Chapter I

INTRODUCTION TO LIQUID CRYSTAL THERMOGRAPHY AND A BRIEF REVIEW OF PAST STUDIES

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I . 1 Introduction

Developing accurate surface temperature and heat transfer coefficient measurement techniques is essential for the improvement of the current physical understanding of convection heat transfer and other thermal phenomena. Flow fields influenced by convection heat transfer frequently include three-dimensional flow, turbulent flow, free stream unsteadiness, separation, reattachment, transitional zones, etc. All of these features create complex spatial distributions of temperature and local heat transfer coefficient. Many modern thermal engineering systems operate at elevated temperature levels mainly because of thermal eficiency considerations. Detailed and accurate knowledge of thermal fields is often of critical importance in the development and design of new thermal engineering systems with improved thermal efficency.

Accurate wall temperature measurement is always the most important factor in convection heat transfer studies since the local convective heat transfer coefficient is defined as the rate of wall heat flux normalized by the temperature difference between the surface of the body concerned and the free stream fluid. Thin foil/film thermocouples are often used in wall temperature measurements, usually resulting in reasonably accurate results. However, this conventional method requires a large number of intrusive sensors and a long chain of data acquisition system components to obtain the wall temperature distribution of a heat transfer model. The sensor may interfere with the flow itself. There are also optical methods using infrared imaging techniques. The infrared imaging may provide high resolution; however, this technique requires a test section made of a special material which is transparent to infrared radiation. The infrared images taken under laboratory conditions also have an inherent noise problem coming from the imaging sensor which is a charge coupled device. In order to eliminate the noise generated by the infrared imaging sensor, cryogenic cooling is usually required. This requirement further complicates the measurement technique. More recent infrared sensors are cooled using Peltier modules that are thermo-ionic cooling systems. A more economical and convenient way of mapping wall temperatures and heat transfer distributions is the implementation of liquid crystals as distributed temperature sensors.

Thermochromic liquid crystals respond to a local temperature change as a local color change. Liquid crystal color can be used as an accurate indicator of temperature. The main advantages of this technique are the direct measurement of local temperatures over the heat transfer model with great spatial resolution and no obstruction to the flow or local heat flux. Using surface mounted liquid crystals for qualitative heat transfer investigations has been a recently encountered practice. Liquid crystals have been successfully applied to even complex three-dimensional heat transfer models. Steady-state and transient heat transfer techniques using liquid crystals require a careful quantitative interpretation of color patterns recorded from the heat transfer surfaces. Most of the previous interpretations of the liquid crystal images are based on human eye color perception which is subjective. Recently, monochromatic digital image processing techniques have been employed to eliminate the human eye color perception (Bunker et al., 1990; Wang et al., 1990). These techniques require lengthy data processing to locate the maximum intensity line or the yellow color band. Furthermore, a large number of images need to be processed to have enough spatial resolution, since only one isotherm is usually available from one video frame. A brief review of a few popular liquid crystal thermography methods are provided in the next section , (section I.2).

I . 2 Review of the Previous Investigations

Liquid crystals which have two distinct melting points are organic compounds derived from esters of cholesterol. At the first melting point the solid turns to a cloudy liquid and at the second the liquid becomes clear. This cloudy phase, called liquid crystal phase or mesomorphic phase, is a condition intermediate between a true solid crystal and an isotropic liquid. In this phase the molecules are movable but still organized in the form of a helical pattern. Mechanically this substance acts like a liquid, but it still has many of the optical properties of crystals. A typical liquid crystal substance reflects lights of different wavelength more or less strongly to different directions due to a re-orientation (rotation) of the liquid crystal's lattice depending on the temperature (Klein, 1968). This selective light reflection usually gives rise to a spectrum of colors on the heat transfer model surface.

The direction of the incoming light also affects the color display. For optimum brilliance, the liquid crystal should be applied as a thin film on a black substrate. The black substrate insures that all light transmitted through the liquid crystal zone is absorbed. Therefore, reflections which compete with the resulting image are avoided (Cooper et al., 1975). The molecular structure and optical and thermal properties of liquid crystals are extensively reviewed by Fergason (1964, 1968).

