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A New Hue Capturing Technique for the Quantitative Interpretation of Liquid Crystal Images Used in Convective Heat Transfer Studies

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ABSTRACT

This study focuses on a new image processing based color capturing technique for the quantitative interpretation of liquid crystal images used in convective heat transfer studies. The present method is highly applicable to the surfaces exposed to convective heating in gas turbine engines. The study shows that, in single crystal mode, many of the colors appearing on the heat transfer surface strongly correlate with the local temperature. A very accurate quantitative approach using an experimentally determined linear hue versus temperature relation is possible. The new hue capturing process is discussed in detail, in terms of the strength of the light source illuminating the heat transfer surface, effect of the orientation of the illuminating source with respect to the surface, crystal layer uniformity and the repeatability of the process. The method uses a 24 bit color image processing system operating in hue-saturation-intensity domain which is an alternative to conventional systems using red-green-blue color definition. The present method is more advantageous than the multiple filter method because of its ability to generate many isotherms simultaneously from a single crystal image at a high resolution, in a very time efficient manner. The current approach is valuable in terms of its direct application to both steady state and transient heat transfer techniques currently used for the hot section heat transfer research in air breathing propulsion systems.

LIST OF SYMBOLS

c	specific heat
CCD	charge coupled device
CIE	Commission Internationale de L'Eclairage
D	jet exit diameter
E	power distribution of the illuminant
h	convective heat transfer coefficient, $h=\dot{q}/(T_{rec}-T_W)$
H	normalized hue
HSI	hue, saturation, intensity, (normalized)
I	local intensity
k	thermal conductivity of air
l	the distance between the white point and the fully saturated color at a given ϕ
L	illumination length to heat transfer plate distance
m	slope of hue versus temperature relation
n	intercept of hue versus temperature relation
Nu	Nusselt number, Nu=hD/k
NTSC	National Television System Committee
$\dot{q}$	heat flux
r	radius
R	reflectance characteristic of the colored surface
R,G,B	red, green, blue, (normalized)
Re	local Reynolds number based on jet exit diameter and centerline velocity
R35C1W	Chiral Nematic liquid crystal starting to respond at about 35 °C with an approximate bandwidth of 1 °C
S	saturation
t	time

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T	temperature
TRS	total tristimulus value
TU	turbulence intensity
U,V,W	three components of mean velocity
x,y,z	chromaticity coordinates
X,Y,Z	tristimulus values
$\bar{x},\bar{y},\bar{z}$	standard psychophysical characteristics of human eye

Greek symbols

α	thermal diffusivity of air $\alpha=k/(\rho c_p)$
β	non-dimensional time, $\beta=h\sqrt{t}/\sqrt{\rho c k}$
δ	actual saturation distance between white point and the specific color at a given hue
θ	illumination angle (measured from the heat transfer surface)
ϕ	hue angle measured from red-white line in degrees
ρ	density of air
λ	wavelength

Subscripts

∞	free stream
w	local wall condition
jet	jet centerline condition at the exit
rec	recovery
p	at constant pressure
i	initial
λ	spectral local value

INTRODUCTION

The performance of present day air breathing propulsion systems can be significantly improved through a better understanding of heat transfer processes in the flow paths of the hot section components. Using surface mounted liquid crystals in mapping temperature and heat transfer distributions has recently been a frequently encountered practice. Steady-state and transient heat transfer techniques using liquid crystals require a careful quantitative interpretation of color patterns recorded from the heat transfer surfaces of hot section components. Cholesteric and chiral-nematic liquid crystals show a very interesting feature from a heat transfer point of view. They will progressively exhibit all colors of the visible spectrum as they are heated through the event temperature range. The phenomena is reversible, repeatable and the color can be accurately calibrated with temperature. 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 a few degrees below zero to several hundred degrees C. A mixture can be obtained with event temperature spans as small as 1 ^{o}C to as large as 50 ^{o}C. An excellent review of the application of liquid crystals in heat transfer measurements is given in **Cooper et al.**,(1975) and **Simonich and Moffat**, (1984). **Hippensteele et al.**, (1983) used cholesteric liquid crystals in developing a liquid crystal sheet and electric heater composite. They used liquid crystals laid on a black plastic sealing material covered with a transparent Mylar layer. The lower layer of the composite was the heater sheet. 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 blade cooling geometries is presented by **Jones and Ireland**, (1985). They used an initially heated heat transfer model in a transient wind tunnel with a mainstream 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 is 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 summarized to this point, the images were processed for the existence of a yellow color region which appears at a very narrow temperature band. A visual detection of a single yellow contour, in a majority of the experiments was the most quantitative description of a single isotherm that could be captured from a specific image. **Baughn et al.**, (1988) described a visual method based on capturing the 0.7 ^{o}C color band of a liquid crystal. Their method was for the investigation of pin fins with an experimental uncertainty of 4.7 % on heat transfer coefficient. **Wang et al.**, (1990) presented an imaging technique using an eight bit black and white frame grabber. They marked the pixels for the appearance of a light intensity peak. By calibrating the intensity peak for the temperature, they were able to determine the isothermal line which represents a specific level of heat transfer coefficient at the specific time measured from the beginning of the transient experiment. **Bunker et al.**, (1990) introduced another single color capturing technique using the chrominance-luminance description of color which is widely used in commercial video applications. Their system was calibrated to capture a light blue liquid crystal color at a surface temperature of 38.4 ^{o}C for the specific thermochromic liquid crystal. The chrominance determination was performed by using the techniques developed by **Hirsch**, (1987).

Numerous previous investigations performed during the last decade were mainly using a single color mode which provided a single isothermal contour per captured image based on the appearance of a very narrow pre-calibrated color band. There were also studies using multiple mixtures of liquid crystals to obtain a few isothermal lines per image. Another approach was employing a number of optical filters to obtain more than one isothermal line from a given liquid crystal image. The current study presents and proves that the majority of the complete spectrum of colors appearing on a liquid crystal sprayed surface can be used to generate many isotherms simultaneously. A wide spectrum of colors from red to yellow, yellow to green and finally from green to a wide blue zone can be calibrated very accurately to define extremely narrow multiple temperature bands. The method is very suitable for transient heat transfer studies. Having multiple (as many as 40) isotherms in each video frame reduces the total number of frames to be captured. The specific color capturing technique on a color image processor provides a highly automated heat transfer method which reduces lengthy data reduction processes and significantly improves the spatial resolution of heat transfer measurements.

INTERPRETATION OF COLOR VISION PRINCIPLES FOR LIQUID CRYSTAL IMAGING STUDIES

Color may be defined as a psychophysical property of light specifically, the combination of those characteristics of light that produces the sensations of hue, saturation and intensity in a normal human observer. Color sensation from a liquid crystal covered surface is generated by a number of characteristics such as the orientation of the crystals on the surface, the spectral characteristics of the light illuminating the liquid crystal covered surface and the spectral response of the color sensing component which may be human eye or an imaging sensor used in a color camera. The orientation of liquid crystals is altered by the local temperature distribution on the heat transfer surface. Any temperature change at a given point on the liquid crystal covered surface results in a significant change in the local spectral reflectivity of this point, and therefore a color change is sensed by human eye or a visual sensor. Intensity of a color refers to the relative brightness of a color. This quantity represents a total sum of the spectral energy incoming to the sensor, emitted by the heat transfer surface at various wavelengths in the visible electromagnetic spectrum. Hue refers to that attribute of color that allows separation into groups by terms such as red, green, yellow, etc.. In visible spectrum, hue directly corresponds to the dominant wavelength of the color. Saturation refers to the degree to which a color deviates from a neutral gray of the same intensity - called pastel, vividness etc.. Saturation may also be defined as a colors purity or the amount of white contained in a specific color. By mixing a main hue (e.g. red) with white at different amounts, one can always generate less saturated colors (e.g. tones of pink). The amount of saturation is directly proportional with the amount of white added. Any color of the spectrum when highly desaturated should approach standard white color. These three characteristics, hue, saturation and intensity represent the total information necessary to define and/or recreate a specific color stimulus. Conceptually, this definition of color is highly convenient and appropriate for an image processing system to be used in the determination of convective heat transfer parameters from a liquid crystal sprayed surface, simply because the temperature of the point of interest is directly related to the hue value of the color displayed at that point. Since the orientation of the liquid crystal is the main controlling parameter for the color (hue, wavelength), a direct relation between the local temperature and the locally measured hue value can be established.

