KSME Journal, Vol. 7, No. 4, pp. 349~363, 1993

An Efficient Way of Convection Heat Transfer Measurement on a Curved Surface

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(*Received March 31, 1993*)

Accurate determination of convective heat transfer coefficients on complex surfaces with high spatial resolution is essential in the design and analysis of thermal systems. This study focuses on the implementation of a recently developed true color image-processing technique for the quantitative interpretation of liquid crystal images obtained from a curved surface. The interpretation includes the use of a linear hue versus temperature relation as an accurate temperature measuring tool, a color image analysis system and a transient heat transfer model for the conversion of time accurate temperature information into heat transfer coefficient maps. A square to rectangular transition duct is used as a heat transfer model representative of a curved geometry. The transient heat transfer experiments are performed with ambient temperature air in the transition duct model which is preheated by a custom designed electric heater. The measurements are performed on the curved bottom surface of the transition duct. Two dimensional surface distributions of heat transfer coefficient on the curved surface are presented with high spatial resolution. The hue-capturing technique provides extremely fine details of heat transfer coefficient when compared to other conventional discrete sensor methods. The technique is a highly automated heat transfer measurement method which reduces lengthy data reduction processes and significantly improves spatial resolution.

Key Words: Convection, Curved Surface, Liquid Crystal

Nomenclature

c	: Specific heat
CCD	: Charge coupled device
h	: Convective heat transfer coefficient, $h=q/(T_w-T_\infty)$(W/m^{2}K)
HSI	: Normalized hue, saturation and intensity
k	: Thermal conductivity
NTSC	: National Television System Committee
q	: Heat flux, $q=-k\partial T/\partial y$(W/m^2)
RGB	: Normalized red, green and blue
R35C1W	: Chiral nematic liquid crystal starting to respond at about 35℃ with an approximate bandwidth of 1℃
T	: Static temperature
t	: Time
y	: Normal distance from the wall surface
α	: Thermal diffusivity of air, $\alpha=k/(\rho c_p)$
β	: Nondimensional time, $\beta=h\sqrt{t}/\sqrt{\rho c k}$
θ	: Normalized temperature, $\theta=(T-T_i)/(T_\infty-T_i)$
ρ	: Density

Subscripts

i	: Initial condition
p	: At constant pressure
w	: Wall condition
∞	: Free stream value

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1. Introduction

Developing accurate surface temperature and heat transfer coefficient measurement techniques is essential for a better physical understanding of convection heat transfer. 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 to obtain the wall temperature distribution of a heat transfer model. The sensor may interfere with the flow itself.

A more economical and convenient way of mapping wall temperatures and heat transfer distributions is the implementation of liquid crystals as distributed temperature sensors. 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 color spectrum on the heat transfer model surface. Liquid crystals progressively exhibit all colors of the visible spectrum as they are heated through the event temperature range. The phenomenon is reversible, repeatable and the liquid crystal color can be calibrated accurately with 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. The use of thermochromic liquid crystals in heat transfer research and testing is extensively reviewed by Parsley (1991).

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 by Hippensteele et al.(1983) and Jones and Hippensteele(1985). Steady-state and transient heat transfer techniques using liquid crystals require a careful quantitative interpretation of color patterns recorded from the heat transfer surfaces. 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 from a specific liquid crystal image gives the most quantitative description of a single isotherm. Most of the previous interpretations of the liquid crystal images are based on human eye color perception which is subjective. Errors in human color determination are inevitable due to individual differences and lack of reproducibility.

There have also been studies using monochromatic digital image processing technique which excludes the human eye color perception. 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. By calibrating the intensity peak for a specific temperature, the isotherm and the corresponding heat transfer coefficient can be obtained. Akino et al.(1989) devised an intensity based imaging technique. A set of sharp band-pass optical filters, attached to a black-and-white video camera, was used to increase spatial resolution. 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. Bunker et al.(1990) introduced another single color capturing technique using one intensity level of the three primary colors, red, green and blue. The monochromatic imaging technique requires 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 available from one video frame.

Recently, a new way of liquid crystal color interpretation based on true color image processing has been developed by Camci et al.(1992). The method is based on color recognition techniques using hue-saturation-intensity description instead of the more widely accepted red-green-blue color definition system. 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. Having multiple isotherms in each video frame reduces the total number of frames to be captured and processed. The specific color capturing technique on a color image processor provides a highly automated heat transfer measurement method which reduces lengthy data reduction process and significantly improves the spatial resolution of heat transfer measurements on surfaces with complex geometry. The method is highly applicable to surfaces exposed to convective heating or cooling in a very complex flow and geometry.