Liquid crystals are conventionally divided into three classes: smectic, chiral-nematic and cholesteric. Cholesteric and chiral-nematic liquid crystals show a very interesting feature from a heat transfer point of view. They are relatively insensitive to normal and shearing stresses (Zharkova et al., 1980) .They progressively exhibit all colors of the visible spectrum as they are heated through the event temperature range. The phenomenon is reversible, repeatable and the color can be calibrated accurately with temperature. The color response of liquid crystals to temperature is very fast and the response time is no more than a few milliseconds (Ireland and Jones, 1987). Both the width of the temperature range and its location on the temperature scale can be controlled by selecting the appropriate cholestric esters and proportions used in a given formulation. Liquid crystals are presently available for a temperature spectrum ranging from -40 to 285 ^{0} C . A mixture can be obtained with event temperature spans as small as 1 ^{0} C to as large as 50 ^{0} C. The use of thermochromic liquid crystals in research and testing is extensively reviewed by Parsley (1991).

Pure liquid crystals without any encapsulation exhibit brilliant colors. However, once they are applied to a model, they deteriorate rapidly in a few days of experimentation. They are contaminated easily with dust and other impurities, since they are mechanically liquid in mesomorphic phase. Furthermore, the detection of a color change is highly influenced by the illumination and the viewing angle. Many of the problems related to pure liquid crystals have either been eliminated or reduced by using a micro-encapsulation process. The micro-encapsulation process involves coating liquid crystals with gelatin in a polyvinyl alcohol binder. The coating results in the formation of small spheroids with a typical diameter of 20-60 microns. The life of a liquid crystal can be extended to several years protecting the crystal from atmospheric contaminants and ultraviolet light. The liquid crystal may either be used in the form of precoated sheet or water based slurry. The latter provides a means to coat manually the model surface with an ordinary brush.

When the liquid crystal coated heat transfer surface is illuminated by white light, a selective reflection of a specific wavelength occurs in the helical structure of the liquid crystal. This can be explained by the "interference of light reflected from the helical layers so that the optical wavelength in the material actually equals the helical pitch", Jones et al. (1992), Collings (1990), de Gennes (1974). The pitch of the crystal helix is very sensitive to temperature and hence the selectively reflected color may be used to indicate temperature.

According to Rau, Vanhalst and Arts (1993), cholesteric and Chiral Nematic Liquid crystals have “cigar-shaped” molecules with the long axis of the molecules parallel to the plane of the layers. Two adjacent layers are twisted by about 15 minutes of arc and this arrangement gives the helical variation in the direction of the molecular ordering. Due to the anisotropic crystalline structure found in liquid crystals an entering light beam (unpolarized) is divided into two beams with opposite (orthogonal) polarization. The two final beams will propagate in different directions with different speeds. The refraction indices for the extraordinary rays transmitted through the liquid crystal is not only a function of wave length but it also depends on the helical twist of the crystalline structure Rau et al. (1993). The change of the helical twist with temperature variation leads to different index of refraction for a given wave length.

A liquid crystal visualization of surface heat transfer on a concavely curved turbulent boundary layer was performed by Simonich and Moffat (1984). Wall traces composed of streak patterns on the surface were observed to appear and disappear randomly. Hippensteele et al. (1983) used cholesteric liquid crystals in developing a liquid crystal sheet and electric heater composite. They obtained a constant heat flux surface by using a vapor deposited gold layer on a polyester film. The local wall temperatures were obtained from the liquid crystal surface by monitoring the narrow yellow band. As a result of an extensive study, they showed that the composite element is a relatively convenient, simple, inexpensive and accurate device for high resolution heat transfer measurements to be performed under laboratory temperature conditions. Local heat transfer measurements on a large scale model turbine blade airfoil using a composite of heater element and liquid crystals is presented by Hippensteele et al. (1985).

A transient liquid crystal technique for a heat transfer study in turbine blade cooling geometries is presented by Ireland and Jones (1985). They used an initially heated heat transfer model in a transient wind tunnel with a mainstream flow at ambient temperature. A liquid crystal and heater element composite for quantitative and high resolution heat transfer coefficients on a turbine blade was used by Hippensteele et al. (1987). Turbulence and surface roughness effects on heat transfer were also included in the investigation. They calibrated the liquid crystal sheet in a temperature controlled water bath. Yellow color provided the narrowest temperature band. They also pointed out the importance of the viewing angle. They indicated that the calibration drift could be minimized if the liquid crystal coated sheet was bonded to an air tight surface. Another transient study focusing on the use of liquid crystals in wind tunnels is described by Jones and Hippensteele (1985). They used a transient heat transfer tunnel with a heated model in an air stream at ambient temperature. The emphasis in the experiments was to eliminate the initial surface temperature variations on the model surface.