To determine specific parameters that describe a color on a heat transfer surface, three highly interrelated factors must be taken into account. 1) Spectral reflectivity of the surface being observed. This quantity is controlled by the liquid crystal layer, uniformly coated on the heat transfer surface. The crystal layer is usually applied on a black coating on the surface. 2) Spectral distribution of the light source illuminating the heat transfer surface. 3) Spectral sensitivity of the imaging sensor. Most of the available present day imaging sensors such as color CCD arrays simulate the spectral sensitivity of the "standard human eye". The main task of the presently developed image processing system hardware and algorithms is to bridge the perceived quantiative color information and the local temperature at a given point on a liquid crystal covered surface for heat transfer research purposes. The method assumes that perceived color changes due to slight changes in the illumination characteristics can be minimized and calibrated. The spectral response of the imaging sensor can also be taken into account during a typical hue versus temperature calibration procedure.

Color vision system uses a number of principles derived from a mathematical color matching model established by Grassman as described in **Wyszecki and Stiles** (1967) and **Pritchard** (1977). The basic principles used in modern tristimulus colorimetry are as follows ;

1) The human eye can distinguish only three kinds of differences, which we now call hue (dominant wavelength), saturation and intensity.

2) In a two component color mixture if one component is held constant and the other changed gradually, the color of the mixture will change gradually.

3) Lights of the same color (same dominant wavelength, saturation and intensity) will produce identical effects in mixtures regardless of their spectral distribution.

4) The intensity produced by a mixture of several lights is equal to the sum of the intensities of the individual lights.

According to the tri-receptor theory of vision, human eye translates radiant energy to visual stimuli by using three sets of cones and rods having individual response curves in the red, green and blue portions of the visible spectrum.

The human eye detector evaluates the intensity of an image by summing the stimuli from the three receptors, while the chromatic attributes, hue and saturation are determined by the ratios of the stimuli. Thus, light sources having widely different spectral distribution may give exactly the same visual color sensation as long as the amount and ratios of the total stimulation are the same. The intensity obtained by summing the stimuli from the three receptors is represented by a luminosity function. The details of the definitions are described in detail by **Overheim and Wagner** (1982), **McIlwain and Dean** (1956), **Zworykin and Morton** (1940), **Fink** (1955), **Pearson** (1975), **Bingley** (1977). The basic principles and analysis given in these references state that only three independent quantities are required to specify a color and that color intensities add linearly. Therefore, a color specification system can be envisioned as involving a three dimensional color space with any set of convenient coordinates, and these coordinates may be transformed mathematically into any other set for convenient measurement or analysis. Colorimetric coordinate systems which can be used include the intensities of three color primaries **(R,G,B)** or hue, saturation and intensity **(H,S,I)**, or intensity and two color difference signals **(I,R-I,B-I)**. The fundamental quantities of tristimulus colorimetry as established by the CIE are as follows;

$$X=\int E_\lambda R_\lambda \bar{x} d\lambda \qquad Y=\int E_\lambda R_\lambda \bar{y} d\lambda \qquad Z=\int E_\lambda R_\lambda \bar{z} d\lambda \tag{1}$$

X , Y and Z are the definitions of tristimulus values and the integrations are taken through the visible region of the spectrum. E_λ represents the spectral power distribution of the illuminant in which the coloured object is viewed. The function R_λ represents the reflectance characteristic of the coloured surface, that is, the proportion of incident light which is reflected, expressed as a function of wavelength. This quantity is strictly controlled by the liquid crystal response to local temperature. The three functions $\bar{x}$, $\bar{y}$ and $\bar{z}$ describe the standard psychophysical characteristics of a standard human eye.

Using the tristimulus values as fundamentals, other related quantities called "chromaticity coordinates" may be defined, as follows;

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} \tag{2}$$

The quantity TRS = (X + Y + Z) is called the total tristimulus value. It may be written that;

$$TRS = (X + Y + Z) = \frac{X}{x} = \frac{Y}{y} = \frac{Z}{z} \tag{3}$$

The tristimulus values express the psychophysical assesment of a color by a standard observer whose characteristics have been established by a number of observers. The tristimulus values can also be transformed into a two dimensional set of values describing the chromaticity values (hue and saturation), independent of intensity. In effect, x, y and z represent the relative amounts of the three imaginary primaries required to match a particular color. Since x + y + z = 1 , once two of the three numbers x, y, z are given, the third is automatically determined. A graphical representation of of x , y coordinates are shown in Figure 1. Every (x,y) point on this diagram represents a unique color or chromaticity. It turns out that the chromaticities for all physically possible spectra are confined to a single region of the chromaticity diagram as shown in Figure 1. This region is called "color locus". Chromaticities outside the color locus are impossible to achieve with any spectrum of light from the visible spectrum. The horse-shoe shaped outer boundary of the color locus represents the characteristics of all pure colors of the visible spectrum. The corresponding wavelengths are labeled around the periphery of this curve, which is also known as the spectrum locus as shown in Figure 1. The lower portion of the locus is bounded by a straight line that connects the blue and red ends of the spectrum locus. The straight line is known as the purple line. Hues along this line are not produced by any single wavelength of light but rather, result from the mixture of red and blue light. Points along the periphery of the color locus (along the spectrum locus and purple line) represent colors of the maximum saturation. As we move towards the center of the color locus, the saturation diminishes until, at the point x=0.333, y=0.333 the saturation becomes zero. This central point labeled M in Figure 1 represents equal energy white. The exact definition of white point may vary slightly in different video standards.

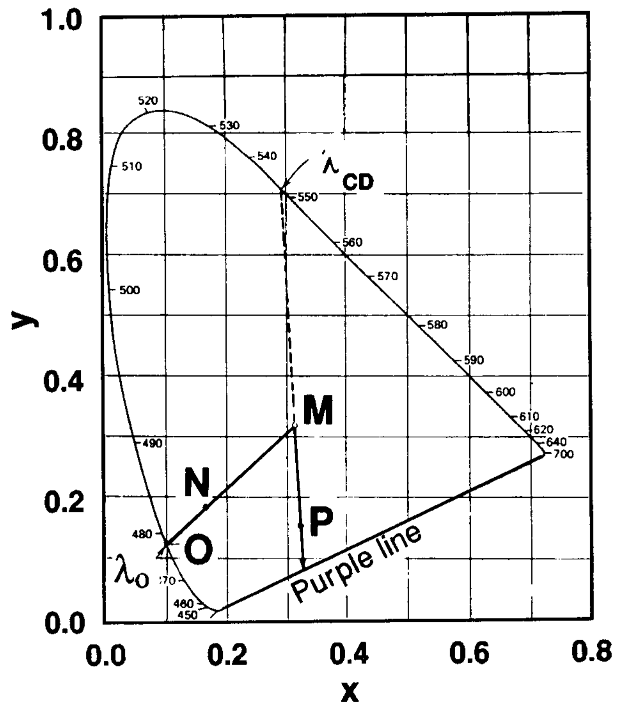


Figure 1
Chromaticity diagram indicating all physically possible colors from the visible spectrum