The present study is aimed at the implementation of the recently developed hue-capturing technique for the quantitative interpretation of liquid crystal images obtained from a curved surface. A square to rectangular transition duct is used as a heat transfer model representative of a curved geometry. The transient heat transfer experiments are performed with ambient temperature air in the transition duct model which is preheated by a custom designed electric heater. The measurements are efficiently performed on the curved bottom surface of the transition duct. The actual visual images (qualitative) and the corresponding reduced heat transfer distributions (quantitative) are presented simultaneously. Two dimensional surface distributions of heat transfer coefficient on the compound curved surface are presented with high spatial resolutin.

2. Liquid Crystal Image Interpretation

2.1 Color principles and image processing

Color perception is a psychophysical phenomenon which results from the human eye's translation of radiant energy into visual stimuli. Color may be defined as the combination of those characteristics of light that produces the sensations of hue, saturation and intensity in a normal human observer. Intensity of a color refers to the relative brightness of a color. This quantity represents total sum of the spectral energy incoming to the eye/sensor, emitted by an object 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 the visible spectrum, hue corresponds directly to the dominant wavelength of the light incoming to the sensor. 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 color purity or the amount of white contained in a specific 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 (Camci et al., 1992). Since the relative 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. 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.

Color sensation from a liquid crystal covered surface is generated by three 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 exclusion of illumination condition and imaging sensor effects on hue versus temperature relation is essential for accurate temperature measurement. The illumination condition including the distance and the angle of the light source should be kept the same both for the calibration and the actual experiment. 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 spectral distribution of the liquid crystal color display is converted into the attributes of three color primaries (**R, G, B**) using a color video camera (Sony, V9). The imaging device used in this study has a high light sensitivity color CCD sensor consisting of 512×512 pixels capable of generating red, green and blue attributes of 30 complete frames in a second. Red, green and blue attributes are then multiplexed and sent to the image-capturing board (Data Translation, DT2871). 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 approximately every two seconds.

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 a **H,S,I** signal for each pixel. The **RGB-HSI** conversion is performed on high performance electronic circuitry in real time. 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. However, the calibration of the image-capturing device is transparent to the heat transfer researcher, if adjustments are not altered in the middle of a research program. Four individual frame buffers each having $512\times512\times8$ bits of video memory is used for storing intensity, saturation, hue and additional graphics and text information. The image processor 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. Further details of this approach are described in Camci et al.,(1992).

2.2 The dependency of liquid crystal color to temperature

A baseline experiment was performed on the liquid crystal coated surface in order to find out the dependency of the specific liquid crystal (Hallcrest, R35C1W) color to temperature. The local temperature of the liquid crystal surface was changed by applying a radiative heat flux from a temperature controlled heated plate. An extremely slow varying color pattern and the thermocouple temperature readout were recorded simultaneously. Two sets of color defining parameters including **R,G,B** and **H,S,I** at the thermocouple location were obtained at different local temperatures as shown in Fig. 1. Temperature smaller than 35.3℃ is a region out of the liquid crystal color response band. Liquid crystal shows almost black color in this region. The term almost black is used here because any pure color may appear almost black under low intensity condition. Liquid crystal covered surface provides a continuous color spectrum from red, yellow, green and finally to blue for the temperature between 35.3 and 37.0℃. Liquid crystal surface shows blue color for a while beyond 37.0°C and finally becomes almost black again.

The color information in the form of hue shows a very linear variation with respect to local temperature between 35.3 and 36.3℃. The hue range between 30 and 140 contains typical colors such as red, orange, yellow, green and blue. A complete color spectrum is corresponded to an almost 1°C wide temperature band. This linear range is the most useful part of the hue versus temperature relation in terms of performing accurate temperature measurements using the true color-capturing technique. The hue-capturing technique converts color information into temperature using the linear hue versus temperature relation. The corre-