In most of the studies reviewed up to this point, the image interpretation was based on human eye color perception which is subjective. Errors in human color determination are inevitable due to individual differences and lack of reproducibility. One way of reducing the possible errors in human color determination is to use narrow band liquid crystals. The liquid crystal images may be processed for the existence of a yellow or green color region which appears at a very narrow temperature band. A visual detection of a single yellow or green contour, in a majority of the experiments gave the most quantitative description of a single isotherm that could be captured from a specific liquid crystal image. Baughn et al. (1988) described a visual method based on capturing the $0.7\ ^0$C color band of a liquid crystal. Their method was for the investigation of pin fins with an experimental uncertainty of $4.7\ ^0$C on heat transfer coefficient. Kasagi et al. (1981) used a monochromatic sodium light source of 589 nm in wavelength which selectively illuminated the single isotherm for better accuracy.

There have also been studies using monochromatic digital image processing which exclude human color sensation. The maximum intensity line corresponds to a certain temperature in this method. In the spectrum of liquid crystal colors, green light carries the highest energy level. The intensity of electromagnetic light emission is maximum only when the green color shows up on the liquid crystal coated heat transfer surface. Wang et al. (1990) presented an imaging technique using an 8 bit black and white frame grabber. They marked the pixels for the appearance of a light intensity peak. These pixels corresponded to green dominated regions. Bunker et al. (1990) introduced another single color capturing technique using one intensity level of the three primary colors, red, green and blue. Their system was calibrated to capture a light blue liquid crystal color at a surface temperature of $38.4\ ^0$C for the specific thermochromic liquid crystal. These methods excluded the employment of the human color sensation, but provided only one isotherm from one image. By calibrating the intensity peak for the temperature, they were able to determine the isotherm which also corresponded to a specific level of heat transfer coefficient, at the specific time measured from the beginning of the transient experiment.

The methods reviewed up to this point are also applicable to steady state heat transfer tests. Multiple isotherms may be obtained by changing the temperature level of the constant heat transfer surfaces. Unfortunately, this procedure requires long waiting times before steady state conditions are achieved. Akino et al. (1989) devised an image processing method which provided many isotherms at a single heating condition in steady state heat transfer tests.Their method was based on the use of a set of sharp band-pass optical filters, attached to a black-and-white video camera. Each band pass filter provided the proper perception of a corresponding color band, representing a temperature level, from liquid crystal coated heat transfer surface. Eighteen video frames obtained with a set of 18 filters were processed to map the temperature distribution on a flat plate, since only one isotherm was available from one video frame. All of these monochromatic image processing techniques required lengthy data processing to locate the maximum intensity line or the yellow color band. Sometimes a false maximum could be treated as a real maximum when the temperature had a wavy profile. A large number of images needed to be processed to have enough spatial resolution, since only one isotherm was available from one video frame. The techniques also required a significantly large computer memory for the storage of all the liquid crystal images.

The multiple filter method discussed by Akino (1989) has been effectively used in a heat transfer study dealing with 180 ^{0} turning duct with rectangular cross section by Rau et al. (1993). The specific version is based on extracting multiple isothermal lines from a heat transfer surface. A number of optical band pass filters (narrow band) ranging from 441 nm up to 770 nm are used to define isochromatic regions (hue bands) from a liquid crystal image. 16 different filters with a bandwidth ranging from 1 nm to 13.1 nm are utilized. Each filter allows the transmittance of light in a well defined (narrow) hue band that can be associated with a narrow temperature range. It is also possible to assign a more precise temperature value (isotherm value) to the peak of the intensity distribution recorded by an imaging sensor. Since the problem is defined as finding the maximum intensity point of a distribution obtained from a pre-calibrated band-pass filter a mono-chromatic camera is usually sufficient. The filter calibration apparatus used by Rau et al.(1993) consists of a temperature controlled Aluminum plate, reference thermocouples mounted on the heat transfer surface, a chromatic CCD imaging sensor, a set of narrow band pass filters and an illumination system. A typical temperature difference of 5 ^{0} C is adjusted over a fixed distance (ranging from 10 mm up to 265 mm) . The temperature gradient is measured by 9 thermocouples over the fixed distance. The heat transfer surface is contained in an evacuated chamber so that the free convection effects are minimized during the calibration. The intensity peak obtained from a given optical filter is associated with the local temperature as measured by the thermocouple array at the peak location. During actual temperature measurements, whenever an intensity peak is captured from a filter by the CCD imaging sensor, the calibrated temperature value is assigned to the location where the peak is apparent. Extensive temperature and Nusselt number distributions on the endwall surface of a 180 ^{0} turning duct is presented by Rau, Vanhalst and Arts (1993).