The chromaticity diagram shown in Figure 1 can be used to analyze color mixtures or determine dominant wavelength and saturation of a color. Point N in Figure 1 represents the chromaticity of some spectrum of light. If a line is drawn from point M through N until the line strikes the spectrum locus at point O, point O will be located at a particular wavelength on the spectrum locus, λ_O. Thus knowing λ_O gives an immediate idea of what kind of color N really is. White point M is considered to have zero saturation while a pure color such as O is considered to be 100 % saturated. Then saturation at point N expressed as a percent is given by;

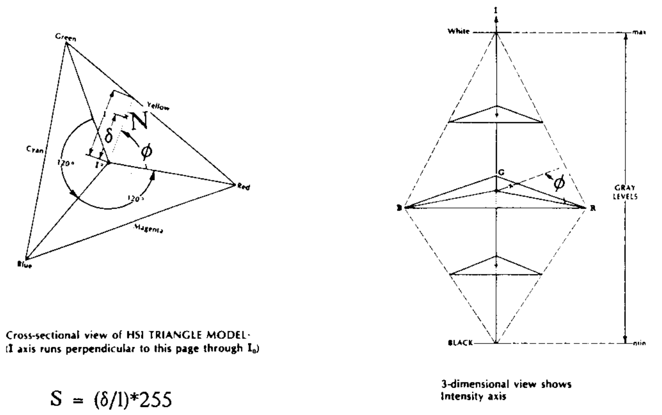
$$S = (\text{length of NM})/(\text{length of OM}) \tag{4}$$

Further details of **RGB** and **HSI** domain color operations are given in **Ohta et al.** (1980), **Kender** (1976) and **Pratt** (1978).

THE PRESENT REAL TIME HUE CAPTURING SCHEME USING AN ELECTRONIC ANALOG CIRCUIT

The present real time hue capturing system operates using an NTSC standard 24 bit color image processing system. The system is capable of converting (R,G,B) information into (H,S,I) on each of the pixels in a 512x480 image, using a real time electronic hue converter. The imaging device used in this study has a high light sensitivity color CCD sensor consisting of about 632,000 pixels capable of generating red, green and blue attributes. 30 complete frames having a spatial resolution of about 512x480 can be scanned in one second. Red, green and blue attributes are then multiplexed and sent to the image capturing board. The current system has the capability of either recording the image on a standard magnetic video tape or transferring the image data directly to the random access memory of the computer. The current computer and the image processor can transfer a complete color image captured in real time on to a hard disk at approximately every two seconds. Direct digital recording on computer memory avoids a significant amount of noise that can be introduced when using standard video tapes. The present color image capturing board may either accept three individual R,G,B signals generated by a color camera or a multiplexed NTSC standard video signal. Three 8 bit video A/D converters generate digital signals before they are converted into an H,S,I signal for each pixel. The RGB-HSI conversion is performed on high performance electronic circuitry in real time. Four individual frame buffers each having 256 KBytes of video memory is used for storing intensity, saturation, hue and additional graphics and text information. There is also a second HSI-RGB converter at the output of the four frame buffers. This section provides a real time display of the contents of the buffers on typical RGB or NTSC color monitors. The buffer contents may be captured whenever needed and the storage process can be initiated by transferring the video image to the random access memory of the computer.

The RGB triangle used by the current system and the relation between HSI and RGB color coordinates is shown in Figure 2. By knowing the red, green, blue attributes inside the RGB triangle, one can always geometrically generate the attributes hue, saturation and intensity. The intensity attribute is dependent on the sum of the R, G and B attributes. The chrominance attributes hue and saturation are based on the relative proportions of R, G and B. Thus the relationships of red, green and blue to the hue or saturation are highly non-linear. A three dimensional view of the HSI triangular model is also shown in Figure 2. The intensity axis is perpendicular through the center of the RGB triangle. The present system uses three 8 bit video A/D converters, therefore each one of the R,G,B signals varies between 0 and 255. When they are converted into HSI values the new values are also normalized in



$S = (\delta/l)*255$

$H = (\phi/360)*255$

$I = (R + G + B)/3$

Figure 2
RGB triangle used by the current system, geometrical description of hue, saturation, intensity and a three dimensional view of the present color model

such a way that they remain between 0 and 255. The definition of intensity is as follows;

$$I = (R + G + B)/3 \quad (5)$$

Saturation is defined as δ/l for the local point N as shown in Figure 2. The lines connecting the R, G and B points of the triangle carries the maximum available saturation of a given hue. Any movement from the maximum saturation line to the center of the HSI triangle makes this specific hue more desaturated. The point at the center of the triangle represent the color white. The saturation values around the periphery of the triangle are at a maximum value of 255. The hue is modeled as the angle (ϕ) rotating around the intensity axis with 0 ° at R, 120 ° at G, and 240 ° at B. In non-dimensional form hue may be expressed as (ϕ/360) for the point N. The normalized expressions of the saturation and hue values in 8 bit integer scale are as follows;

$$S = (\delta/l)*255 \quad (6)$$

$$H = (\phi/360)*255 \quad (7)$$

The (δ/l) and (ϕ/360) can be calculated from the R,G,B attributes. The model resulting from the following expressions is based on an equal sided triangle with the white point located exactly on the center of gravity of the triangle. The conversions from R,G,B attributes are described in detail in **Camci et al.** (1991) and **Berns** (1989).

THE MODEL

In order to validate the current hue capturing technique on a liquid crystal covered heat transfer surface, a 19.7 mm thick flat plexiglass plate was manufactured. The plate had a total surface area of 1.0 x 1.0 m^2. One side of the plexiglass plate was coated with a chiral nematic liquid crystal layer (R35C1W). The crystals used were encapsulated. After the application of the crystal layer, a black coating was applied on top of the temperature sensitive liquid crystal layer as shown in Figure 3. The top surface of the model was designated as heat transfer surface. Convective heat flux was always applied from the top surface. However, the imaging camera was located at the bottom of the plexiglass model. This approach provided a viewing angle which was normal to the heat transfer surface. This configuration avoided a number of distortion corrections when viewing two dimensional complicated images. The illumination system was also located on the camera side of the plate. The model was carefully covered in order not to damage the crystals from exposure to ultraviolet light. A direct exposure of the liquid crystal surface to sun light was avoided. It was also expected that most of the ultraviolet light was going to be filtered during passage from laboratory windows and the thick (19.7 mm) plexiglass plate. Four fast response K type thin foil thermocouples were flush mounted at separate locations on the heat transfer model for calibration purposes. The thermocouples had typical time response of about 2 milliseconds. The temperature measurement chain was carefully calibrated. The uncertainty of the temperature measurement with the foil thermocouple was expected to be within ∓ 0.15 ° C. Temperature recording was performed by using a 4 1/2 digit temperature read

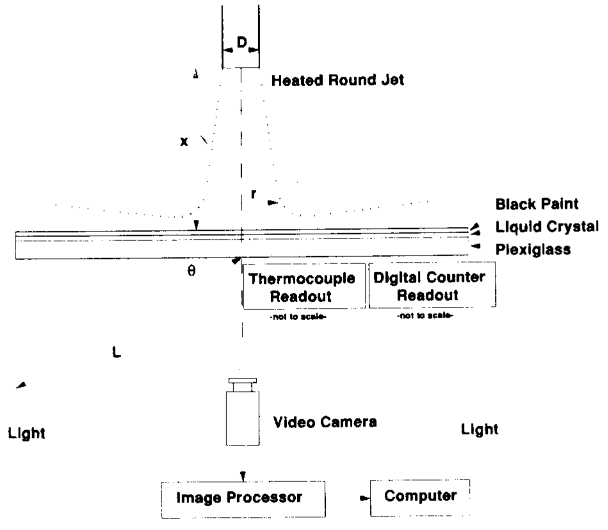


Figure 3
Experimental setup, the heated round jet and the heat transfer surface

out made up of red 7 segment light emitting diodes. The readout was located on the camera side of the heat transfer plate. The video recordings of the liquid crystal image also carried the instantaneous temperature information at a local point. The time response of the whole temperature measurement chain was in the order of 100 Hz. This response guaranteed a correct temperature recording on each of the sequentially captured images, captured at a standard rate of 30 frames per second .