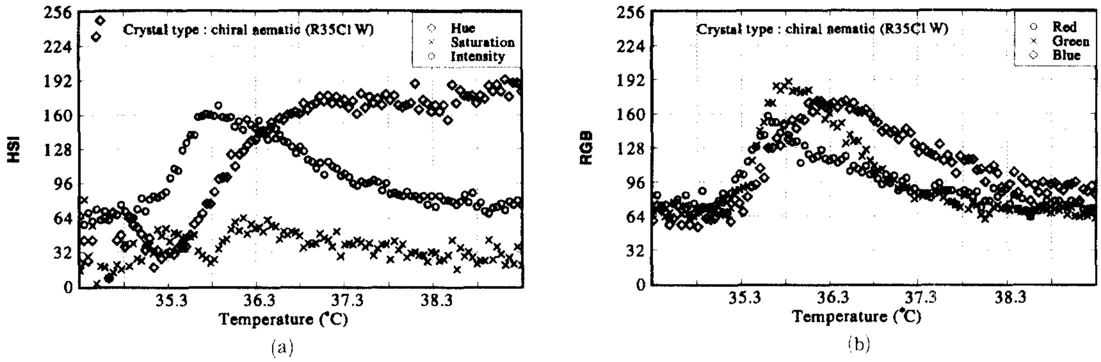


Fig. 1 Variations of (a) **HSI** and (b) **RGB** with temperature

sponding intensity values varies between 60 and 170. The peak intensity point corresponds to the temperature at which a green color appears, around a hue value of 90. The color information in the form of intensity also can be an accurate temperature sensor, since the intensity peak always appears at the same temperature. Monochromatic digital image processing techniques are based on this information. The saturation values do not show any interesting features for the variation of temperature. This is due to the fact that local temperature correlates only with the wavelength of the color from a liquid crystal image, not with the amount of white contained in the specific color. The peaks of red, green and blue attributes appears at 35.6, 35.8 and 36.2℃, respectively. The color informations of these three primaries can be treated as intensity value in monochromatic imaging techniques, since the peak of each color component also appears at the

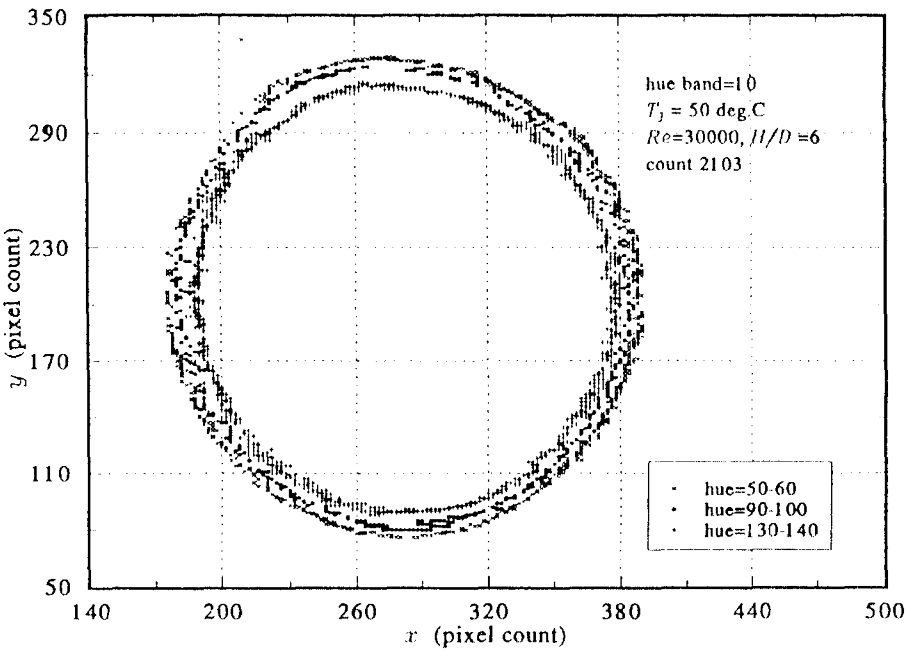


Fig. 2 Three hue levels (isotherms) mapped using an image processor from a concentric liquid crystal image (R35C1W)

same temperature.

In order to show the applicability of the hue-capturing technique, a concentric coloured ring generated by a steady axisymmetric temperature distribution on the plate with maximum temperature at the center is observed. The present color image is sampled with a pixel resolution of 512×512, resulting in large data files containing 778 KBytes of digital information. At this resolution, in the useful (linear hue versus temperature) portion of the image, the temperature measurement resolution is much higher than the measurement techniques utilizing discrete point sensors, such as thermocouples, resistance thermometers, thermistors, etc. A computerized process is shown to be very effective in extracting many distinct isothermal lines or very narrow temperature bands from a color image file.