A true color digital image processing was first applied to the measurement of the temperature distribution on a specimen from its color video image by Hollingsworth, Moffat et al. (1989). Their effort was limited to steady state experiments. A wide-band 28-34 ^{0} C liquid crystal paint was calibrated for its temperature versus hue angle (wavelength) relationship. The RGB signals taken from a standard color video image were digitized to calculate a hue angle. For this case, RGB to hue conversion at each pixel of an image requires a set of computer calculations. The maximum temperature uncertainty was given around ± 10 % of the liquid crystal bandwidth. The initial validation of the hue-capturing technique that is used very frequently throughout the next five chapters employed an impinging jet model. Impinging jets are very attractive in heat transfer augmentation technology. Convective heating or cooling of a selected area of solids can be accomplished effectively with jet impingement because of the high local heat transfer coefficients around the stagnation point. They also show several interesting flow features such as the free jet layer, stagnation flow and wall jet layer. Since the impinging round jet flow and its associated heat transfer character is chosen as a validation test vehicle, a brief literature review on this phenomena will be provided in this section.

There have been numerous experimental and numerical investigations on impinging jet heat transfer. Reviews of the earlier studies on the heat transfer of impinging jets are given in Downs and James (1987) and Martin (1977). A number of studies investigated the influence of Reynolds number, the distance between the nozzle exit and the impingement plate, and the radial distance from the stagnation point on heat transfer from a heated plate to impinging cold jets (Gardon and Cobonpue, 1962; Hrycak, 1983). The optimum nozzle-to-plate distance was found to coincide with the length of the potential core. The Nusselt number increased with Reynolds number with the power of 0.5 in the stagnation region and 0.7 in the wall jet region.

Among the widespread literature on the jet impingement heat transfer phenomena, there are still large differences in distributions of the local heat transfer coefficient, particularly at small nozzle-to-plate distances and in the vicinity of the stagnation point. These discrepancies are caused mainly by the different flow structures of the jets produced by different flow systems. Obot et al. (1979) carried out an extensive study to see the effect of nozzle inlet shape (contoured and sharp edged) and nozzle length to diameter ratio on impingement heat transfer. They found that nozzle geometry influenced mainly the heat transfer coefficient in the stagnation region at small nozzle-to-plate distances. Two extreme nozzle conditions (square edged pipe and orifice) were employed by Gundappa et al. (1989). The pipe nozzle generally showed higher heat transfer coefficients due to the large degree of mixing of the jet with the surrounding air. The mixing with the ambient air was restricted for the orifice nozzle. Contoured nozzles were considered to be somewhere in the middle of the two extremes. In addition, the turbulence level at the nozzle exit was found to affect the heat transfer characteristics by Amano (1983) and Gardon and Akfirat (1965).

Most of the previous studies on impinging jet heat transfer were performed with a heated plate and ambient temperature jet; however, Popiel et al. (1980) employed a heated jet with an ambient temperature plate. The heat transfer characteristics for incompressible flow are the same whether the plate is heated or cooled relative to the jet temperature, since the energy conservation equation is linear when the flow properties are assumed constant. But there are two different surrounding fluid temperature conditions:

(i) surrounding fluid at jet temperature and

(ii) surrounding fluid at plate temperature.

They showed different heat transfer characteristics for the two conditions. When a heated jet impinges on the plate, the cold surrounding fluid is entrained into the jet. This thermal entrainment changes the temperature distribution of the jet and affects the heat transfer from the impinging jet to the plate.