EXPERIMENTAL RESULTS AND DISCUSSION

Hue versus Temperature Relation

Hue versus temperature calibrations were performed locally in order to find out the dependency of liquid crystal color to temperature on the heat transfer surface. Hue values at a pixel located at the center of the plate were recorded at different local temperature values as shown in Figure 4. The local temperature of the pixel was changed by applying a radiative heat flux from a temperature controlled hot plate. A fast response thin foil thermocouple of K type was flush mounted at the specific pixel location. Slowly varying color pattern and the measured temperature from the thermocouple were simultaneously recorded on a video tape. Figure 4 shows the variation of the local temperature measured by the thermocouple with respect to the color information captured by using a digital image processing system. The color information in the form of hue shows a very linear variation with respect to local temperature between 35.3 °C and 36.3 °C . The hue values smaller than 30 representented the black zone appearing just before red for the specific liquid crystal used, (R35C1W). This area is the coldest zone on the heat transfer surface. The absolute value of the hue assigned to each color is strictly controlled by the calibration of the RGB to HSI analog conversion unit. Standard video calibration sources are needed to calibrate the color image capturing device. The hue range between 30 and 140 contained typical colors such as red, orange, yellow, green and blue. This linear range was the most useful part of the hue versus temperature relation in terms of performing accurate temperature measurements using the color capturing technique. A complete spectrum of colors was located in an almost 1 °C wide temperature band. The discrete data points shown in Figure 4 showed an uncertainty band of less than ∓ 0.1 °C in the hue range between 30 and 140. The hue values above 140 corresponded to the wide dark blue zone which is very typical of liquid crystal images. The present color image processing system uses an eight bit discretization for the hue capturing process. This feature allowed division of the complete color range into 255 units. For the specific liquid crystal calibrated (R35C1W), the slope of the useful hue range suggested that a 0.1 °C change in the local temperature corresponded to a relative hue change of 12 hue units.

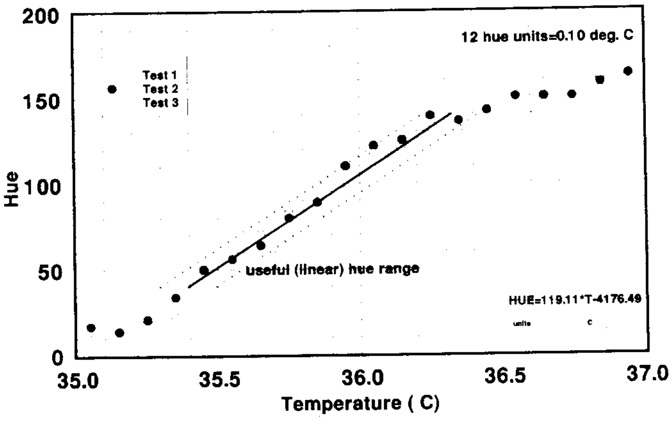


Figure 4
Hue versus temperature relation for a typical pixel located on the heat transfer surface, (R35C1W)

Effect of Illumination Source to Model Distance

It is a known fact that color perception from a liquid crystal image is influenced by the type of liquid crystal applied, the amount of light illuminating the surface, spectral response of the color image sensing device, uniformity of the sprayed liquid crystal layer, in addition to the selective reflectivity of the surface which is controlled by the liquid crystals in function of the local temperature. The effect of the amount of the light illuminating the heat transfer surface on color capturing process is given in Figure 5.a. An incandescent light source (500 W, 3200 °K) contained in a reflector was used to illuminate the liquid crystal applied surface. The light source was kept at θ=40 degrees to the surface for all of the experiments, unless otherwise stated. All of the experiments were performed during the night in complete darkness in order to eliminate the contribution of all other light sources, except the illuminating source. Figure 5.a compares the results from 5 different experiments each with a different light source to model distance with the same source. The distances were varied from 1.25 m to 1.50, 1.75, 2.00 and 2.25 m. The figure shows that the change in captured hue values due to the varying amounts of illuminating light intensity was not very significant. When all of the points were compared, the uncertainty introduced

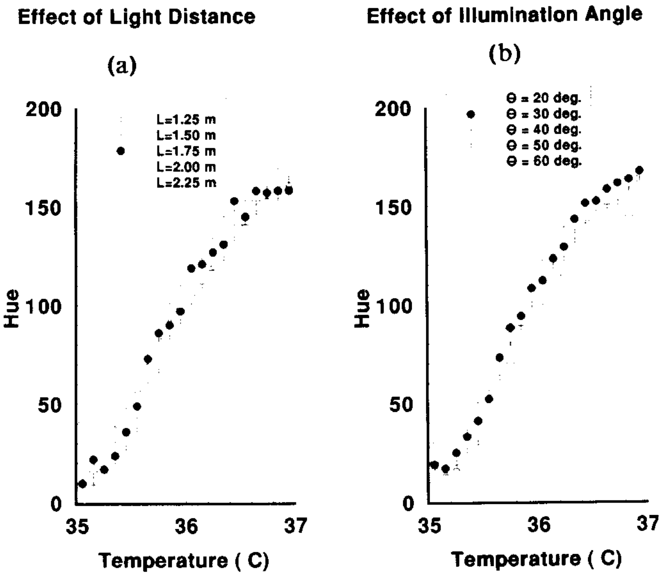


Figure 5
Effect of light source distance and illumination angle on hue capturing process, (R35C1W)

by the light source distance variations was well within ∓ 0.08 °C.

Effect of Illumination Angle

Figure 5.b shows the influence of illumination angle on hue measurements. For the experimental results shown in this figure, the light source to model distance was always kept constant at 1.75 m. The illumination angle was measured from the flat heat transfer surface. At small angles (θ=20 °, 30 ° and 40 °), the influence of the illumination angle was negligible as far as the linearity of the hue-temperature relation was concerned. However, after θ=40 ° , the deviation from the linear part of the hue versus temperature line became increasingly larger. At θ=60 ° , the temperature uncertainty increased to values as large as ∓ 0.20 ° C, especially for the temperature range above 36.0 ° C. The range below 35.0 ° C was not significantly influenced by the illumination angle variations. Figures 5.a and 5.b suggest that, color capturing process on a liquid crystal covered surface should be performed always with the same illuminating source, the same light distance and the same illumination angle. The light source, distance and the angle should be kept the same both for the calibration and the actual experiment, in order to keep the temperature measurement uncertainty within ∓ 0.10 ° C. The camera conditions such as imaging sensor (circuit) gain, filter adjustment, diaphram aperture, optical adjustments (zoom, etc.) should also be kept unchanged for all of the tests including the hue versus temperature calibration process. The image processing system color capturing adjustments have to be locked during the calibration and actual testing efforts.

