307
Mar., 1986
JP. 63-290903 Nov., 1988 JP.

Other References

Primary Examiner: Tran; Phuoc
Attorney, Agent or Firm: Foley & Lardner

Claims

1. A measuring apparatus, comprising: a coloring member whose color condition changes according to change of a predetermined physical quantity; color detecting means for detecting the color condition of said coloring member; a data base section for constructing a three-dimensional color space having three coordinate axes corresponding to each of tristimulus values of color of said coloring member, a relationship between the predetermined physical quantity and the tristimulus values being represented in the three-dimensional color space as a single valued function; and physical quantity calculating means for calculating the physical quantity of an object to
be measured on the basis of the tristimulus values of color of said coloring member detected by said color detecting
means and with reference to said relationship in said data base section.

2. The measuring apparatus of claim 1, wherein said color detecting means comprises: a color sensor for
detecting the color condition of said coloring member; and calculating means for calculating the tristimulus values
on the basis of the color condition detected by said color sensor.

3. The measuring apparatus of claim 2, wherein: said color sensor is an image sensor for detecting the color
condition at each spacial position of said coloring member; and said calculating means is image processing and
calculating means for calculating the tristimulus values at each spacial position on the basis of the color condition at
each spacial position detected by said color image sensor.

4. The measuring apparatus of claim 3, wherein: said color image sensor detects the color condition at each
spacial position at a plurality of pixels; and said calculating means calculates the tristimulus values at each spacial
position by processing the color condition data detected at the pixels statistically.

5. The measuring apparatus of claim 2, wherein: said color sensor is a color point sensor for detecting the
color condition at each spacial position of said coloring member; and said calculating means is image processing and
calculating means for calculating the tristimulus values at each spacial position on the basis of the color condition at
each spacial position detected by said color point sensor.

6. The measuring apparatus of claim 1, wherein said data base section has a calibration line obtained by
representing the relationship between the predetermined physical quantity and the tristimulus values in the three-
dimensional color space.

7. The measuring apparatus of claim 6, wherein the predetermined physical quantity is obtained on the
calibration line represented in the three-dimensional space as a one-valued function.

8. The measuring apparatus of claim 6, wherein the calibration line is a continuous line obtained by
interpolating relationship between a plurality of the discrete physical quantities and a plurality of the discrete
tristimulus values each corresponding to each of the discrete physical quantities.

9. The measuring apparatus of claim 6, wherein said data base section has an allowable error range pipe
extending along the calibration line so as to enclose the calibration line in the three-dimensional color space.

10. The measuring apparatus of claim 6, wherein said physical quantity calculating means has calibration
on-line discriminating means for discriminating whether the tristimulus values of the detected color of said coloring
member lie on the calibration line or not.

11. The measuring apparatus of claim 9, wherein said physical quantity calculating means has allowable
error range in-pipe discriminating means for discriminating whether the tristimulus values of the detected color of
said coloring member lie in the allowable error range pipe or not.

12. The measuring apparatus of claim 1, wherein the predetermined physical quantity is temperature.

13. The measuring apparatus of claim 1, wherein said coloring member is a thermo-sensible liquid crystal
member.

14. The measuring apparatus of claim 13, wherein said thermo-sensible member is sprayed onto a surface
of an object to be measured.

15. The measuring apparatus of claim 13, wherein said thermo-sensible member is a sheet shaped liquid
crystal member which is attached onto a surface of an object to be measured.

16. The measuring apparatus of claim 13, wherein said thermo-sensible member is mixed turbidly into an
object to be measured.

17. The measuring apparatus of claim 1, wherein said coloring member is a gap formed between a first
member and a second member so as to produce an interference pattern when irradiated by light.

18. The measuring apparatus of claim 17, wherein the first member is a head surface of a disk apparatus,
and the second member is a disk surface.

19. The measuring apparatus of claim 18, wherein the first member is a semiconductor wafer whose
flatness is to be measured, and the second member is a reference flatness body.

20. The measuring apparatus of claim 1, wherein the predetermined physical quantity is a gap width formed
between the first member and the second member so as to produce an interference pattern when irradiated by light.

21. The measuring apparatus of claim 1, wherein the tristimulus values are RGB values.

22. The measuring apparatus of claim 1, wherein the tristimulus values are L*a*b* values.

23. A measuring method, comprising the steps of: constructing a three-dimensional color space having
three coordinate axes by allowing each value of tristimulus values of color to correspond to each of the coordinate
axes; changing a predetermined physical quantity for a coloring member whose color condition changes according
to change of the physical quantity; detecting the color condition of the coloring member to obtain the tristimulus
values thereof according to various physical quantities; constructing a data base section by representing a
relationship between the various physical quantities and the tristimulus values in the three-dimensional color space as a single valued function; detecting the tristimulus values of the coloring member included in an object to be measured; and calculating the physical quantity of the object to be measured with reference to the relationship in the data base section.

Description

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a measuring apparatus and a measuring method of detecting color condition of a coloring member (e.g., a thermo-sensible liquid crystal) whose color condition changes according to change of physical quantity (e.g., temperature), and for calculating the physical quantity thereof on the basis of tristimulus values of the color of the coloring member.

Description of the Prior Art

A prior art temperature measuring apparatus related to the present invention will be described hereinbelow by taking an example of thermo-sensible liquid crystal which is widely used as a coloring member whose color condition changes according to change of the physical quantity thereof.

When various products are searched or designed, there are many cases where it is required to know a wide temperature distribution on or over the surface of an object. In these cases, in general, it is necessary to arrange a number of thermometers (e.g., thermo couples) for measuring the temperature distribution on or over the surface of the object to be measured. In this method, however, when the thermometers are arranged in contact with the object to be measured, the object to be measured is subjected to unnecessary disturbance. Therefore, when there exists an airflow in the vicinity of the surface of the object, there arises a problem in that the temperature field of the measured object is distorted due to the disturbance caused by the thermometers themselves. In addition, there exists such a difficulty that the measurement points must be previously specified on the surface of the measured object. Further, as a matter of course, there exists a limit of the number of the measurement points, because data obtained at the measurement points must be all processed.

On the other hand, there exists a non-contact surface measurement method, for instance such as radiation thermometer or infrared thermo-camera. In this method, the temperature distribution can be measured in a relatively wide range. In this non-contact method, however, the cost of the instrument is as high as several millions yen or higher.

Due to the above-mentioned background, as a relatively low-costly method of measuring a temperature field extending in two- or three-dimensions on the surface of an object to be measured, a method of using a liquid crystal (thermo-sensible liquid crystal) having such a feature that the color changes according to temperature thereof has been widely developed. In this method, the measured color data are detected by a CCD camera and then inputted to a computer for image processing. In the method of using a thermo-sensible liquid crystal, wide temperature data can be obtained on the basis of the correspondence between the color and the temperature obtained by quantitatively processing the color change of the liquid crystal. In this method, however, since the relationship between the color data (e.g., RGB values) and the temperature is represented by an extremely complicated non-linear function in general as shown in FIG. 7, various methods of deciding the color and the temperature unequivocally and quantitatively have been so far proposed.

For instance, Kasagi, et al., have succeeded in obtaining an isothermal line on a measured surface by irradiating the liquid crystal surface with a monochromatic light source and by clearly visualizing only the temperature range corresponding to a wavelength (Kasagi, Hirata, Kumata; JSME International Journal Series B, Vol. 48 No. 430 (1982)).

Further, Kunugi, et al. have developed the Kasagi's method by use of white light having a uniform spectrum as the light source and by use of a plurality of optical filters each having an extremely narrow transmission wavelength range, to decide each isothermal line which corresponds to each transmission wavelength in sequence, so that a plurality of isothermal lines can be obtained in sequence by a single experiment (Kunugi, Ueda, Akino; JSME International Journal Series B, Vol. 53 No. 485 (1987)).

Further, recently, Kimura et al. have reported a method of obtaining the correspondence between temperature and color by allowing a neural network to learn the RGB values of the color image data changing according to temperature (Kimura, Uchide, Ozawa; Proceeding of Japan Visualization Association Vol. 12, Suppl. No. 1, pp. 7-10 (1992)).

Further, Farina, et al. have proposed such a method of obtaining the correspondence between color and temperature by obtaining HSI values (Hue, Saturation, and Intensity) of the color image data changing according to
temperature and by noting the Hue values having a wide one-valued function range with respect to temperature (Farina, Hacker, Moffat. Eaton; Exp. Thermal Fluid, Sci. 9,1-12. (1994)).

In the Kasagi et al. method, however, it is necessary to set the heat transfer surface to various temperature levels in order to obtain a plurality of isothermal lines. Further, in the Kunugi et al. method that improves the Kasagi et al. method, although a plurality of isothermal ranges can be decided by only a single experiment, since a number of filters are necessary, there exists a problem in that the measurement work is rather complicated.

Further, in the Kimura et al. method, although the subsidiary devices such as filters can be eliminated, since a plurality of learning patterns must be determined and further a great number of learning operations must be repeated, there arises another problem in that a relatively long time is needed in the pre-processing.

Further, in the Farina et al. method, although the corresponding range between color and temperature can be tended on the basis of the newly-defined Hue values, the range where temperatures and Hue values can be represented on the basis of a one-valued function cannot be extended all over the coloring area, so that this method is not a method of measuring the temperature of the liquid crystal all over the coloring area of the liquid crystal, with the result that the measured temperature range is inevitably narrowed.

As described above, in the temperature measuring methods using the thermo-sensible liquid crystal so far proposed, there have been various problems in that complicated processing is necessary to obtain the correspondence between color data and temperature and in addition the colored area of the thermo-sensible liquid crystal is not sufficiently utilized.

In addition, in the prior art magnetic disk apparatus, there exists the following problem when a gap width between an magnetic head and a magnetic disk is measured:

Prior to the description of this problem, a flying head slider used for the magnetic disk apparatus will be explained hereinbelow, as an example of the prior art measuring apparatus used for the magnetic disk apparatus.

In the case of a magnetic disk apparatus used as an external memory apparatus of a computer, it is necessary to fly the magnetic head from the magnetic disk by a micro height in data recording and reading operation. With the advance of the high density of the magnetic disk apparatus, recently, this flying height has become as small as 0.1μm or less.

Here, since the change of the flying height of the magnetic head is directly related to a recording characteristic of the apparatus, it is important to check whether the magnetic head can be kept-flown by a micro distance away from the magnetic disk during the development or researching of the recording apparatus as described above.

As the method of measuring the micro gap such as the flying height of the magnetic head from the magnetic disk, a method has been so far proposed, by which light of a known wavelength is irradiated upon a measured surface to obtain an interference fringe (or pattern) formed on the measured surface. In this method, however, there exists a problem in that the gap can be measured only when the gap corresponds to integer times of 1/4 wavelength of the incident light.

To overcome this problem, Tanaka and Sugawara have proposed the following method, as disclosed in Japanese Published Unexamined (Kokai) Patent Application No. 61-44307. In this method, a gap between the magnetic head and the magnetic disk can be measured on the basis of an interference fringe as follows: the interference fringe can be obtained by irradiating white light onto the measured surface (e.g., the magnetic disk) through an optical head; the interference colors produced by the measured surface are photographed with the use of a TV camera; the hue components composed of R, G and B signals generated by the TV camera are obtained; and the obtained hue component values are compared with the reference values on the basis of the previously determined relationship between the gap and the hue component values by executing various calculations (as shown in FIG. 13).