Striegl and Diller (1984a, 1984b) carried out analytical and experimental studies on the thermal entrainment effect on impinging jet heat transfer. In their investigations, the jet temperature was varied between the ambient temperature and the temperature of the heated target plate. They stated that entrainment is an inherent feature of jet arrays, even for the ambient temperature jet with the heated plate. Hollworth and Wilson (1984) and Hollworth and Gero

(1985) showed the effect of the entrainment of surrounding air at a different temperature from that of the jet. Goldstein et al. (1990) concluded that the heat transfer coefficient is independent of the relative magnitude of nozzle exit temperature and the ambient temperature, if the recovery temperature is used as a reference temperature in the definition of heat transfer coefficient. Therefore, the heat transfer coefficients for
impinging jets at ambient temperature, which have been studied extensively, can be used for jets at
temperature different from that of surrounding fluid if the local adiabatic wall temperature is known. An extensive use of round impinging jet on a flat heat transfer surface is made in Chapter II for liquid crystal thermography technique validation purposes.

I . 3 Outline of the Lectures

The present set of lectures is aimed at development and validation of a complete liquid crystal thermography method used in thermal systems research. Quantitative interpretations of liquid crystal images used in thermal studies are provided for a wide range of popular applications . The specific techniques using the hue-capturing method presented in this set of lectures are usually accurate, convenient and reliable. The color recognition process makes extensive use of digital image processing including true color processing methods. The particular efforts reported in this document employ micro-encapsulated chiral-nematic thermochromic liquid crystals for accurate, non-intrusive wall temperature measurements.

Chapter I is an introduction to liquid crystal thermography including a brief summary of the past studies relevant to the lectures. Fundamentals of the selective light reflection process that makes liquid crystal thermography possible are discussed in terms of the molecular structure of the liquid crystals. The volume of the first chapter is kept to a minimum by including only the studies directly related to thermography issues. For further details on specific methods the reader is encouraged to refer to the publications that are enclosed at the end of the chapter.

Chapter II describes the specific color recognition technique used in temperature and heat transfer measurements during the last 10 years in the Turbomachinery Heat Transfer Laboratory of the Pennsylvania State University. Since the discussions provided in the last five chapters of this document extensively uses the specific color recognition approach (hue capturing technique), a detailed discussion of this method is provided in Chapter II.

An implementation of the color recognition method described in the previous paragraph to a transient heat transfer experiment is described in Chapter III. A turbulent round jet impinging on a flat heat transfer surface is used as a test vehicle for the completion of the heat transfer measurement methodology in the transient mode. The heat transfer results are supported via extensive fluid mechanics field documentation including mean flow and turbulent flow details. Heat transfer results from liquid crystal thermography are compared to past studies that extensively documented the impinging round jet configuration.

Chapter IV focusses on the use of liquid crystal thermography on highly curved surfaces. Curved bottom surface of a square to rectangular transition duct is mapped for heat transfer coefficients using a transient heat transfer method. An application of a liquid crystal mixture containing three different slurries responding at three different temperature zones is explained. The high resolution nature of the specific mapping procedure is discussed.

A steady state heat transfer method is described over a flat heat transfer surface with arbitrarily specified external boundaries in Chapter V. The composite heat transfer surface uses a thin foil (Inconel) type heat flux surface. However, the heat transfer surface is far from a thermal boundary condition that can be described as a constant heat flux surface. Because of the arbitrarily specified external boundary shape, joule heating over the heat transfer surface is not constant. Specifying the distribution of local heat flux in the present approach is achieved by predicting the local heat flux in function of the arbitrarily specified shape of the external boundary and the electrical boundary conditions. The prediction is obtained by solving the electro-static boundary value problem over the heat transfer surface using a finite element method. The specific method yields an overall experimental uncertainty value of less than 4 % on convective heat transfer coefficient. The technique is highly applicable to heat transfer surfaces with multiple film cooling holes and rows. An evaluation of the method on the endwall surface of a 90^{0} turning duct is discussed in detail.

The last chapter (Chapter VI) deals with the problem of measuring temperature in a rotating frame of reference in a non-intrusive manner. Details of a liquid crystal thermography technique are described for the test case of a rotating free disk. A detailed investigation of the influence of rotation on the color response of liquid crystals is presented. The liquid crystal hue at many different rotational speeds on the disk surface is correlated with an infrared point sensor based temperature measurement. It is clearly shown that the centrifugal acceleration and aerodynamic shear stress can not alter the static color (hue) calibration of liquid crystals in a wide centrifugal acceleration range found in turbomachinery applications. Temperature measurements from an adiabatic free disk experiment are compared to a well established rotating disk heat transfer theory with good agreement.

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