Figure 2 shows three hue bands each having a bandwidth of 10 hue units obtained from the captured concentric image. Cross symbols denote the hue values between 50 and 60 which correspond to a temperature band of 0.09°C starting from 35.49℃ (H=50). While solid circular symbols represent a temperature band 35.86～35.95°C. Plus symbols show the maximum measurable temperature range which indicates a temperature band of 0.09℃ with a starting temperature of 36.23℃. The corresponding hue band is between 130 and 140. Three distinct temperature bands are located between 35.49 and 36.32℃. A three-level contouring required a total of 27 seconds on the specific image processor described in this study.

3. Transition Duct Experiments

The new hue-capturing technique has been implemented for the interpretation of the liquid crystal images obtained from a curved surface. The bottom surface of the square to rectangular transition duct is a compound curved surface with a complex geometry.

3.1 Wind tunnel and transition duct

A continuous flow wind tunnel is adapted such that the flow can be switched suddenly through the test section. The transition duct and the wind tunnel are shown in Fig. 3. The tunnel operates from a main laboratory vacuum system. Ambient temperature air is drawn from the laboratory through the test secion. The transient experiment is started by opening a pneumatically controlled fast acting valve located at about 3 meters downstream of the test section. The pneumatic valve connects the test section intake to the main vacuum system. The timing system is triggered through a switch located on the valve for data acquisition and video frame syncronization purposes. A light emitting diode in the video image is turned on and another electrical trigger pulse is released as a data acquisition trigger by a microswitch mounted on the quick opening valve, as soon as the quick opening valve is activated. A precision video timer is also started at this specific time in order to time stamp the video frames.

The model tested was a transition duct from a 20.8 cm $\times$ 20.8 cm square to a rectangular cross section of 32.2 cm $\times$ 10.7 cm. The details of the duct geometry are given in Fig. 4. The transition duct model was precisely machined from clear acrylic (plexiglass). The heat transfer at the bottom wall of the transition duct was measured. Three fast response thin foil thermocouples were mounted on the duct floor. The bottom surface of the transition duct was coated with black backing paint for effective display of liquid crystal colors. A mixture of three chiral-nematic liquid crystals was then sprayed simultaneously. The color display temperatures of the three liquid crystals each having a color bandwidth of approximately 1°C was around 37.5, 42.7 and 47.8℃, respectively. The chiral nematic liquid crystal images were recorded by a color video camera located in a normal direction to the transition duct floor. A light emitting diode provided a reference time on the video recording in addition to a precision timer signal superimposed on the actual image. Model illumination was provided by fluorescent lights located about 50 cm away from the duct floor, parallel to the tunnel axis for both calibration and real experiments.

The transition duct was preheated by an electric heater chamber. The heater was kept active about 5 hours prior to a transient run. This long period of heating time guaranteed a uniform