Further, Kubo has proposed the following method, as disclosed in Japanese Published Unexamined (Kokai) Patent Application No. 63-290903. In this method, in the same way as above, the flying height of the magnetic head from the magnetic disk can be obtained, by irradiating light upon the measured surface, by photographing interference colors by a TV camera, by obtaining hue components on the basis of R, G and B signals obtained by the TV camera, and by comparing the obtained hue components with the reference hue components on the basis of the previously obtained relationship between the hue components and the gap.

Both the above-mentioned methods are different from each other only in the used transform formulae for obtaining hue values on the basis of R, G and B signals. In both the methods, the micro gap can be measured continuously. In these methods, however, when the hue values are obtained on the basis of the R, G and B signals, since the complicated discriminants are required according to the mutual relation between R, G and B signals, there still exists a problem in that complicated signal processing must be executed.

SUMMARY OF THE INVENTION
With these problems in mind, therefore, it is the object of the present invention to provide a measuring apparatus and measuring method, which can easily measure the physical quantity of a coloring member whose color condition changes according to change of a predetermined physical quantity, extending all over the coloring area thereof.

The present invention has been achieved to overcome the afore-mentioned various problems on the basis of the following considerations: Here, the gist of the invention will be described hereinbelow by taking the case where the coloring member is a liquid crystal, and the physical quantity is temperature.

When the relationship between color data and temperature is seen from the two-dimensional standpoint, in both the case where the RGB values are adopted and arranged as the color tristimulus values (as shown in FIG. 7) or the case where the L*a*b* values are adopted and arranged as the color tristimulus values (as shown in FIG. 8), the relationship between temperature and R, G and B values or L*, a*, b* values is usually represented as a multi-valued function, so that the correspondence between the temperature and the tristimulus values is very complicated.

To overcome this problem, although Farina et al. have proposed such a method of defining Hue values in order to represent the relationship between the color characteristics and the Hue values by use of a one-valued function, the range in which the relationship between the temperature and the Hue values can be represented as a one-valued function is limited to a small coloring area of the liquid crystal, with the result that the measurable temperature range is inevitably narrowed.

In contrast with this, the Inventors have found the following facts: when the data of color tristimulus values are arranged in three-dimensional space, the color data of the liquid crystal can be arranged continuously and further smoothly all over the coloring area of the liquid crystal according to change of the temperature. On the basis of the above-mentioned discovery, the Inventors have noticed that it is possible to allow the color tristimulus values to correspond to a physical quantity (e.g., temperature) on the basis of a one-valued function in a three-dimensional color space, while extending all over the coloring area of the liquid crystal.

Further, in the above-mentioned description, although the temperature is taken as an example of the physical quantity and further the liquid crystal is taken as an example of the coloring member. The gist of the present invention can be applied to many other cases, for instance as when the physical quantity is a gap width or a flying height between a first member (e.g., a magnetic head) and a second member (e.g., a magnetic disk) and the coloring member is an interference fringe formed when the above-mentioned gap is irradiated with light.

To achieve the above-mentioned object, the present invention provides a measuring apparatus, comprising: a coloring member whose color condition changes according to change of a predetermined physical quantity; color detecting means for detecting the color condition of said coloring member; a data base section for constructing a three-dimensional color space having three coordinate axes each corresponding to each of tristimulus values of color of said coloring member, relationship between the predetermined physical quantity and the tristimulus values being represented in the three-dimensional color space; and physical quantity calculating means for calculating the physical quantity of an object to be measure on the basis of the tristimulus values of color of said coloring member detected by said color detecting means and with reference to said data base section.

Further, it is preferable that said color detecting means comprises: a color sensor for detecting the color condition of said coloring member; and calculating means for calculating the tristimulus values on the basis of the color condition detected by said color sensor.

Further, it is preferable that said color sensor is an image sensor for detecting the color condition at each spacial position of said coloring member; and said calculating means is image processing and calculating means for calculating the tristimulus values at each spacial position on the basis of the color condition at each spacial position detected by said color image sensor.

Further, it is preferable that said color image sensor detects the color condition at each spacial position at a plurality of pixels; and said calculating means calculates the tristimulus values at each spacial position by processing the color condition data detected at the pixels statistically.

Further, it is preferable that said color sensor is a color point sensor for detecting the color condition at each spacial position of said coloring member; and said calculating means is image processing and calculating means for calculating the tristimulus values at each spacial position on the basis of the color condition at each spacial position detected by said color point sensor.

Further, it is preferable that said data base section has a calibration line obtained by representing the relationship between the predetermined physical quantity and the tristimulus values in the three-dimensional color space.

Further, it is preferable that the predetermined physical quantity is obtained on the calibration line represented in the three-dimensional space as a one-valued function.
Further, it is preferable that the calibration line is a continuous line obtained by interpolating relationship between a plurality of the discrete physical quantities and a plurality of the discrete tristimulus values each corresponding to each of the discrete physical quantities.

Further, it is preferable that said data base section has an allowable error range pipe extending along the calibration line so as to enclose the calibration line in the three-dimensional color space.

Further, it is preferable that said physical quantity calculating means has calibration on-line discriminating means for discriminating whether the tristimulus values of the detected color of said coloring member lie on the calibration line or not.

Further, it is preferable that said physical quantity calculating means has allowable error range in-pipe discriminating means for discriminating whether the tristimulus values of the detected color of said coloring member lie in the allowable error range pipe or not.

Further, it is preferable that the predetermined physical quantity is temperature.

Further, it is preferable that said coloring member is a thermo-sensitive liquid crystal member.

Further, it is preferable that said thermo-sensitive member is sprayed onto a surface of an object to be measured.

Further, it is preferable that said thermo-sensitive member is a sheet shaped liquid crystal member which is attached onto a surface of an object to be measured.

Further, it is preferable that said thermo-sensitive member is mixed turbidly into an object to be measured.

Further, it is preferable that said coloring member is a gap formed between a first member and a second member so as to produce an interference pattern when irradiated by light.

Further, it is preferable that the first member is a head surface of a disk apparatus, and the second member is a disk surface.

Further, it is preferable that the first member is a semiconductor wafer whose flatness is to be measured, and the second member is a reference flatness body.

Further, it is preferable that the predetermined physical quantity is a gap width formed between the first member and the second member so as to produce an interference pattern when irradiated by light.

Further, it is preferable that the tristimulus values are RGB values.

Further, it is preferable that the tristimulus values are L*a*b* values.

Further, the present invention provides a measuring method, comprising the steps of: constructing a three-dimensional color space having three coordinate axes by allowing each value of tristimulus values of color to correspond to each of the coordinate axes; changing a predetermined physical quantity for a coloring member whose color condition changes according to change of the physical quantity; detecting the color condition of the coloring member to obtain the tristimulus values thereof according to various physical quantities; constructing a data base section by representing relationship between the various physical quantities and the tristimulus values in the three-dimensional color space; detecting the tristimulus values of the coloring member included in an object to be measured; and calculating the physical quantity of the object to be measured with reference to the data base section.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1(a) is an illustration showing an RGB space adopted as the three-dimensional color space; and FIG. 1(b) is the contents of the data base section of the measuring apparatus according to the present invention; FIG. 2 is an illustration showing a color-temperature calibration curve, obtained by interpolating the color-temperature calibration curve shown in FIG. 1(a); FIG. 3(a) is an illustration showing an L*a*b* system color space adopted as the three-dimensional space; FIG. 3(b) is the contents of the data base section of the measuring apparatus according to the present invention; FIG. 4 is an illustration showing a color-temperature calibration curve, obtained by interpolating the color-temperature calibration curve shown in FIG. 3(a); FIG. 5 is a block diagram showing a first embodiment of the measuring apparatus according to the present invention; FIG. 6 is a flowchart showing the measuring procedure of the first embodiment of the measuring method according to the present invention; FIG. 7 is a graphical representation showing the relationship between temperature and color represented by the prior art RGB system; FIG. 8 is a graphical representation showing the relationship between temperature and color represented by the prior art L*a*b* system;
FIG. 9 is a block diagram showing a second embodiment of the measuring apparatus according to the present invention;

FIG. 10 is an illustration showing an RGB space adopted as the three-dimensional color space, in which a color-floating quantity calibration curve is shown;

FIG. 11 is an illustration for assistance in explaining the generation of the interference pattern, when a gap is formed between an optical head and a pseudo-magnetic disk and further light is irradiated thereupon;

FIG. 12 is an illustration for assistance in explaining the floated quantity \( H \) of the optical head at a gap formed between the optical head and a magnetic disk;

FIG. 13 is a graphical representation showing a prior art relationship between the RGB values of the interference pattern formed at the gap and the floating quantity \( H \) (gap width); and

FIG. 14 is a flowchart showing the measuring procedure of the second embodiment of the measuring method according to the present invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Embodiments of the measuring apparatus of the present invention will be described hereinbelow with reference to the attached drawings.

FIG. 5 is a block diagram showing a first embodiment of the measuring apparatus according to the present invention. In FIG. 5, the measuring apparatus comprises a coloring member 2 whose color condition changes according to change of a physical quantity, color detecting means 5 for detecting the color condition of the coloring member 2, a data base section 8, and physical quantity calculating means 9.

The coloring member 2 is a liquid crystal member whose color condition changes according to a physical quantity (e.g., temperature) of the object 1 to be measured. The coloring member 2 is sprayed onto the surface of the object to be measured or attached thereto as a sheet. Further, it is also possible to mix the coloring member 2 with a liquid object to be measured (e.g., water).

The color detecting means 5 is composed of a color CCD camera 6 (a color image sensor) and image processing and calculating means 7.

Further, when temperature at a point is required to be measured (without detecting the temperature distribution all over the surface of the object to be detected), it is also possible to use a point color sensor which can discriminate color, instead of the color image sensor. Further, when the data base section 8 is formed, it is also possible to use the point color sensor which can discriminate color, instead of the color image sensor. As the example of the point color sensor, a compact sensor composed of a single color pixel or a small number of color pixels can be used, for instance.

When the temperature distribution on the surface of an object to be measured is required to be obtained, it is necessary to measure the color distribution on the surface of the object by use of color image sensors.

Here, since the color CCD camera 6 is composed of a great number of pixels, it is possible to detect image color data at spatial positions for each pixel corresponding to each spatial position of the coloring member 2. The image processing and calculating means 7 processes the image color data detected by the CCD camera 6 to eliminate noise and to smoothen the image color data, and then calculates the tristimulus values of the coloring member 2 at each spatial position of the coloring member 2.

On the other hand, the data base section 8 can be formed by use of a reference coloring member 3 formed of the same substance as the coloring member 2, by changing the physical quantity (e.g., temperature) of the reference coloring member 3 with the use of physical quantity changing means 4 (e.g., heating means), and by detecting the color condition of the reference coloring member 3 due to changes of the physical quantity with the use of the color detecting means 5.