Spatial Distribution of Liquid Crystal Color Response and Repeatability of the Hue Capturing Technique

The Chiral Nematic liquid crystal and the binder mixture was sprayed by using a pressurized air brush as uniformly as possible. In order to check the spatial uniformity of the color response, three individual thin foil themocouples were flush mounted at separate locations on the flat heat transfer surface. The hue versus temperature calibrations were repeated at each location individually using a number of local temperature levels. The results are presented in Figure 6.a. The comparison of hue versus temperature curves at the three locations indicated that the liquid crystal color response provided a very consistent and reliable temperature measurement. The uncertainty band for the uniformity confirming experiments was better than ∓ 0.04 °C.

Figure 6.b presents the repeatability tests performed on three separate days at the same thermocouple location. The thin foil thermocouple located at the center of the plate was used for these tests. The exact same calibration procedure resulted in highly repeatable calibration curves as shown in Figure 6.b. The maximum repeatability error was easily within ∓ 0.05 °C in the linear portion of the hue versus temperature curve.

Hue versus Intensity

The present color image processing technique provided simultaneous hue, saturation and intensity values at each pixel location in real time. A very linear, reliable and repeatable hue-temperature relation is shown in Figure 4. The experiments in the present program showed that, intensity information may also be used in processing liquid crystal data for quantitative heat transfer measurements. Figure 7 shows a high resolution hue versus temperature relation from a few hundred discrete hue-temperature measurements using the present digital image processing system. A slowly varying temperature pattern on the thermocouple location was recorded on a video tape with its complete color image at a rate 30 frames per second. The image also consisted of the real time 7 segment LED display indicating the instantaneous thermocouple measurement. The details of the simul-

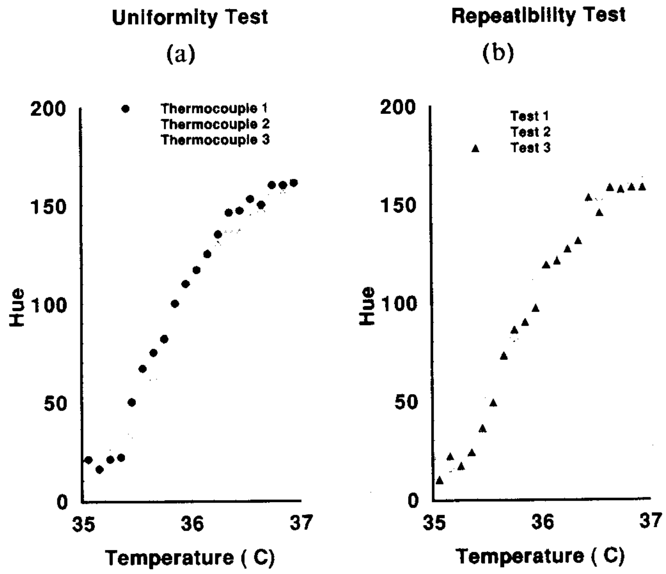


Figure 6
Effect of liquid crystal layer uniformity and repeatability on hue capturing process, (R35C1W)

taneous hue and intensity measurements for a liquid crystal with a color play temperature of 42.8 °C are given in Figures 7, 8 and 9. The total bandwidth of the Chiral Nematic liquid crystal was approximately 1.0 °C, (R42C1W). The experiments performed with a high temperature resolution showed that, there was always a very distinct intensity peak in the intensity versus temperature variation as presented in Figure 8. The peak appeared at 43.05 °C, corresponding to a very narrow color band was mainly dominated by green. A close examination of Figures 7 and 8 showed that the local temperature corresponding to the intensity peak may easily be determined. Figure 8 suggested that a single isotherm could be captured in a very accurate manner by carefully determining the peak intensity levels from a given image. For example, in an actual test under the same illumination conditions, the locus of intensity peak points may be associated with the isothermal line of 43.05 °C occuring at a hue level of 109.5 hue units. Cross plotting hue and intensity is a very useful tool in setting up the illuminating system for a succesful heat transfer experiment with well defined hue points. It is a known fact that color image sensors do not respond in a healthy manner when the local intensity level is below a certain value. The illumination system should be adjusted in such a way that a typical hue distribution is obtained at reasonably high local intensity levels. Figure 9 shows a hue-intensity cross plot at the location of the calibration thermocouple. All of the colors locally appearing from red to blue located themselves between a hue level of 0 and 170, on a slightly curved line. Figure 7 correspondingly showed that the hue levels above 140 are out of the linear portion of the calibration curve for the specific liquid crystal used (R42C1W). Above a hue value of 140, the captured data points remained in the dark blue-black zone of the liquid crystal. Figure 9 indicated an overall intensity pattern smoothly varying in a range between 50 and 100. The experiments showed that the present hue capturing process worked very efficiently in an overall intensity range between 50 and 200. The hue versus intensity curve may be easily shifted to the right hand side of the intensity scale (Figure 9) by simply increasing the strength of the illuminating light source. It was found that the intensity levels above 200 affected the hue capturing method in a detrimental manner due to the saturation of the CCD sensor. It is also well known that very low overall illumination levels (e.g. intensity levels less than 50) makes the hue capturing process unstable. Construction of a hue versus intensity chart using the intented illumination configuration (distance, angle, light source strength) provides a valuable and crucial check before the execution of an actual experimental program. Overall intensity levels between 50 and 200 (preferrably between 100 and 200) were the typical levels for the hue capturing process performed on the color image processing system described in this study.

Further Implementation of the Method

The experimental calibration technique to convert color information into accurate temperature measurement was developed and tested at a local point having a fast response thermocouple flush mounted on the heat transfer surface. However, one of the final goals in this study was to obtain high resolution distributions of temperature and convective heat transfer coefficients on surfaces with complex geometry or characteristic lines. In order to show the