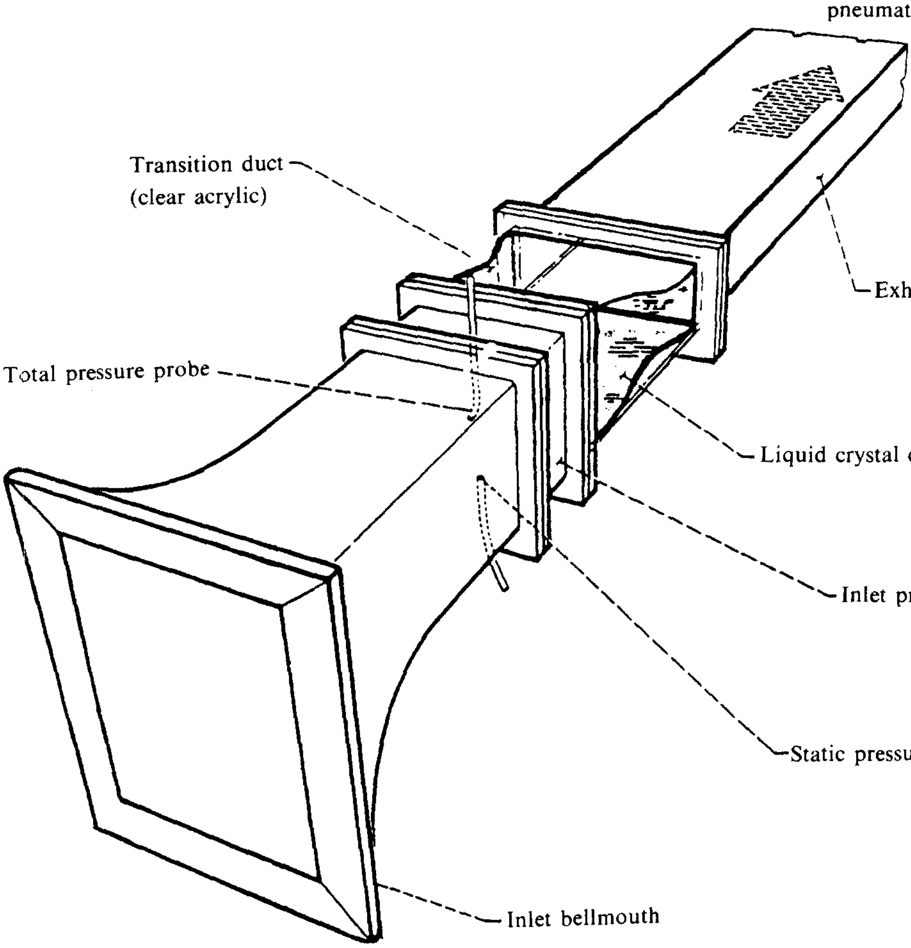


Fig. 3 Wind tunnel and transition duct

initial wall temperature distribution just before the transient experiment. A uniform distribution was required in order to reduce the experimental uncertainty on the convection heat transfer coefficient. The uniformity was confirmed by taking thin foil thermocouple measurements at 10 different (inside and outside) locations on the duct surfaces. The initial temperature of the liquid crystal covered bottom surface of the duct was about $T_i = 55.7$℃. This initial temperature was well above the color play temperature of all the three liquid crystals existing on the bottom surface.

The tunnel operating conditions, including inlet temperature, inlet velocity, a number of wall static signals, the thermocouple outputs and the valve timing information are monitored by a computer controlled data acquisition system with 16 bit accuracy. A miniature bare thermocouple with a typical time response of 20 milliseconds is employed to monitor the timewise variations of the room temperature air entering into the duct. A continuous recording of the tunnel inlet temperature, inlet velocity from a Pitot probe and fast