In the data base section 8, a three-dimensional color space 10 is constructed by allowing each of the color tristimulus values of the reference coloring member 3 detected by the color detecting means 5 to correspond to each of the three coordinates of the color space 10. When the physical quantity is temperature, for instance, the temperature of the reference coloring member 3 is detected by known temperature detecting means, and the tristimulus values of the detected color are obtained by the color detecting means 5. Further, in the data base section 8, the relationship between the detected temperatures and the obtained tristimulus values are plotted in the three-dimensional color space 10, as shown in FIG. 1(a).

Further, FIG. 1(a) shows the case where the reference coloring member 3 is provided in addition to the coloring member 2. Without being limited thereto, it is also possible to use in common both the coloring member 2 and the reference coloring member 3.

The practical example of the data base section 8 will be explained hereinbelow.
In the data base section 8 shown in FIGS. 1(a) and 1(b), RGB values are adopted as the tristimulus values of the color, and each of the tristimulus values R, G and B is allocated to each of the three coordinates of the three-dimensional color space 10, in order to form a three-dimensional RGB color space 10 and to show the relationship between the liquid crystal temperature and the RGB values of the liquid crystal.

In FIG. 1(b), a point A indicates the lowest temperature condition, and a point B indicates the highest temperature condition. Therefore, when the temperature is raised from the point A to the point B, it is possible to obtain the color-temperature calibration curve 11, by measuring the temperature of the liquid crystal at each point by use of the known temperature detecting means, by calculating the RGB values in accordance with the known method by use of the color detecting means, and by plotting the calculated RGB values in the three-dimensional RGB color space 10.

As shown in FIG. 1(b), when the RGB values are arranged in the three-dimensional RGB color space 10, it is possible to recognize that the color data are arranged smoothly and continuously from the points A to B according to the temperature change thereof all over the coloring area of the liquid crystal.

In the data base section 8 shown in FIG. 1(a), there exist intervals of data between a measurement point of temperature and the RGB values and an adjacent measurement point thereof, respectively. However, these data intervals can be interpolated in accordance with the interpolation method where necessary.

A method of obtaining calibration data of the data base section 8 will be explained hereinbelow with reference to FIGS. 2 and 6.

First, as shown in FIG. 6, in step ST1, the color images of the liquid crystal are photographed by the color CCD camera 6 in sequence by changing the liquid crystal temperature of the reference coloring member 3 at a constant interval (e.g., 1 degree C.) by the physical quantity changing (i.e., temperature control) means 4. The photographed liquid crystal images are inputted to the image processing and calculating means 7.

Successively, in step ST2, the images inputted to the image processing and calculating means 7 are arranged as the color tristimulus values (e.g., RGB values), and then each of the Ri, Gi and Bi values corresponding to each temperature Ti is obtained at each measurement point i.

Further, in step ST3, the Ri, Gi and Bi data obtained at each temperature Ti are developed in the three-dimensional RGB color space 10. Further, these data are interpolated in the three-dimensional color space 10 where necessary, to obtain a color-temperature calibration curve 11. As the interpolation method, it is possible to execute the linear interpolation or a high-order interpolation for obtaining a smoother calibration curve.

As shown in FIG. 1(b), when the RGB values are arranged in the three-dimensional RGB color space 10, it is possible to recognize that the color data are arranged smoothly and continuously from the points A to B according to the temperature change thereof all over the coloring area of the liquid crystal.

In the data base section 8 shown in FIG. 1(a), there exist intervals of data between a measurement point of temperature and the RGB values and an adjacent measurement point thereof, respectively. However, these data intervals can be interpolated in accordance with the interpolation method where necessary.

A method of obtaining calibration data of the data base section 8 will be explained hereinbelow with reference to FIGS. 2 and 6.

First, as shown in FIG. 6, in step ST1, the color images of the liquid crystal are photographed by the color CCD camera 6 in sequence by changing the liquid crystal temperature of the reference coloring member 3 at a constant interval (e.g., 1 degree C.) by the physical quantity changing (i.e., temperature control) means 4. The photographed liquid crystal images are inputted to the image processing and calculating means 7.

Successively, in step ST2, the images inputted to the image processing and calculating means 7 are arranged as the color tristimulus values (e.g., RGB values), and then each of the Ri, Gi and Bi values corresponding to each temperature Ti is obtained at each measurement point i.

Further, in step ST3, the Ri, Gi and Bi data obtained at each temperature Ti are developed in the three-dimensional RGB color space 10. Further, these data are interpolated in the three-dimensional color space 10 where necessary, to obtain a color-temperature calibration curve 11. As the interpolation method, it is possible to execute the linear interpolation or a high-order interpolation for obtaining a smoother calibration curve.

FIG. 2 shows an interpolated curve obtained by executing sequential quadratic interpolation for the data existing at three continuous points, respectively. When the color data are interpolated as described above, it is possible to develop a string-shaped color-temperature calibration curve 11 in the three-dimensional color space 10 as a calibration line. Further, instead of the color-temperature curve 11 developed as the calibration line, it is also possible to form a calibration table obtained by the correspondence between each temperature Ti and the Ri, Gi and Bi values at each temperature Ti.

Successively, in steps from ST4 to ST6, the temperature of the object 1 is measured. In more detail, in step ST4, the images of the coloring member (liquid crystal) 2 attached to the object 1 to be measured is obtained by the color CCD camera 6.

Further, in step ST5, the RGB values are calculated by the image processing and calculating means 7 on the basis of the liquid crystal images obtained by the color CCD camera 6.

Further, in step ST6, with reference to the color-temperature calibration curve 11 obtained in step ST3, a point at which the RGB values calculated in step ST5 can be specified on the color-temperature calibration curve 11 is obtained, and then the temperature of the object 1 to be measured is calculated by the physical quantity calculating means 9.

Here, the color-temperature calibration curve 11 is a curve along which the corresponding relationship between the temperature and the color tristimulus values (RGB values) has been obtained on the basis of the physical nature of the coloring member. Therefore, as far as the RGB values of the coloring member 2 can be obtained, it is natural that the point specified by the obtained RGB values in the three-dimensional color space 10 lies on the color-temperature calibration curve 11 from the theoretical standpoint.

In practical temperature measurement, however, the point specified by the obtained RGB values in the three-dimensional color space 10 may not necessarily lie accurately on the color-temperature calibration curve 11.

One of the reasons is that the color characteristics of the thermo-sensitive liquid crystal somewhat differ according to the illumination angle or the visual angle.

Therefore, for instance, when there exists a difference in the illumination and visual angles between the step of forming the color-temperature calibration curve 11 by use of the reference coloring member 3 and the step of detecting the images of the coloring member 2 to obtain the temperature of the object 1 to be measured, the point
specified by the obtained RGB values in the three-dimensional color space 10 does not necessarily lie on the color-
temperature calibration curve 11.

Accordingly, it is necessary to obtain the liquid crystal images of the coloring member 2, under the same
illumination and visual angle conditions as when the color-temperature calibration curve 11 is formed for
calibration.

However, there exists the case where it is impossible to secure the same illumination and visual angle
conditions between both the steps. In this case, the reliability of the measurement data can be improved by the
following processing:

The color images of the coloring member 2 of liquid crystal sprayed or attached onto the object 1 to be
measured are photographed by the color CCD camera 6.

Then, the RGB values thereof are obtained for each pixel of the color CCD camera 6. Successively, a
plurality of the pixels are classified into appropriate groups, and the RGB values of the pixels included in each group
are averaged and then processed statistically, to extract the RGB values from which errors are excluded for each
group. The RGB values obtained for each group as described above are substituted for the color-temperature
calibration curve 11, to obtain the temperature corresponding to each group.

In addition, as another method of excluding the error included from the actually measured data, the
following processing can be adopted:

The color-temperature calibration curve 11 must be a curve having no thickness from an idealistic
viewpoint. Therefore, when an allowable error width of the RGB values is assumed and further the color-
temperature calibration curve 11 is enclosed, it is possible to obtain an allowable error range curved pipe 12
extending along the color-temperature calibration curve 11, as shown in FIG. 2. The formed curved pipe 12 is stored
in the data base section 8. Further, in FIG. 2, only a part of the allowable error range curved pipe 12 extending along
the color-temperature calibration curve 11 is shown.

Therefore, as far as the RGB values obtained by actually measuring the coloring member 2 lie within the
allowable error range pipe 12, the measured data can be adopted as reliable data. That is, a point on the color-
temperature calibration curve 11 existing the shortest distance away from the point specified by the RGB values in
the three-dimensional color space 10 is obtained, and a temperature corresponding to the obtained point is adopted
as the measured temperature. Further, when the RGB values obtained by actually measuring the coloring member 2
do not lie within the allowable error range pipe 12, the measured data are discriminated as being not reliable, so that
the measured data are not adopted.

Further, the physical quantity calculating means 9 includes calibration on-line discriminating means for
discriminating whether the tristimulus values of the detected color of the coloring member lie on the color-
temperature calibration curve 11 or not. Further, the physical quantity calculating means 9 includes allowable error
range in-pipe discriminating means for discriminating whether the tristimulus values of the detected color of the
coloring member lie in the allowable error range pipe 12 or not.

In the above-mentioned embodiment, the case where the RGB values are adopted as the color tristimulus
values has been described. Instead of the RGB values, however, it is also possible to adopt L*a*b* values as the
color tristimulus values, for instance.

FIGS. 3(a) and 3(b) show an example of a color-temperature calibration curve 11 obtained by plotting the
obtained L*a*b* values in the three-dimensional color space 10. In the obtained L*a*b* color space, it can be
recognized that the color data can be arranged smoothly and continuously from a low temperature point C to a high
temperature point D, in the same way as with the case of the RGB color space.

Further, FIG. 4 shows the color-temperature calibration curve 11 obtained by interpolating the color data
shown in FIG. 3(a) in accordance with the interpolation method. Further, the present embodiment can be applied to
the cases where an HSI system display, an XYZ system display, etc. are adopted as the tristimulus values, in
addition to the RGB system display and the L*a*b* system display.

As described above, in the first embodiment of the present invention, since the relationship between the
physical quantity (e.g., temperature) and the tristimulus values of color can be formed in a three-dimensional color
space 10, and the formed three-dimensional color space 10 is stored in the data base section 8, it is possible to obtain
the correspondence between the physical quantity (e.g., temperature) and the color tristimulus values in accordance
with a one-value function all over the coloring area of the coloring member, so that a wide-range temperature
measurement can be made in a wide area of an object to be measured.

As a result, it is possible to construct an easy temperature measuring system utilizing the whole coloring
area of the liquid crystal, without need of any additional device (e.g., filters) and any complicated processing.
Therefore, the two- or three-dimensional wide-range temperature measurement can be made by preparing only the
general-purpose CCD camera and the color data processing (e.g., RGB system).
Further, in general, when the liquid crystal is colored, color non-uniformity somewhat occurs. Therefore, after the color is converted into the temperature, there inevitably exists a measurement error. In the present embodiment, however, when the color data are allowed to correspond to the color-temperature calibration curve, the corresponding relationship between the two can be somewhat controlled. In practice, since the reliable data can be discriminated on the basis of a distance between the data and the calibration curve, it is possible to easily decide an allowable error range of color non-uniformity during the measurement.