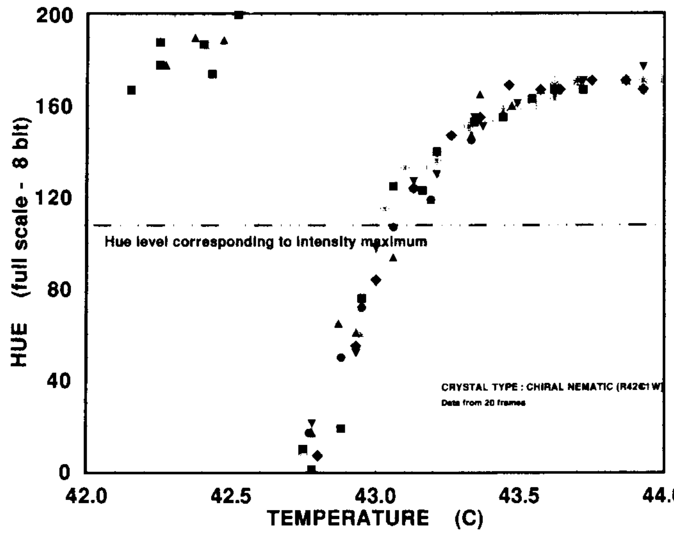


Figure 7
High resolution hue versus temperature curve,

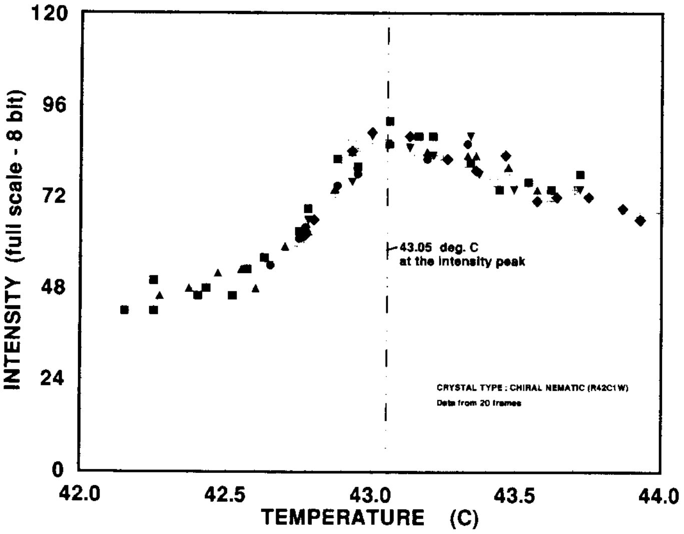


Figure 8
Variation of local intensity with temperature,

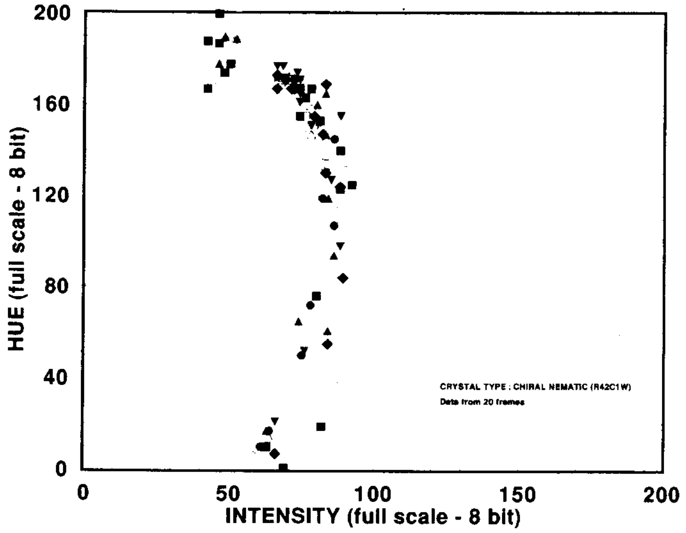


Figure 9
Variation of local hue versus local intensity,

further applicability of the method, a baseline experiment was designed by using a heated round jet of air, stagnating on a flat wall. The heated jet originating from a round pipe was stagnated on a flat plate as shown in Figure 3. The exit of the round pipe was square cut. The jet to plate distance was about 12 jet diameters and the jet exit velocity was measured to be 28 m/sec at the centerline of the jet. The local temperature distribution on the liquid crystal covered model surface was known to be strongly affected from the geometry of the jet exit section. This effect was observed to be very strong at small jet-plate distances such as x/D=4. The round pipe was 5.08 cm in diameter, with a length of 55 cm. The pipe wall thickness was 0.4 cm. The air was heated using a 4 KW adjustable electric heater designed and built for this purpose. The heater was formed around a 50 cm long refractory rod of 0.8 cm diameter. The heater rod was located along the centerline of the steel tube. This configuration provided a jet centerline temperature of 52.4 ° C with a typical variation of ∓ 0.15 ° C for a duration of at least 5 minutes. The transient experiment was initiated with a cold jet. At this time the steadily flowing jet was deflected sufficiently far away from the flat heat transfer surface, by using a circular elbow section manually attached to the exit section of the pipe. Then, the heater was turned on to obtain a steady state heated jet in terms of both velocity and temperature profiles at the exit. Special attention was paid in order not to disturb the flat heat transfer surface coated with liquid crystals in terms of its initial wall temperature uniformity. The liquid crystal surface was also carefully covered with a thermal barrier blanket, temporarily. The exit temperature distribution of the deflected jet reaches a steady state within the first 10 minutes of the heater start up. The centerline temperature of the deflected jet was continuously monitored. The deflecting elbow was removed manually within a maximum of 60 milliseconds which is much shorter than the time scale of the transient experiment. This initial period was checked by using a video camera and a display unit which could accurately time stamp individual video frames. For this kind of impulsively starting heat transfer experiments, the definition of the beginning of the experiment and the elapsed time is needed in an accurate form in order to reduce the total uncertainty value on the convective heat transfer coefficient. The elapsed time was measured using an electronic counter operating at 30 Hz counting frequency to time stamp individual video frames. The video imaging system was recording at a 30 frame per second rate. Figure 10 shows the distributions of hue, saturation and intensity along the radius within the first two jet diameters radial distance. The circumferential uniformity of the jet flow was carefully checked and adjusted so that the information shown in Figure 10 represented all of the circumferential positions for this non-swirling jet flow. The hue distribution provided a very wide color spectrum from red, yellow, green and finally to blue. The hue values ranged from 0 to 170 between r/D=0.7 and r/D=1.20. The corresponding intensity values in the same radial band varied between 100 and 210. The peak intensity point corresponded to the radius at which a very narrow green color appeared, around a hue value of 90. The experiment presented in Figure 10 and many other similar experiments run by the authors showed that, the intensity peak is closely related to the green color observed on the surface. The saturation values obtained at each pixel location were not very helpful in obtaining accurate heat transfer results. Saturation of a color is strongly altered by the strength and by

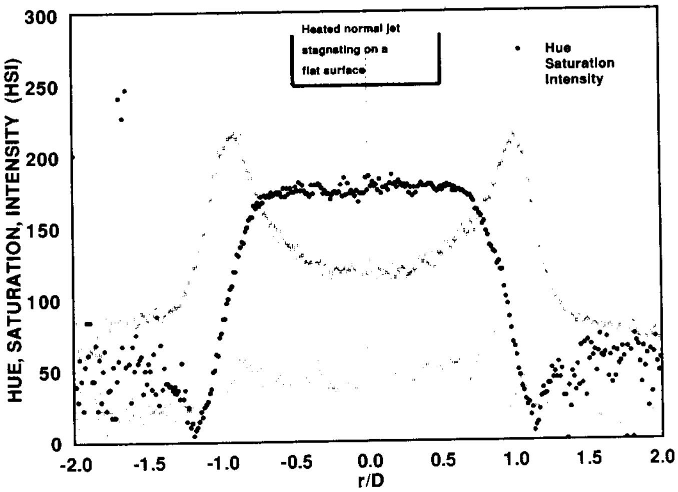


Figure 10
A simultaneous representation of hue, saturation and intensity for a heated round jet stagnating on a flat plate, (R35C1W)

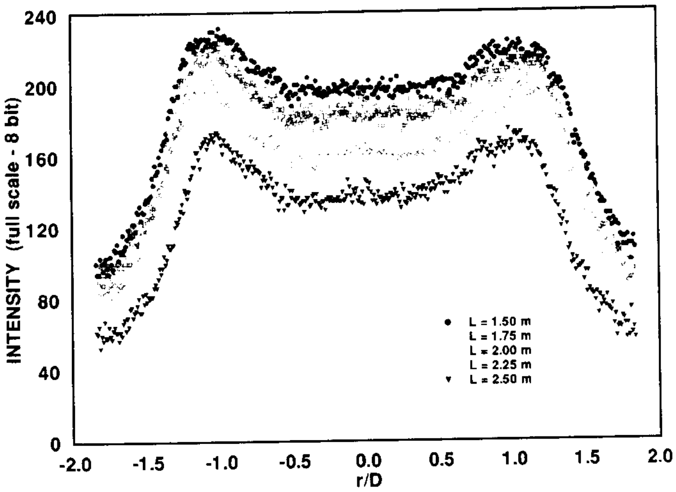


Figure 11
Variation of local intensity values under strong illumination level changes along the radius, (R35C1W)