A second embodiment of the measuring apparatus according to the present invention will be described hereinbelow with reference to the attached drawings.

In FIG. 9, the measuring apparatus comprises a micro gap 22 (considered as a coloring member, equivalently) for producing an interference fringe when a magnetic disk apparatus 21 is irradiated with light, color detecting means 25 for detecting the color condition of the micro gap 22, a data base section 28, and physical quantity calculating means 29 for obtaining color tristimulus values on the basis of the color condition of the micro gap 22 detected by the color detecting means 25 with reference to the data base section 28 and for calculating a gap or a flying height H of a magnetic head 40 (as the physical quantity) on the basis of the obtained tristimulus values.

As shown in FIG. 12, the micro gap 22 of the magnetic disk apparatus 21 is formed between a magnetic head 40 (a first member) and a magnetic disk 41 (a second member). The micro gap 22 can be represented by a flying height H of the optical head 40 away from the surface of the magnetic disk 41. In FIG. 12, an arrow B indicates the rotational direction of the magnetic disk 41.

The color detecting means 25 comprises a color CCD camera (as a color image sensor) 26 and image processing and calculating means 27.

The data base section 28 can be formed as follows:

As shown in FIG. 11, a reference micro gap 23 is formed between a pseudo magnetic disk 42 and the magnetic head 40. As the pseudo magnetic disk 42, a light transmissive member having a high flatness can be used. The flying height H of the magnetic head 40 from the pseudo-magnetic disk 42 can be changed by moving the magnetic head 40 up and down by use of physical quantity changing means 24 (e.g., micro displacement controlling means). When light is allowed to be incident upon the micro gap 22, an interference fringe 44 can be formed by the light interference produced at the reference micro gap 23. In this case, since another interference fringe produced between both side surfaces of the pseudo magnetic disk 42 can be discriminated and further eliminated, it is possible to extract only the interference fringe produced at the micro gap 22 for image processing. The color condition of the interference fringe produced between the reference micro gap 23 can be detected by the color detecting means 25 in correspondence to the change of the flying height H of the magnetic head 40.

In the data base section 28, a three-dimensional color space 30 is constructed by allowing each of the color tristimulus values of the reference coloring member using the pseudo magnetic disk 42 to correspond to each of the three coordinates of the color space 30. That is, the data base section 28 can be obtained by plotting the relationship between the flying height H and the tristimulus values in the three-dimensional color space 30.

The practical example of the data base section 28 will be explained hereinbelow.

In the data base section 10 shown in FIG. 10, RGB values are adopted as the tristimulus values of the color, and each of the tristimulus values R, G and B is allocated to each of the three coordinates of the three-dimensional color space 30, in order to form a three-dimensional RGB color space 30 and to show the relationship between the flying height H of the magnetic head 40 and the RGB values of the interference fringe obtained by the flying height H.

In FIG. 10, a point J indicates the largest flying height, and a point B indicates the lowest flying height. Therefore, when the magnetic head 40 is lowered from the point J to the point K, it is possible to obtain the color flying height calibration curve 31, by measuring the flying height H at each point by use of the known micro displacing means, by calculating the RGB values in accordance with the known method by use of the color detecting means 25, and by plotting the calculated RGB values in a three-dimensional RGB color space 30.

As shown in FIG. 10, when the RGB values are arranged in the three-dimensional RGB color space 30, it is possible to recognize that the color data can be arranged smoothly and continuously from the point J to the point K according to the micro gap change all over the coloring area of the interference fringe. In the data base section 28 shown in FIG. 10, there exist data intervals between a measurement point of the flying height and the RGB values and an adjacent measurement point thereof, respectively. However, these data intervals can be interpolated in accordance with the interpolation method where necessary.

A method of obtaining calibration data of the data base section 28 will be explained hereinbelow with reference to FIG. 14.

First, as shown in FIG. 14, in step ST11, the color images of the interference fringe 44 are photographed by the color CCD camera 26 in sequence by changing the flying height H of the magnetic head 40 relative to the
surface of the pseudo magnetic disk 42 at a constant interval (e.g., 0.02 \mu m) by the micro displacement controlling means 24. The photographed interference fringe images are inputted to the image processing and calculating means 7.

Successively, in step ST12, the images inputted to the image processing and calculating means 27 are arranged as the color tristimulus values (e.g., RGB values), and then each of the Ri, Gi and Bi values corresponding to each flying height \( H_i \) is obtained.

Further, in step ST13, the Ri, Gi and Bi data corresponding at each flying height \( H_i \) are developed in the three-dimensional RGB color space 30. Further, these data are interpolated in the three-dimensional color space 30 where necessary, to obtain a color-flying height calibration curve 31. As the interpolation method, it is possible to execute the liner interpolation or a high-order interpolation for obtaining a smoother calibration curve.

FIG. 10 shows an interpolated curve obtained by executing sequential quadratic interpolation for the data existing at three continuous points, respectively. When the color data are interpolated as described above, it is possible to develop a string-shaped color-flying height calibration curve 30 as a calibration line. Further, instead of the color-flying height calibration curve 31 developed as the calibration line, it is also possible to form a calibration table obtained by the correspondence between each flying height \( H_i \) and the Ri, Gi and Bi values at each flying height \( H_i \), respectively.

Successively, in steps from ST14 to ST16, the interference fringe of the magnetic head 40 is measured. That is, in step ST14, the images of the interference fringe are obtained by irradiating light 43 to the micro gap 22 between the magnetic disk 41 and the magnetic head 40 (as shown in FIG. 11) and further by the photographing the produced interference fringe by use of the color CCD camera 26.

Further, in step ST15, the RGB values are calculated by the image processing and calculating means 27 on the basis of the interference fringe images obtained by the color CCD camera 26. Further, in step ST16, with reference to the color-flying height calibration curve 31 obtained in step ST13, a point at which the RGB values calculated in step ST15 can be specified on the color-flying height calibration curve 31 is obtained, and then the flying height \( H \) of the magnetic head 40 is calculated by the physical quantity calculating means 29.

Here, the color-flying height calibration curve 31 is a curve along which the corresponding relationship between the flying height \( H \) and the color tristimulus values (RGB values) has been obtained on the basis of the physical nature of the micro gap 22. Therefore, as far as the RGB values of the interference fringe can be obtained, it is natural that the a point specified by the obtained RGB values in the three-dimensional color space 30 lies on the color-flying height calibration curve 31 from the theoretical standpoint.

In the practical flying height measurement, however, the point specified by the obtained RGB values in the three-dimensional color space 30 does not necessarily lie accurately on the color-flying height calibration curve 31.

One of the reasons is that the interference fringe at the micro gap 22 somewhat differs according to the illumination angle or the visual angle. Therefore, for instance, when there exists a difference in the illumination and visual angles between the step of forming the color-flying height calibration curve 31 by use of the reference micro gap 23 and the step of obtaining the flying height \( H \) at the actual micro gap 22 to be measure, the point specified by the obtained RGB values in the three-dimensional color space 30 does not necessarily lie on the color-flying height calibration curve 31.

Accordingly, it is necessary to obtain the interference fringe images at the micro gap 22, under the same illumination and visual angle conditions as when the color-flying height calibration curve 31 is formed for calibration.

However, there exists the case where it is impossible to secure the same illumination and visual angle conditions between both the steps. In this case, the reliability of the measurement data can be improved by the following processing:

The color-flying height calibration curve 31 must be a curve having no thickness from an idealistic viewpoint. Therefore, when an allowable error width of the RGB values is assumed and further the color-flying height calibration curve 31 is enclosed, it is possible to obtain an allowable error range curved pipe 32 extending along the color-flying height calibration curve 31, as shown in FIG. 10. The formed curved pipe 32 is stored in the data base section 28. Further, in FIG. 10, only a part of the allowable error range curved pipe 32 extending along the color-flying height calibration curve 31 is shown.

Therefore, as far as the RGB values obtained by actually measuring the flying height \( H \) at the micro gap 22 lie within the allowable error range pipe 32, the obtained data are adopted as reliable data. That is, a point on the color-flying height calibration curve 31 existing the shortest distance away from the point specified by the RGB values in the three-dimensional color space 30 is obtained, and a flying height corresponding to the obtained point is adopted as the measured flying height. Further, when the RGB values obtained by actually measuring the flying
height H do not lie within the allowable error range pipe 32, the measured data are discriminated as being not reliable for some reasons, so that the measured data are not adopted.

Further, the physical quantity calculating means 29 includes calibration on-line discriminating means for discriminating whether the tristimulus values of the detected interference fringe lie on the color-flying height calibration curve 31 or not. Further, the physical quantity calculating means 29 includes allowable error range in-pipe discriminating means for discriminating whether the tristimulus values of the detected interference fringe lie in the allowable error range pipe 32 or not.

Further, although an example of the error processing methods has been described by way of example, there are many other error processing methods.

Further, in the above-mentioned embodiment, the case where the RGB values are adopted as the color tristimulus values has been described. Instead of the RGB values, it is also possible to adopt \( L^*a^*b^* \) values as the color tristimulus values, for instance. Further, the present embodiment can be applied to the cases where an HSI system display, an XYZ system display, etc. are adopted as the tristimulus values, in addition to the RGB system display and the \( L^*a^*b^* \) system display.

As described above, in the second embodiment of the present invention, since the relationship between the flying height H of the magnetic head 40 (as the physical quantity) and the color tristimulus values of the interference fringe is represented in the three-dimensional color space 30, and the formed three-dimensional color space 30 is stored in the data base section 8, it is possible to obtain the correspondence between the flying height H of the magnetic head and the color tristimulus values of the interference pattern as a one-value function all over the coloring area of the interference fringe, so that the measurement of the flying height H can be made in a wide area thereof.

As a result, it is possible to easily measure the flying height H difficult to measure in general by preparing only the general-purpose CCD camera and the color data processing (e.g., RGB system).

Further, in general, when the interference fringe is produced, color non-uniformity somewhat occurs. Therefore, after the color is converted into the flying height H, there inevitably exists a measurement error. In the present embodiment, however, when the color data are allowed to correspond to the color-flying height calibration curve 31, the corresponding relationship between the two can be somewhat controlled. In practice, since the reliable data can be discriminated on the basis of a distance between the data and the calibration curve, it is possible to easily decide the allowable error range of the color non-uniformity during the measurement.

Further, in the above-mentioned method, although the flying height H of the magnetic head 40 has been measured on the basis of the micro gap between the magnetic head 40 (as the first member) and the magnetic disk 41 (as the second member), without being limited only thereto, it is also possible to set a semiconductor wafer as the first member and a reference flat body such as a glass plate of high flatness as the second member. In this case, it is possible to measure the flatness of the semiconductor wafer in the same way as with the case of the flying height H.

In the above-mentioned description, although the measuring apparatus and method according to the present invention have been explained by taking temperature or the flying height H related to a micro gap as the physical quantity and taking the liquid crystal and the micro gap as the coloring member, the physical quantity is not limited only to the temperature and the flying height, and in the same way the coloring member is not limited only to the chemical substance such as liquid crystal or the interference pattern. As far as the physical quantity can be allowed to correspond to the color tristimulus values as a one-valued function in the three-dimensional color space, magnetic field, electric field, pressure, etc. can be adopted as the physical quantity. Further, a chemical substance other than liquid crystal can be also adopted as the coloring member.

According to the sorts of liquid crystal, there are some liquid crystals whose color changed according to pressure, electric field, and the other physical quantity, respectively. Further, in substances other than liquid crystal, there exist many chemical substances whose color changes according to various physical quantities.

When a chemical substance whose color changes according to pressure is used, it is possible to obtain a wide pressure distribution in the same way as with the case of the above-mentioned embodiments. Further, when a chemical substance whose color changes according to electric field is used, it is possible to obtain a wide electric field distribution in the same way as with the case of the above-mentioned embodiments. Further, when there exists a chemical substance whose color changes according to a physical quantity other than above, it is possible to easily obtain a detailed quantitative distribution in the same way as above.

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Apparatus and method for full-field calibration of color response to temperature of thermochromic liquid crystals

Abstract
An apparatus and method for accurately calibrating the full-field color response to temperature of a thermochromic liquid crystal (12, 76) (TLC) located on a substrate material (10, 78). The apparatus uses a camera (50) to measure a reflected light (101) reflected by the TLC (12, 76) from a light source (54) which preferably illuminates the TLC with a full visible light spectrum (100). To achieve a temperature distribution over its surface the TLC (12, 76) is placed on a thermal element (14, 80) and allowed to reach a steady state. An optically transmissive pane (36) covers the TLC and contact assurance elements (38) which ensure contact pressure between the thermal element (14, 80) and the TLC. A set of optically transmissive plates (42, 44) mounted on top of one another and separated by air gap (46) covers the optically transmissive pane (36) and provides a thermal resistance to prevent heat leakage. The apparatus has a preferably ring-shaped light source (54) mounted above the set of optically transmissive plates (42, 44) for illuminating the TLC. For increased calibration accuracy the apparatus has an infrared filter (56) and an ultraviolet filter (58) mounted upstream from the light source (54) for removing ultraviolet and infrared radiation. Additionally, the apparatus has two polarizers (64, 66) to only admit circularly polarized light into the camera (50).

Inventors: Moffat; Robert J. (18375 Corral Del Cielo, Salinas, CA 93908); Farina; Dino J. (79 Fessenden St., Newton, MA 02160)

Claims
1. An apparatus for calibrating the full-field color response to temperature of a thermochromic liquid crystal located on a substrate material by measuring a reflected light of a visible light spectrum used to illuminate said thermochromic liquid crystal, said apparatus comprising:
   a) a heating bar with said thermochromic liquid crystal placed thereon for applying a geometrically predetermined temperature distribution to said thermochromic liquid crystal;
   b) a set of thermal elements in thermal contact with said heating bar for creating said geometrically predetermined temperature distribution;
   c) an optically transmissive pane for covering said thermochromic liquid crystal;
   d) pressing means mounted on top of said optically transmissive pane for producing contact pressure between said optically transmissive pane and said thermochromic liquid crystal;
   e) a set of optically transmissive plates, mounted on top of one another and separated by air gaps, for covering said optically transmissive pane and activating said pressing means and for providing thermal insulation between said thermochromic liquid crystal and the surroundings;
f) a light source mounted at a predetermined distance from said set of optically transmissive plates for illuminating said thermochromic liquid crystal with said visible light spectrum through said set of optically transmissive plates and said optically transmissive pane; and

g) a light analyzing means, mounted above said set of optically transmissive plates, sensitive to said reflected light.

2. The apparatus of claim 1 further comprising a set of infrared and ultraviolet filters mounted upstream from said light source for removing ultraviolet and infrared radiation from said light spectrum, thereby removing from said light source substantially all light carrying thermal energy and energy degrading to said thermochromic liquid crystal.

3. The apparatus of claim 2 further comprising:
   a) a first polarizing means with a predetermined axis of polarization mounted on said light source;
   b) a second polarizing means with a predetermined axis of polarization mounted on said light analyzing means and oriented substantially perpendicular to the predetermined axis of polarization of said first polarizing means, whereby only circularly polarized light passing through said first polarizing means can be passed through said second polarizing means.

4. The apparatus of claim 1 wherein said light source is ring-shaped.

5. The apparatus of claim 1 wherein said light source is ring-shaped and mounted concentrically around said light analyzing means, whereby said light spectrum issuing from said ring-shaped light source is collinear with said reflected light received by said light analyzing means.

6. The apparatus of claim 1 wherein said light source and said light analyzing means are mounted at different spatial and angular positions above said thermochromic liquid crystal.

7. The apparatus of claim 1 wherein said heating bar has the shape of a parallelepiped and said set of thermal elements comprises two thermal elements mounted substantially at two opposite sides of said heating bar.

8. The apparatus according to claim 7 wherein said two thermal elements are impressed with two different temperatures, thereby setting up a temperature gradient between the two opposite sides of said heating bar to produce said geometrically predetermined temperature distribution.

9. The apparatus of claim 1 wherein said heating bar has the shape of a disk and said set of thermal elements comprises two thermal elements, one mounted substantially in the middle of said heating bar and one mounted along the circumference of said heating bar.

10. The apparatus according to claim 9 wherein said two thermal elements are maintained at two different temperatures, thereby setting up a radial temperature gradient between the center of said heating bar and the circumference of said heating bar to produce said geometrically predetermined temperature distribution.

11. The apparatus of claim 1 wherein said heating bar has a curved surface and said set of thermal elements comprises two thermal elements mounted substantially at two opposite sides of said heating bar.

12. The apparatus according to claim 11 wherein said two thermal elements are maintained at two different temperatures, thereby maintaining a span-wise uniform temperature and setting up a temperature gradient between the two opposite sides of said heating bar to produce said geometrically predetermined temperature distribution.

13. The apparatus of claim 1 wherein said substrate material is a thermal conductor.

14. The apparatus of claim 1 wherein said set of optically transmissive plates comprises two optically transmissive plates and one gap between said plates, said gap containing air.

15. The apparatus of claim 14 wherein said pressing means comprise a set of springs actuated by the pressure exerted by one of said two optically transmissive plates.

16. A method for calibrating the full-field color response to temperature of a thermochromic liquid crystal located on a substrate material by measuring a reflected light of a visible light spectrum used to illuminate said thermochromic liquid crystal, said method comprising:
   a) placing said thermochromic liquid crystal on a heating bar;
   b) applying a geometrically predetermined temperature distribution to said heating bar using a set of thermal elements in contact with said heating bar;
   c) covering said thermochromic liquid crystal with an optically transmissive pane;
   d) assuring contact between said thermochromic liquid crystal and said heating bar using a pressing means for producing contact pressure between said optically transmissive plate, said thermochromic liquid crystal, and said heating bar;
   e) mounting over said optically transmissive pane a set of optically transmissive plates, arranged on top of one another and separated by air gaps to thermally insulate said thermochromic liquid crystal from the surroundings;
   f) exerting pressure on said optically transmissive pane;
   g) activating said pressing means by exerting pressure on said pressing means;
h) illuminating said thermochromic liquid crystal with said visible light spectrum through said set of optically transmissive plates and said optically transmissive pane using a light source mounted at a predetermined distance above said set of optically transmissive plates; and
i) analyzing said reflected light with light analyzing means mounted above said set of optically transmissive plates.

17. The method of claim 16 wherein said analyzing step comprises analyzing the entire spectrum of said reflected light simultaneously, thereby providing continuous calibration of said thermochromic liquid crystal.

18. The method of claim 16 further comprising:
a) eliminating infrared and ultraviolet light from said visible light spectrum, thereby removing from said light source substantially all light carrying thermal energy and energy degrading to said thermochromic liquid crystal; and
b) admitting into said light analyzing means only a circularly polarized part of said reflected light.

19. The method of claim 16 additionally comprising the following step: measuring whether said geometrically predetermined temperature distribution in said heating bar is constant in time using a set of thermocouples; and wherein said step of analyzing said reflected light includes analyzing said reflected light when said geometrically predetermined temperature distribution is constant in time.

Description

BACKGROUND - FIELD OF THE INVENTION

The present invention relates to the field of thermochromic liquid crystals, and in particular to an apparatus and method for calibrating the color response of such crystals to temperature.

BACKGROUND - DESCRIPTION OF PRIOR ART

When illuminated by white light a thermochromic liquid crystal (TLC) will reflect a unique color component of that light depending on its temperature. As that temperature changes so does the color component of light reflected by the TLC. When the temperature drops below or exceeds the TLC's color play interval the TLC becomes transparent. This response is repeatable and reversible, thus rendering a TLC very useful for temperature measurements, e.g., as regular thermometers.

In practical uses, a TLC is usually encased in a protective material which shields it from harmful radiation, chemicals, and other degrading factors. In the encapsulated form (the capsules are usually 5-50 μm in diameter) a TLC can be suspended in a sprayable binder material and sprayed onto objects of various shapes or substrate materials which are then placed on objects. For example, a TLC can be applied to an entire surface of an object. The temperature distribution of that surface can then be easily monitored based on the TLC's color pattern. This kind of full-field measurement is extremely useful in practice, e.g., for tracing hot spots on elements exposed to thermal stress under operating conditions or indicating the temperature of a part which needs to be touched by a human operator.

However, to use TLCs as quantitative temperature sensors one has to first establish an accurate relation between the TLC's color and its temperature. The most common calibrating method is the successive isotherm technique. This method uses a series of full-field color images taken at successive temperature levels. The colors of these successive images are graphed against the temperature levels to obtain a calibration curve.

Clearly, this approach is extremely time consuming and tedious, especially if a large number of isotherms are used. It also requires continuous control and adjustment of the temperature of the TLC surface to ensure accurate measurements. Furthermore, the color response of the TLC between any two temperatures has to be approximated by interpolation. This can lead to an inaccurate calibration and poor resolution.

In addition, the perceived color of a TLC depends on the lighting/viewing arrangement, the color spectrum of light used for illumination, and the optical properties of the measurement path. The effect of the lighting/viewing arrangement is important because each point in a TLC image has a different lighting and viewing angle in a practical situation. This effect could require that a very cumbersome point-wise rather than a full-field calibration be used.

Furthermore, background light also affects the perceived color of a TLC. First, since the background light may have a different spectral distribution (e.g., contain different amounts of color components than the illuminating light), the effective illumination light is altered. Second, a significant fraction of the light reaching the camera for taking the image is reflected directly as gloss or glare. This light is not modified in its spectral content to contain the color of the TLC.

Thus it can be seen that an accurate, full-field calibration of a TLC color-to-temperature response is very complicated. In fact, there are no prior-art apparatus and/or methods known to the inventors to address the above calibration problems in a satisfactory manner.

OBJECTS AND ADVANTAGES OF THE INVENTION
In view of the above it is an object of the invention to provide an apparatus and a method for full-field calibration of the color response to temperature of a thermochromic liquid crystal. Further, it is an object of the invention to ensure that such apparatus provides high-accuracy results and thus enables a high resolution. Another object of the invention is to design the calibration apparatus to enable a continuous calibration without the necessity for performing any interpolations. Yet another object is for the method to be simple to practice and for the apparatus to be user-friendly. Finally, it is an object of the invention to provide the apparatus at low cost.