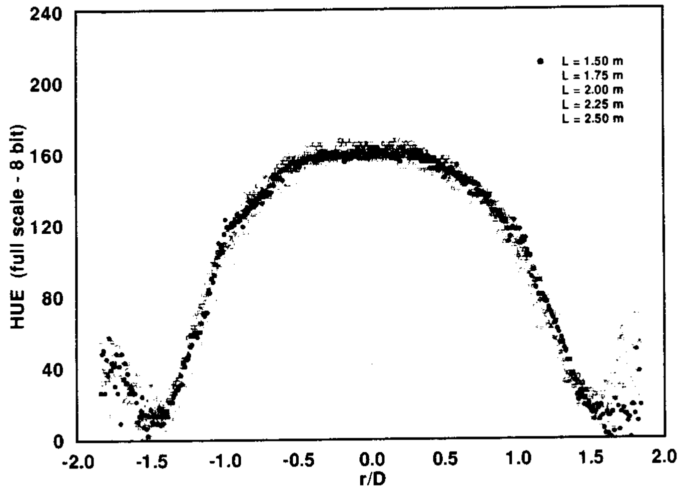


Figure 12
Variation of local hue values under strong illumination level changes along the radius, (R35C1W)

the geometrical orientation of the illuminating system. The saturation values were almost at an overall flat level of 40 units for the pixels having a local intensity value of greater than 100. The hue distribution shown in Figure 10 can easily be converted into accurate temperature distribution by using the calibration curve provided in Figure 4. The calibration showed that hue versus temperature relation was linear between hue values of 30 and 140. For the points having an r/D value greater than 1.25, hue capturing was not very succesful due to relatively low intensity values generated by the "almost black" color which is showing the coldest zone on the heat transfer surface. The "almost black" color is an indication of a region out of the liquid crystal color response band. The term "almost black" was used here because any pure color may appear "almost black" under low intensity, low saturation conditions.

Robustness of Hue Capturing Technique Under Strong Illumination Variations

An experiment was designed to see the robustness of hue capturing process under different illuminating light strengths. An incandescent light source (500 W, 3200 °K) oriented at θ=40 degrees to the surface was used to generate different illuminating conditions on the same heat transfer image. The heated jet having a free stream temperature of T_{jet}=52.4 °C (at the exit) was located 12 jet diameters away from the wall. The jet exit velocity was measured to be 28 m/sec at the centerline. A steady state heat transfer pattern was reached by running the heated jet approximately 2 hours. The steady state color pattern was then imaged when the light to model distance was at L=1.50 m. A color video image was captured and processed for intensity and hue information useful for heat transfer studies. The data points in Figure 11 also show the variation of local intensity values under strong illumination level changes. The light to model distance was changed from L=1.5 m to 1.75, 2.00, 2.25 and finally to 2.50 m. A surface mounted thin foil thermocouple monitored the surface temperature pattern at the center of the jet. No significant variation of wall temperature was observed at different light distances. It was found that the local intensity value was shifted from a value of 200 down to 135 when the same light source was moved from L=1.50 m to L=2.50 m, Figure 11. However, the qualitative distribution of intensity remained almost the same.

The hue distributions corresponding to the light distance experiments given in Figure 11 are shown in Figure 12. An excellent feature of Chiral-Nematic liquid crystals of encapsulated type was observed as the extremely weak intensity dependency of surface hue distributions. Very strong local intensity variations created by moving the light source did not strongly alter the main color defining parameter "hue". This feature was expected because of the definition of the quantity "hue". Hue is a direct measure of the dominant wavelength at which the electromagnetic light emission from the heat transfer surface occurs. For the same light source located at several other distances, the only varying parameter is the amount of total energy incoming into the surface as electromagnetic energy. The variations of the incoming total electromagnetic energy results in strong variations in the amount of reflected light from the liquid crystal covered surface. However, the spectral character of the illuminating light source was always the same for all of the experiments performed in this study. Therefore, it was expected that the spectral character of the reflected light from the heat transfer surface was not going to change if the surface temperature pattern was not altered by external means. A number of surface temperature checks also showed that thermal radiation contribution to the surface temperature pattern from the light source was quite negligible for all of the experiments presented in Figure 12. The maximum local temperature variation at the center of the jet was within ∓ 0.10 °C for all of the cases with different distances. It was concluded that by significantly changing the intensity of illuminating light, the local hue values did not vary in a strong manner. All of the measured hue points obtained at 5 separate light distances were within a hue band of ∓ 10 hue units. The corresponding temperature band was calculated as ∓ 0.08 ° C using the relation in Figure 4. There are a few scattered data points with unexpected magnitudes, located at the extreme edges of the stagnation area on the surface. They were attributed to color capturing deficiencies of both the camera sensor and the RGB-HSI analog conversion process at very low local intensity levels, corresponding to "almost black" regions, (r/D>1.25). From a signal processing point of view, these are highly noisy parts of a typical liquid crystal image. The very slight variation in local hue values may include some thermal radiation effects due to varying distance or shape factors. In practice, model to light distance is most of the time unchanged from experiment to experiment. If one always uses the same illuminating source at the same angular position and distance for both the calibration process and actual experiments, very accurate quantitative measurements of local temperature may be obtained as shown in Figures 5 and 6.

Automatic Temperature Mapping Using the Present Hue Capturing Technique

The present color images from the stagnating heated jet experiment were sampled with a pixel resolution of 512x480, resulting in large data files containing 880 KBytes of digital information. At this resolution, in the useful (linear hue versus temperature) portion of the image, the temperature measure-

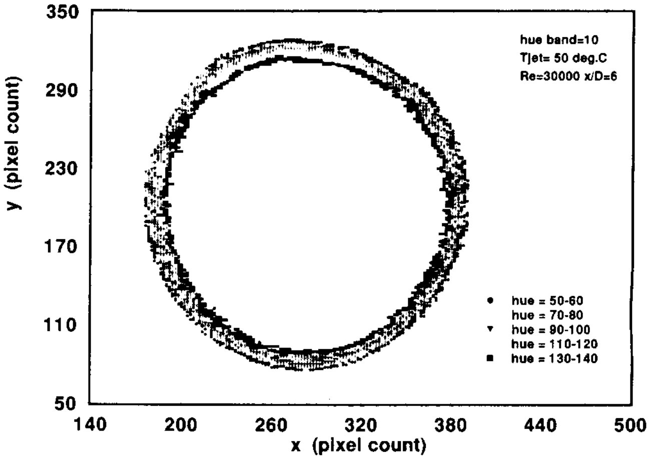


Figure 13
5 discrete hue (isotherm) bands mapped using an image processor from a liquid crystal image, (R35C1W)

ment resolution is much higher than the measurement techniques utilizing discrete sensors, such as thermocouples, resistance thermometers, thermistors, etc. A computerized process was shown to be very effective in extracting many distinct isothermal lines or very narrow temperature bands from a color image file containing 880 KBytes of digital image data. Figure 13 shows five hue bands each having a bandwidth of 10 hue units in an experiment having a jet exit temperature of 50.0 °C, Re=30,000 and x/D=6. Solid circular symbols denote the hue values between 50 and 60 which corresponded to a temperature band of 0.08 ° C starting from 35.5 ° C (hue= 50). Solid square symbols show the maximum measurable temperature range. A solid symbol also indicates a temperature band of 0.08 ° C with a starting temperature of 36.3 ° C. The corresponding hue band was between 130 and 140. Five distinct temperature bands were located between 35.5 and 36.3 ° C. This kind of contouring was performed in a very time effective manner. A five level contouring required a total of 45 seconds on the specific image processor described in this study.