These and other objects and advantages will become more apparent after consideration of the ensuing description and the accompanying drawings.

SUMMARY OF THE INVENTION

The apparatus and method according to the invention are designed to accurately calibrate the full-field color response to temperature of a thermochromic liquid crystal which is conveniently located on a thermally conductive substrate material by measuring a reflected light from a visible light spectrum used to illuminate the thermochromic liquid crystal. To do this the apparatus has a heating bar for placing thereon the substrate material coated with the thermochromic liquid crystal and a set of thermal elements for applying a geometrically predetermined temperature distribution to the heating bar. An optically transmissive pane covers the thermochromic liquid crystal and a pressure maintenance means, preferably a set of springs, mounted on top of the optically transmissive pane, produces contact pressure between the heating bar and the thermochromic liquid crystal by pressing the thermochromic liquid crystal against the heating bar. A set of optically transmissive plates, mounted on top of one another and separated by air gaps, cover the optically transmissive pane and activate the pressing means.

The apparatus has a ring-shaped light source mounted above the set of optically transmissive plates for illuminating the thermochromic liquid crystal with a light spectrum through the set of optically transmissive plates and the optically transmissive pane. Further, the apparatus has a light analyzing means, preferably a color camera, mounted above said set of optically transmissive plates for analyzing the reflected light. For increased calibration accuracy the apparatus has a set of infrared and ultraviolet filters mounted upstream from the light source for removing ultraviolet and infrared radiation from the light spectrum used for illumination. The filters remove from the light source the light which carries thermal energy and energy degrading to the thermochromic liquid crystal. Additionally, the apparatus has two polarizing means, preferably two polarization plates, which are mounted in perpendicular orientation to each other over the light source and light analyzing means to only admit circularly polarized light into the light analyzing means.

The light source itself is preferably ring-shaped, in order to approximate a point-like source, and mounted concentrically around the light analyzing means or at a different spatial and angular position. The thermal elements produce a thermal gradient in the heating bar, which can exhibit various shapes, and the substrate material, preferably a conductor, ensures that the temperature of the thermochromic liquid crystal corresponds to that of the plate. To prevent heat transfer to the outside the set of optically transmissive plates have air gaps between them.

In the method of the invention the heating bar is impressed with a geometrical temperature distribution which varies sufficiently slowly, or remains constant, to provide a continuous calibration of the color-to-temperature response of the thermochromic liquid crystal. In the preferred embodiment the temperature is monitored with a set of thermocouple elements.

A detailed description of the apparatus and method of the invention is set forth below in reference to the enclosed drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded perspective view of a rig of the preferred apparatus of the invention for holding the thermochromic liquid crystal.

FIG. 2 is a side view of the entire preferred apparatus according to the invention.

FIG. 3 is a plan bottom view of the color camera and light source from FIG. 2 equipped with polarizers according to the invention.

FIG. 4 is a schematic diagram illustrating the equivalent thermal resistances of the portion of the preferred apparatus from FIG. 1.

FIG. 5 is a side view of four types of heating bars according to the invention.

FIG. 6 is a top view of the color distribution of the thermochromic liquid crystal during a calibration performed on a heating bar in the shape of a parallelepiped.

FIG. 7 is a top view of the color distribution of the thermochromic liquid crystal during a calibration performed on a disk-shaped heating bar.
FIG. 1 shows an exploded perspective view of a rig 11 of the preferred calibration apparatus. A substrate material 10 in the form of a rectangular strip is covered with a thermochromic liquid crystal (TLC) 12. TLC 12 is preferably in the form of microcapsules 5-50 μm in diameter and is applied onto substrate material 10 by spraying, coating, immersing, or some other conventional process. Material 10 is preferably a thermal conductor, such as a conductive film, aluminum, Mylar, or any other material onto which TLC 12 can be conveniently applied. Indeed, even nonconductive materials such as paper can be used in some cases.

Below substrate material 10 is located a heating bar 14 made of a thermally conducting material. In the preferred embodiment bar 14 is made of aluminum and it has the shape of a parallelepiped with dimensions 1.5”×1.5”×25 cm (height, width, length). Of course, a wide range of dimensions is allowable as long as they do not negatively influence the heat distribution in bar 14. Embedded inside bar 14 approximately along its center line is a set of standard thermocouples 16. Although FIG. 1 only shows three thermocouples 16 it is preferable to use a greater number, to provide better information about the temperature distribution in bar 14. For example, in the preferred embodiment nineteen 36-gauge, precision grade, type K thermocouples 16 are used. Each thermocouple is embedded in bar 14 using thermally conductive epoxy. Thermocouples 16 are designed to measure temperature to determine the geometrical temperature distribution in bar 14. Although thermocouples 16 shown in FIG. 1 are embedded along the center line, they can be embedded at various locations inside bar 14, e.g., along its sides.

Below bar 14 is located an insulating bed 20. Bed 20 is designed to receive bar 14 covered with substrate material 10 sprayed with TLC 12 inside a channel 22.

Insulating bed 20 is made of a thermally insulating material, e.g., balsa wood, to insulate the lateral sides and the bottom of bar 14 from the surroundings. A set of wires 26 is used to guide the electrical signals from thermocouples 16 through the body of bed 20, and to an external electronic temperature measuring device (not shown). The temperature measuring device and other well-known electronic instruments (not shown) are used for monitoring the geometrical temperature distribution inside bar 14.

Two thermal elements 28 and 30 are located at the open ends of channel 22. Elements 28 are connected to conventional power sources (not shown) by sets of leads 32 and 34 respectively. Elements 28 and 30 can either both be regular rubber patch-style heaters or some other high-efficiency heating devices. The choice of suitable elements 28 and 30 depends on the temperature which is to be applied to the two ends of bar 14. Many stable, high-efficiency, conventional heaters capable of maintaining a set temperature are commercially available. In the preferred embodiment, element 28 is a rubber patch-style heater and element 30 is a water-cooled aluminum heat sink. The temperature of element 30 is held constant by using a bulk water pre-heater (not shown) and a second patch heater (not shown). This arrangement enables element 30 to efficiently remove the heat conducted by bar 14 from element 28.

An optically transmissive pane 36 is dimensioned to fit inside channel 22 and cover TLC 12. Pane 36 is made of a low-reflectivity glass or other optical material which reduces glare. A set of coil springs 38 is affixed along the edges of pane 36.

A frame 40 holding a set of two optically transmissive plates 42 and 44 with a gap 46 between them is positioned above pane 36. In the preferred embodiment gap 46 contains air and its width is sufficient to provide a thermal buffer between plates 42 and 44. Both plates 42 and 44 are made of low-reflectivity glass or similar material.

As illustrated in FIG. 2, the surface of bottom plate 42 is designed to press against springs 38 to push pane 36 against TLC 12 when frame 40 is in position on top of insulating bed 20. Fastening elements (not shown) can be provided to hold frame 40 in place on bed 20 to ensure that frame 40 fits snug against bed 20 and plate 42 compresses springs 38. The pressure produced by springs 38 keeps TLC 12 coated on material 10 in good thermal contact with bar 14. Also, when springs 38 are properly compressed, an air gap 39 of width h is left between pane 36 and plate 42.

Further, FIG. 2 shows the rig 11 of the preferred calibrating apparatus resting on a rigid support 48. In the preferred embodiment support 48 is pivotable to permit adjustment of the inclination of rig 11.

A color camera 50 with an objective 52 is positioned directly above rig 11 at a distance d from the surface of plate 44. A ring-shaped light source 54 is mounted around objective 52. Light source 54 is designed to deliver a visible light spectrum 100. In the preferred embodiment spectrum 100 is free of infrared and ultraviolet light, which is filtered out by an infrared filter 56 and an ultraviolet filter 58 mounted inside a light guiding duct 60. A primary light source 62 is connected to duct 60 upstream from filters 56 and 58. Source 62 can be any light source capable of delivering a full and uniform spectrum of at least the visible light. In the preferred embodiment source 62 is a 3200K white light source.

Camera 50 is a high-resolution camera capable of distinguishing fine differences in color, e.g., Sony DXC-151 RGB/CCD. Further, camera 50 is capable of acquiring full-field red-blue-green (RGB) images at 640×480.
OPERATION

According to FIG. 1, in practicing the method of the invention heating bar 14 is first placed in position in channel 22 of rig 11. Then TLC 12 on substrate material 10 is placed on top of bar 14. To ensure good thermal contact between TLC 12 and bar 14, pane 36 is placed on top of TLC 12. Springs 38 of pane 36 are subsequently compressed by placing frame 40 with plates 42 and 44 on top of bed 20. In this position pane 42 presses down on springs 38. Consequently, pane 36exerts pressure against TLC 12 ensuring good thermal contact with bar 14.

Once rig 11 is prepared as described above, thermal elements 28 and 30 are set to two different temperatures and turned on. Typically, for calibrating a TLC with a narrow color play interval the difference in temperature between thermal elements 28 and 30 can be as low as a fraction of a degree, e.g., 0.1 degree C. to 0.9 degree C. On the other hand, TLCs with a wide color play interval may require a temperature difference of several tens of degrees Celsius, e.g., 30 degree C. to 70 degree C., to demonstrate their entire range of color response. The preferred rig 11 can be used in both cases.

After setting the required temperature range for TLC 12 rig 11 is allowed to reach a steady state in which the temperature distribution in bar 14 no longer varies with time. This usually lasts 30 to 45 minutes and can be verified by monitoring the temperature measured by thermocouples 16. Because of good thermal contact between bar 14 and TLC 12 the latter has the same temperature distribution as bar 14. Of course, if a difference in temperature does exist between bar 14 and TLC 12 a correction factor can be introduced to compensate for it. In the preferred embodiment the steady-state temperature distribution is span-wise uniform, because of the shape of bar 14 and position of elements 28 and 30, and varies linearly from one end of bar 14 to the other.

The heat generated in heating TLC 12 is contained inside rig 11 because of air gap 39, plate 42, air gap 46, and plate 44. This effect is best explained with the aid of FIG. 4 which shows the thermal resistances of all the above elements. Since resistance A of bar 14, resistance B between bar 14 and material 10 sprayed with TLC 12, and resistance C between TLC 12 and pane 36 are all relatively small, heat is easily transferred between these elements. Thus, bar 14, TLC 12, and pane 36 exhibit virtually the same temperature distribution. Meanwhile, resistance D of air gap 39, resistance E of plate 42, resistance F of air gap 46, resistance G of plate 44, and parallel resistance H to the surroundings and to zero reference at infinity are very much larger than resistance A+B+C. Consequently, these last elements act as thermal buffers and ensure that only a negligible amount of heat is leaked to the outside of rig 11.

As shown in FIG. 2, ring-shaped light source 54 illuminates TLC 12 from distance d at an angle normal to rig 11 with visible light spectrum 100. In the preferred embodiment the angle of illumination β is adjustable by rotating source 54 together with camera 50 as indicated by the phantom lines. Also, the angle of illumination can be varied by tilting pivotable support 48. Distance d is selected to be large enough for light source 54 to appear as a
point source at the location of TLC 12. In the preferred embodiment this distance is approximately 50 cm for a light source 54 of approximately 7 cm in diameter. In making a calibration measurement angle \( \beta \) and distance \( d \) are selected to best reflect the field illumination conditions under which TLC 12 will be used.

Primary light source 62 delivers light, which contains at least visible light spectrum 100, to source 54. The ultraviolet portion of the light, which is harmful to TLC 12, and the infrared portion, which carries undesirable thermal energy, are filtered out by ultraviolet filter 58 and infrared filter 56 respectively. The remaining visible light spectrum 100 is delivered to source 54 by light guiding duct 60. Finally, when exiting source 54 on the way to TLC 12, the light of spectrum 100 is polarized by polarizer 64.

Because plates 44 and 42, as well as pane 36 are made of a low-reflectivity glass most of spectrum 100 from source 54 is transmitted to the surface of TLC 12. Here, the different regions of TLC 12 exhibiting different temperatures (according to the temperature distribution) reflect different color portions of spectrum 100 from source 54. This is best shown by FIG. 6. The ends of TLC 12 near thermal elements 28 and 30 turn transparent because the end temperatures exceed the color play interval of TLC 12. Meanwhile, in the middle of TLC 12 reflected light 101 spans the entire visible light spectrum. In addition to reflecting different colors of light TLC 12, by its nature (chirality), also rotates reflected light 101 to impart it with a circular polarization.

The circularly polarized, reflected light 101 travels back up through pane 36, gap 39, plates 42, gap 46, and plate 44 to color camera 50. Before entering objective 52 light 101 passes through polarizer 66. Since the axis of polarization of polarizer 66 is perpendicular (crossed) with the axis of polarization of polarizer 64, only circularly polarized, reflected light 101 is admitted inside objective 52. This ensures that only light originating from source 54 and reflected by TLC 12 will be measured by camera 50. That, in turn, reduces calibration errors due to stray light which might otherwise enter objective 52.

Camera 50 resolves light 101 into a fine color range to calibrate the color/temperature response of TLC 12 over its color play interval. Suitable computers and electronic image processing devices (not shown) can be used in this process according to well known image processing techniques.

The method of the invention is also advantageously employed with heating bars of different shapes, as shown in FIG. 5. In these cases the remaining elements of rig 11 are adapted to the geometry of bar 70, 72, and 74. The advantage of using the apparatus and method of the invention with non-planar surface bars 70, 72, and 74 is the ability of collecting color response data at various angles at the same time. This is frequently more indicative of actual field conditions under which a TLC is viewed.

Finally, FIG. 7 shows another embodiment of the invention in which TLC 76 is coated on a circular substrate material 78 placed on a heating plate 80 with is disk-shaped. This embodiment operates analogously to the previous ones, but the temperature gradient is set up radially. For example, thermal element 84 located at the center of plate 80 is set at a higher temperature. Meanwhile, thermal element 86 located along the circumference of plate 80 is set at a lower temperature. Upon reaching steady state the resulting temperature gradient is radially symmetric, as shown.

**SUMMARY, RAMIFICATIONS, AND SCOPE**

Described above is a calibration apparatus for full-field calibration of thermochromic liquid crystals and a method for performing such calibrations which is very accurate and allows a high resolution of the color response. In fact, this resolution is mostly limited by the equipment used to process the color image of the TLC and not the apparatus. The apparatus makes it possible to carry out a continuous calibration without the necessity for performing any interpolations to estimate the color response at temperatures which were not measured. The method of the invention is simple to practice and the apparatus is user-friendly and economical.

Many alterations can be made to the apparatus presented above within the scope and in the spirit of the invention. For example, other than ring-shaped light sources can be employed. Preferably, these light sources will resemble a point source from the point of view of the TLC. These light sources can use limited ranges of the visible light spectrum for testing only particular color play intervals of the TLC.

Furthermore, the light source does not need to be mounted around the objective of the camera. In fact, the camera can be positioned to receive the reflected light at a completely different distance and angular orientation than the light source. This is very useful for calibrating TLCs which will be viewed at an angle appreciably different from the angle of illumination. Finally, the number of transmissive plates and air gaps between the surface of the TLC and the exterior of the rig can be changed. More air gaps will ensure better thermal insulation, provided they are calculated to of such width as to prevent convection. Therefore, the scope of the invention should be determined, not by examples given, but by the appended claims and their legal equivalents.
## Appendix – B

### Parts List

<table>
<thead>
<tr>
<th>QTY</th>
<th>PART</th>
<th>SUPPLIER</th>
<th>DESCRIPTION</th>
<th>UNIT COST</th>
<th>TOTAL COST</th>
</tr>
</thead>
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<td>device accessories</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>lab cart</td>
<td>McMaster-Carr</td>
<td>2602T66, 34&quot; x 22 1/4&quot;</td>
<td>$127.83</td>
<td>$127.83</td>
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<tr>
<td>2</td>
<td>*Kapton heaters</td>
<td>Tayco</td>
<td>2.48&quot; x 1.24&quot;</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>1</td>
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<td>Onlinesteel.com</td>
<td>3&quot; x 3&quot;x 0.5&quot;</td>
<td>$8.91</td>
<td>$8.91</td>
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<tr>
<td>3</td>
<td>*thermocouples</td>
<td>Omega</td>
<td>Type J, SS 1/16&quot; sheath</td>
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<td>$0.00</td>
</tr>
<tr>
<td>1</td>
<td>*PCMCIA card</td>
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<td>DT7102</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
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<td>Data Translation</td>
<td>DT784</td>
<td>$0.00</td>
<td>$0.00</td>
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<td>1</td>
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<td>$0.00</td>
</tr>
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<td>$25.62</td>
<td>$25.62</td>
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<td>$0.89</td>
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<td>ac/dc converter</td>
<td>Allied</td>
<td>298-9825, Output 24VDC, 24 VDC 2.5A</td>
<td>$53.32</td>
<td>$53.32</td>
</tr>
<tr>
<td></td>
<td>computer, camera, &amp; software</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>*Digital camera</td>
<td>Mustek</td>
<td>VDC 3500</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>1</td>
<td>IXLA</td>
<td>Mustek</td>
<td>camera software</td>
<td>$10.00</td>
<td>$10.00</td>
</tr>
<tr>
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<td>camera manual</td>
<td>Mustek</td>
<td>VDC 3500</td>
<td>$5.00</td>
<td>$5.00</td>
</tr>
<tr>
<td>1</td>
<td>camera AC adapter</td>
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<td>AD310-A</td>
<td>$20.00</td>
<td>$20.00</td>
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B - 1
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<tr>
<th>Item Description</th>
<th>Brand</th>
<th>Model/Details</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Total Price</th>
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<td>model 7755</td>
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<td>$0.00</td>
<td>$0.00</td>
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<td>*HPVEE</td>
<td>Hewlett Packard</td>
<td>data acquisition software</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>*MATLAB v.5.3</td>
<td>Mathworks</td>
<td>statistical software</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td><strong>lighting accessories</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum angle</td>
<td>Crown Bolt</td>
<td>1-1/2&quot; x 36&quot;, 1/8&quot; thk</td>
<td>1</td>
<td>$5.71</td>
<td>$5.71</td>
</tr>
<tr>
<td>Flood light kit</td>
<td>Red Dot</td>
<td>S912E</td>
<td>1</td>
<td>$6.97</td>
<td>$6.97</td>
</tr>
<tr>
<td>Square box</td>
<td>Romex</td>
<td>71695K43</td>
<td>1</td>
<td>$0.52</td>
<td>$0.52</td>
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<tr>
<td>Flat box cover</td>
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<td>71695K71</td>
<td>1</td>
<td>$0.59</td>
<td>$0.59</td>
</tr>
<tr>
<td>Flex tube</td>
<td>Gardner Bender</td>
<td>FLX-3810, 3/8&quot;</td>
<td>2</td>
<td>$2.28</td>
<td>$4.56</td>
</tr>
<tr>
<td>Conduit locknut</td>
<td>Halex</td>
<td>46191, 1/2&quot;</td>
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<td>$0.76</td>
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<tr>
<td>Screw connectors</td>
<td>Halex</td>
<td>20511, 3/8&quot;</td>
<td>1</td>
<td>$0.78</td>
<td>$0.78</td>
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<tr>
<td>Handy box</td>
<td>Romex</td>
<td>71695K81</td>
<td>2</td>
<td>$0.55</td>
<td>$1.10</td>
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<tr>
<td>Blank cover plate</td>
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<td>71695K27</td>
<td>2</td>
<td>$0.24</td>
<td>$0.48</td>
</tr>
<tr>
<td>Toggle switch</td>
<td>Romex</td>
<td>7030K32</td>
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<td>$0.24</td>
<td>$0.24</td>
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<tr>
<td>8' cord</td>
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<td>P-136-49-MSHA</td>
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<td>$7.50</td>
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<td>ET60, PVC vinyl</td>
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<td>$0.49</td>
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</tr>
<tr>
<td>*light bulbs</td>
<td>Sylvania</td>
<td>MU1, Superflood BBA</td>
<td>2</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
</tbody>
</table>

$281.27

* denotes parts provided by Northeastern
Appendix – C

Engineering Drawings

Figure 33 – Copper Plate Drawing
Figure 34 - Insulation Block Drawing
Appendix – D

Image Analysis Program

\%Runner Program initiates color quantification program and sets initial values
\%initial ScreenSize [1 1 1024 768], 96 Pixels pro inch
sscrsz = get(0,'ScreenSize'); \%finds Screensize
\% sizer makes the figure conform to the size of the monitor screen
sizer = [sscrsz(3)/1024 sscrz(4)/768 sscrz(3)/1024 sscrz(4)/768];
prefixedit=65; \%default prefix
\%Initial Comment in Comment Box
comment=('Welcome to the TLC Color Processing and Calibration Program. Please enter the file prefix value and then press run');
clf; \%clear screen
axes2=axes('Position',[.35 .35 .3 .3],'FontSize',8);
imshow welcome.jpg
\%Control Buttons on Figure 1
\%Places "Color Quantification Program" string
prefixedit=uicontrol('Style', 'edit',
   'String', num2str(prefixedit),...
   'Position', [860 50 70 20],\%sizer,....
   'BackgroundColor', 'w',....
   'FontName', 'Times',....
   'FontSize', 10,....
   'Callback', 'file prefix value');
\%Places "File Prefix" string
uicontrol('Style', 'pushbutton',
   'String', 'File Prefix',....
   'Position', [690 50 150 20],\%sizer,....
   'BackgroundColor', [.4 .2 .35],....
   'ForegroundColor', 'w',....
   'FontName', 'Times',....
   'FontSize', 10,....
   'FontWeight', 'bold',....
   'Callback', 'edit quantify');
\%Places "Color Quantification Program" string
uicontrol('Style', 'pushbutton',
   'String', 'Color Quantification Program',....
   'Position', [60 670 385 40],\%sizer,....
   'BackgroundColor', 'y',....
   'FontName', 'Times',....
   'FontSize', 18,....
   'FontWeight', 'bold',....
   'Callback', 'edit quantify');
\%Places "Run" control button that reruns program
uicontrol('Style', 'pushbutton',
   'String', 'Run',....
   'Position', [500 80 155 30],\%sizer,....
   'Callback', 'quantify',....
   'BackgroundColor', [0.3 .5 .75],....
   'TooltipString','Run Program',....
   'ForegroundColor', 'w',....
   'FontName', 'Times',....
   'FontSize', 14);
%Places "Close" control button that closes figure
uicontrol('Style', 'pushbutton',...
   'String', 'Close',...
   'Position', [240 80 135 30],*sizer, ...  
   'Callback', 'close',...
   'BackgroundColor',[0.3 0.5 0.75],...
   'TooltipString','Close Window',...
   'ForegroundColor','w',...
   'FontName','Times',...
   'FontSize',14);