Application of the Technique in Obtaining Convective Heat Transfer Coefficients

A very powerful application of the present method is the generation of convective heat transfer coefficients from time stamped color images, using transient heat transfer techniques. The transient technique used very frequently in the past required the elapsed time measured from the beginning of a transient experiment, local wall temperature, free stream recovery temperature at the specific location, initial temperature of the model, and thermophysical properties of the model material (ρ, c_p, k) having the liquid crystal coating. The technique also assumed a one dimensional heat flow into a semi-infinite body. The convective heat transfer coefficients can be carefully evaluated if the elapsed time measurement is accurate enough, with a reasonably uniform initial wall temperature distribution. Knowing the free stream recovery temperature distribution in an accurate form is also a crucial factor in reducing the uncertainties related to the convective heat transfer coefficient defined between the free stream recovery temperature and the local wall temperature. Figure 14 shows the constructed convective heat transfer coefficients obtained using 16 individual color images sampled at different times. The results presented in Figure 14 correspond to the flow conditions of the heated stagnating jet experiment described in Figure 14. The measured recovery temperature distribution for the experiment having a Re=30,000 and x/D=6 is also presented in a non-dimensional form in Figure 14. The first image was captured at t=7.80 s from the beginning of the transient experiment and the last image was taken at t=104.30 s. The multiple temperature points corresponding to many of the colors which could be captured using the present technique improves the spatial resolution of the final heat transfer coefficient distribution greatly, compared to the previous techniques which provided only one single temperature point per video frame. The present method as shown in Figure 14 provided more than 600 individual heat transfer coefficient measurements by using very accurately calibrated color information assigned to each pixel in the image. The initial wall temperature was uniformly distributed over the plate at ambient level. The initial wall temperature uncertainty was approximately ∓ 0.1 ° C. The

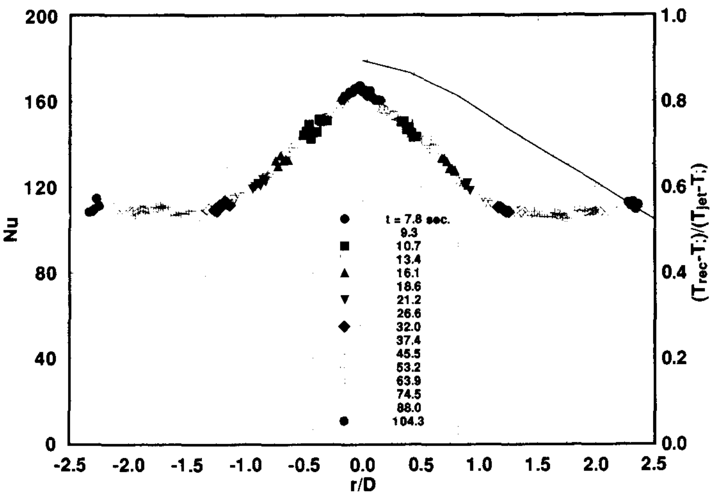


Figure 14
Convective heat transfer coefficient and non-dimensional recovery temperature distribution obtained using 16 individual color images sampled at different times, (R35C1W)
[Heated round jet stagnating on a flat plate]

elapsed time measurement was performed by using an electronic counter. The time measurement uncertainty including the very initial transient flow establishment time was within ∓ 2 milliseconds. This is extremely small compared to the typical time scale of the experiment which is in the order of seconds. The overall uncertainty of convective heat transfer coefficient was estimated to be around 5 percent using standard uncertainty prediction methods.

CONCLUSIONS

A new digital image processing technique based on a color capturing method was developed for the quantitative interpretation of liquid crystal images used in convective heat transfer studies. Quantitative color perception using a Hue-Saturation-Intensity based description was proven to result in excellent results for surface temperature measurements using Chiral-Nematic liquid crystals.

It was shown that the local color play of the liquid crystal could be documented using a local hue quantity which was a direct measure of the wavelength of the light selectively reflected from the liquid crystal surface. Since the selective reflection process was controlled by the liquid crystal as a natural response to local temperature, a hue versus temperature calibration was possible. A highly linear hue-temperature relationship was established by performing at least a few hundred local quantitative color-temperature measurements at a few calibration locations on the heat transfer surface.

The present technique allows the researcher to use many of the visible colors appearing on the liquid crystal coated surface in contrast to many previous methods only utilizing a very narrow, distinct color band which formed a single isothermal line. It was concluded that the data density in a typical heat transfer coefficient distribution could be improved about 40 times with the present hardware, compared to the techniques using only a narrow color band as a single isotherm.

The new technique described was tested for the variations of illumination light strength. An excellent feature of Chiral-Nematic liquid crystals of encapsulated type was observed as the extremely weak intensity dependency of surface hue distributions. It was clearly shown that the variation of local light intensity captured from a pixel did not strongly alter the hue value which is the direct measure of the local temperature. The uncertainty introduced by appreciable light source distance variations was well within ∓ 0.08 ° C.

Effect of viewing angle was varied in a wide range from θ=0 degrees to 60 degrees. At small angles, the influence of the illumination angle was negligible as far as the linearity of the hue-temperature relation was concerned. However, after θ=40 degrees, the deviation from the linear part of the calibration curve became increasingly larger. At θ=60 degrees, the temperature uncertainty increased to values as large as ∓ 0.20 ° C, especially for the temperature range above 36.0 ° C. It was concluded that, color capturing process should always be performed with the same illumination angle and the same illumination source fixed at a specific location for both the calibration process and actual experiments.

The camera conditions such as imaging sensor gain, filter adjustments, diaphram aperture and optical adjustments(zoom,etc.) should be kept unchanged for all of the experiments, including the calibration process. The image processing system color capturing adjustments have to be locked during the calibration and actual testing efforts.

The calibrations performed at discrete points on the heat transfer surface showed good spatial uniformity in terms of color response of the crystal layer. The uncertainty band for the uniformity confirming experiments repeated at discrete positions was better than∓0.04 ° C, in the linear part of the hue versus temperature curve.

Tests were also performed at the same location but at different times. The maximum uncertainty band for the repeatibility error was about ∓ 0.05 ° C. The tests were performed to plot local intensities as a function of temperature. There was always an intensity peak at the location where the green color appeared dominantly. It was also shown that, hue versus intensity curve could be utilized in improving the hue capturing process, by quantitatively checking the overall intensity distribution on the heat transfer surface.

The present technique was implemented for a heated round jet stagnating on a flat wall. High resolution isothermal mapping was completed in a very time efficient manner. Five distinct isothermal lines in a range from 35.5 ° C to 36.3 ° C were computer generated in a total duration of 45 seconds, by processing 880 Kbytes of digital color image data.

A very powerful application of the present liquid crystal method is the generation of convective heat transfer coefficients with high resolution. The accurate temperature and elapsed time measurements performed on the liquid crystal covered surface were used in obtaining heat transfer coefficients. A transient method assuming one dimensional heat flow into semi-infinite flat plate was employed. The color images captured at 16 different time steps measured from the beginning of the transient experiment, provided at least 600 discrete convective heat transfer coefficient measurements because of the multiple color processing capability of the present method. The pixel by pixel color capturing capability of the present method is extremely useful for two dimensional processing of color information on more complex heat transfer surfaces. The overall uncertainty of convective heat transfer coefficient was estimated to be around ∓5 percent, using standard uncertainty estimation techniques.

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