%Places "New Start" control button that reruns program with initial values
uicontrol('Style', 'pushbutton',...
   'String', 'New Start',...
   'Position', [385 80 100 30],*sizer, ...
   'Callback', 'starter',...
   'BackgroundColor',[0.3 0.5 0.75],...
   'TooltipString','New Start',...
   'ForegroundColor','w',...
   'FontName','Times',...
   'FontSize',14);

uicontrol('Style', 'pushbutton',...
   'String', 'R ',...
   'Position', [95 20 25 25],*sizer, ...
   'Callback', 'R G B',...
   'BackgroundColor','r',...
   'TooltipString','RGB',...
   'ForegroundColor','w',...
   'FontName','CountryBlueprint',...
   'FontSize',12);

uicontrol('Style', 'pushbutton',...
   'String', 'G ',...
   'Position', [127 20 25 25],*sizer, ...
   'Callback', 'R G B',...
   'BackgroundColor', [0.1 1.1],...
   'TooltipString','RGB',...
   'ForegroundColor','k',...
   'FontName','CountryBlueprint',...
   'FontSize',12);

uicontrol('Style', 'pushbutton',...
   'String', 'B ',...
   'Position', [159 20 25 25],*sizer, ...
   'Callback', 'R G B',...
   'BackgroundColor','b',...
   'TooltipString','RGB',...
   'ForegroundColor','w',...
   'FontName','CountryBlueprint',...
   'FontSize',12);

%==============================================================================Comment Box-----
%
%Comment Box
uicontrol('Style', 'pushbutton', ...
   'String', 'Comments:',...
   'Position', [830 130 100 17],*sizer, ...
   'BackgroundColor', [0.4 0.2 0.35],...
   'ForegroundColor','w',...
   'FontSize',8);
uidef='Style', 'edit',...
  'String', comment,....
  'Position', [690 80 240 45], 'sizer',...
  'BackgroundColor', 'w', '...
  'FontSize', 8, 'Max', 3, '...
  'HorizontalAlignment', 'left');
  \% uicontrols are GUI commands
  \% Place "File" block
uidef='Style', 'pushbutton',...
  'String', 'File', '....
  'Position', [60 425 50 16], 'sizer',...
  'BackgroundColor', 'b', '...
  'ForegroundColor', 'w', '...
  'FontName', 'Times', '...
  'FontSize', 8, '...
  'Callback', 'edit color');
  \% Place "Temperature" block
uidef='Style', 'pushbutton',...
  'String', 'Temperature (C)', '....
  'Position', [120 425 85 16], 'sizer',...
  'BackgroundColor', 'y', '...
  'FontName', 'Times', '...
  'FontSize', 8, '...
  'Callback', 'edit color');
  \% Place "Hue Value" string
uidef='Style', 'pushbutton',...
  'String', 'Hue Value', '....
  'Position', [210 425 70 16], 'sizer',...
  'BackgroundColor', [0.4 0.2 .77], '...
  'ForegroundColor', 'w', '...
  'FontName', 'Times', '...
  'FontSize', 8, '...
  'Callback', 'edit color');

\% Color Quantification and Interface Program
\% Temperature from data acquisition
\% Currently is manually input to demonstrate processing

\texttt{temp=[39.5,39,38.5,38,37.5,37,36.5,36,35]; \% Temperature that corresponds with image 1}

\texttt{n=size(temp,2);}

\texttt{vert=400; horz=.05;}

\texttt{figure(1) \% opens up figure 1}
\texttt{prefix=str2num(get(prefixedit,'string'));}

\texttt{for i=1:1:n;}
  \%-----------------------------------------------
  \% Image n
  \texttt{axes1=axes('Position',[horz .75 .08 .08],'FontSize',8);
  \% calls image n}
  \texttt{kookie=strcat(num2str(prefix), '00', num2str(i), '.jpg');}
imshow ('kookie')

RGB = imread('kookie');
    x = [100];
    y = [100];
    pixels = impixel(RGB,x,y);
    HSV = rgb2hsv(pixels);
    hue(i)=HSV(1);
    
    %reads image
    % x pixel coordinate on image
    % y pixel coordinate on image
    % evaluates RGB values of pixel at [x,y]
    % translates RGB values to HSV values

% Place temperature value
uicontrol('Style', 'edit',
    'String', num2str(prefixedTemp),
    'Position', [60 vert 50 40],
    'BackgroundColor', 'w',
    'FontSize', 10,
    'Callback', 'edit quantify');

% Place temperature value
uicontrol('Style', 'edit',
    'String', num2str(temp(i)),
    'Position', [135 vert 50 40],
    'BackgroundColor', 'w',
    'FontSize', 10,
    'Callback', 'edit quantify');

uicontrol('Style', 'edit',
    'String', num2str(hue(i)),
    'Position', [220 vert 50 40],
    'BackgroundColor', 'w',
    'FontSize', 10,
    'Callback', 'edit quantify');

horz = horz + 0.75;
vert = vert - 25;
end

delete(axes2);
axes2 = axes('Position', [35 .35 .3 .3], 'FontSize', 8);
plotted on

pD = polyfit(temp, hue, 2);
pDg = pD(1)*temp.^2 + pD(2)*temp + pD(3);

% Polynomial
% Trendline Matrix

for i = 1:n
    xlabel('Temperature(C)');
    ylabel('Hue Value');
    hold on
    plot(temp(i), hue(i), 'b.');
    % plot temperature/hue
end
for tag=temph(1):01:temph(1);
pDg=pD(1)*tag^2+pD(2)*tag+pD(3);
%c Trouline Matrix
plot(tag,pDg,'r'); %plot temperature/hue
end

pixval % Creates bar at the bottom of figure that displays x,y pixel coordinates
       %, corresponding RGB values, and distance of dragged line
       % for image that the crosshairs are on
Appendix – E

Thermal Analysis Program

% Capstone Design
% February 25, 2000
% Copper Plate Static Analysis - 2nd version
% LC assumed to give no thermal resistance

clear all
k_c=388; % thermal conductivity of copper (W/m*K)
k_ins=3.29; % thermal conductivity of Butterboard (W/m*K)
k_cap=0.163; % thermal conductivity of Kapton (W/m*K)
k_glue=0.220; % thermal conductivity of Adhesive (W/m*K)
k_wood=0.170; % thermal conductivity of Wood base (W/m*K)

% properties of air @ 300K
k_a=26.3E-3; % thermal conductivity of air (W/m*K)
v=15.89E-6; % kinematic viscosity of air (m^2/s)
alpha=22.5E-6; % alpha for air (m^2/s)
T_o=20; % ambient temp (C)
Toabs=T_o+273.15; % absolute ambient temp (K)
L=3; % length copper plate (in)
A=L^2; % area of plate (m^2)
t_c=0.5; % thickness of copper plate (in)
t_glue=0.0005; % thickness of glue layers (in)
t_cap=0.002; % thickness of Kapton layers (in)
t_ins=2; % thickness of Butterboard under heater (in)
t_wood=1.031; % thickness of wooden stand base (in)
g=9.81; % gravity (m/s^2)
T_initial=50; % assumed value of T2
steps=100; % number of increments for heat flux
q_fa=[1:steps];
qa=q_fa*A;
R1a=t_glue/k_glue/A;
R2a=t_cap/k_cap/A;
R3a=t_glue/k_glue/A;
R4a=t_c/k_c/A;
R1b=R1a;
R2b=R2a;
R3b=R3a;
R4b=t_ins/k_ins/A;
R5b=t_wood/k_wood/A;
for n=1:steps
T4a(n)=T_first;
tol=5;
count=1;
while tol>0.0005
Ra(n)=g*(1/Toabs)*(T4a(n)-To)*L^3/v/alpha;
end
if $10^7 > \text{Ra}(n)$
    \[ h_a(n) = k_a/L \cdot 0.5 \cdot \text{Ra}(n)^{0.25}; \]
else if $10^7 <= \text{Ra}(n) & 10^{11} >= \text{Ra}(n)$
    \[ h_a(n) = k_a/L \cdot 0.15 \cdot \text{Ra}(n)^{(1/3)}; \]
else
    \[ n = 100 + 1; \]
end

$R_5 = 1/ha(n)/A$;
$R_{tot} = R_1 + R_2 + R_3 + R_4 + R_5$;
$T_{start}(n) = To + qa(n) \cdot R_{tot}$;
$T_{4a\_new}(n) = T_{start}(n) - qa(n) \cdot (R_1 + R_2 + R_3 + R_4 + R_5)$;
$tol = abs(T_{4a\_new}(n) - T_{4a}(n))$;
$T_{4a}(n) = T_{4a\_new}(n)$;
$\text{count} = \text{count} + 1$;
end

$T_{3a}(n) = T_{start}(n) - qa(n) \cdot (R_1 + R_2 + R_3)$;
$R_{6b\_temp}(n) = 1/ha(n)/A$;
$qb\_temp(n) = (T_{start}(n) - To)/(R_1 + R_2 + R_3 + R_4 + R_5 + R_{6b\_temp}(n))$;
$T_{5b}(n) = T_{start}(n) - qb\_temp(n) \cdot (R_1 + R_2 + R_3 + R_4 + R_5)$;
$tol = 5$;
$\text{count}2 = 1$;
while $tol > 0.0005$
    \[ \text{Ra}(2)(n) = g \cdot (1/Toabs) \cdot (T_{5b}(n) - To) \cdot L^3/v/\alpha; \]
    \[ h_b(n) = k_a/L \cdot 0.27 \cdot \text{Ra}(2)(n)^{0.25}; \]
    $R_{6b}(n) = 1/hb(n)/A$;
    $qb(n) = (T_{start}(n) - To)/(R_1 + R_2 + R_3 + R_4 + R_5 + R_{6b}(n))$;
    $T_{5b\_new}(n) = T_{start}(n) - qb(n) \cdot (R_1 + R_2 + R_3 + R_4 + R_5)$;
    $tol = abs(T_{5b\_new}(n) - T_{5b}(n))$;
    $T_{5b}(n) = T_{5b\_new}(n)$;
    $\text{count}2 = \text{count}2 + 1$;
end

plot = [qa', qb', Tstart', T3a', T4a', T5b'];

fid = fopen('plot.txt', 'w');
count = fprintf(fid, '%e  %e  %e  %e  %e\n', plot);
close(fid);
## Appendix – F

### Gantt Chart

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