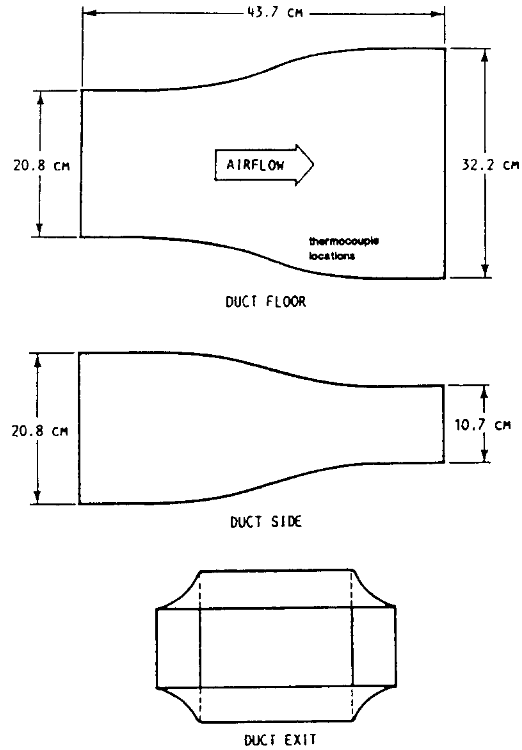


Fig. 4 Details of the transition duct geometry

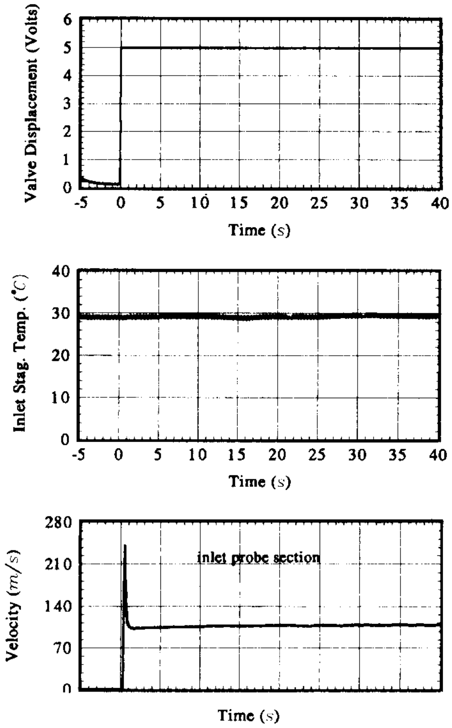


Fig. 5 Valve opening time, temperature and velocity at the inlet probe section

acting valve initial transient behaviour are shown in Fig. 5. All of the initial transients in the flow field due to the opening of the valve are contained within the first 50 milliseconds of the experiment. The total temperature measured just in front of the inlet bellmouth was not significantly influenced throughout the run from the sudden opening of the pneumatic valve. The recorded inlet total temperature level was almost the same as the ambient temperature ($T_\infty=28.6$℃) measured just before the transient experiment. The Pitot probe traverse along the height was performed at the centerline of the duct. The mean velocity component of the inlet probe section showed a very uniform distribution of about 97.5 m/s. The inlet boundary layer thickness at the bottom wall of the inlet probe section was measured to be 8.9 mm. It was also confirmed that the top wall boundary layer has a very similar distribution. The freestream turbulence intensity measured by a single sensor hot-wire in the mainstream of the inlet probe section was about 1.0%.

3.2 Calibration of the liquid crystals

Hue versus temperature calibrations of the three liquid crystals were performed locally in order to find out the dependency of local liquid crystal hue to temperature on the heat transfer surface. A heat gun with a free stream temperature of 85°C was directed to the thermocouple location. Moving the heat gun close to the thermocouple location allows an increase to the temperature level of the heat transfer surface. A T-type thin foil thermocouple was flush mounted underneath the liquid crystal layer, at this specific pixel location. As slowly varying color pattern obtained by gradually moving the heat gun and the measured temperature from the thermocouple were simultaneously recorded on a video tape.

Figure 6 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 for all of the

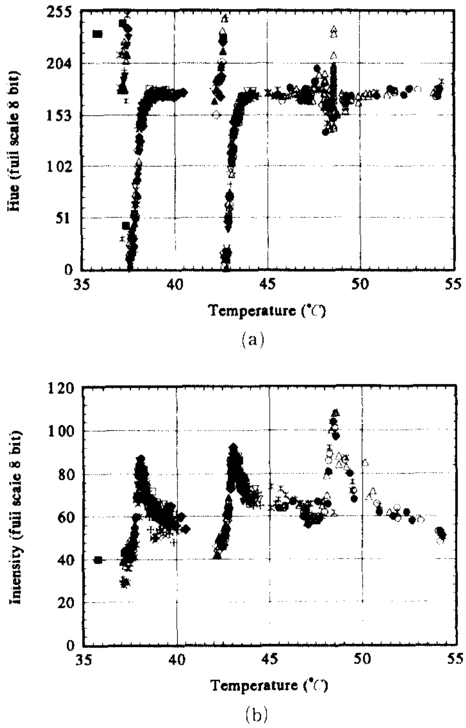


Fig. 6 (a) Hue and (b) intensity versus temperature for all of the three liquid crystals sprayed in the form of a mixture

three liquid crystals. The highest temperature crystal started to display red color at about 47.8℃. The medium temperature and the lowest temperature crystal started to display red at 42.7 and 37.5℃, respectively. It was observed that after the passage of the colors originating from the lowest temperature liquid crystal (the latest passing color being very dark blue), a narrow almost black zone appeared on the thermocouple location just before the appearance of the colors from the medium temperature crystal, at about 42.7°C. The hue values around 170 with an almost zero hue-temperature slope represented the wide blue zones associated with all three crystals.

After the passage of the color spectrum from the medium temperature crystal, an almost black zone was expected to show up around 47.5℃. The highest temperature liquid crystal did not show the passage of a distinct black zone, since the blue zone of the medium temperature crystal still existed at 47.5℃. The colors generated by the highest temperature liquid crystal were mixed with the blue color of the medium temperature crystals around the temperature. The highest temperature crystal also showed a limited number of colors between hue values of 135 and 170. Only six pairs of (hue-temperature) data could have been captured for the highest temperature crystal when compared to the vast amount of data collected for the lowest and medium temperature crystal. A very quick change in temperature and its associated color was related directly to the amount of heat flux applied by the heat. During the calibration of the highest temperature crystal, in order to generate the highest temperature range at about 47℃, the heat gun was moved very close to the thermocouple. Under these conditions the amount of lateral conduction occuring tangential to the surface is the highest compared to the medium and lowest temperature liquid crystal calibration experiments. The distance between the heat gun and the thermocouple was directly related to the geometrical width of the color band occuring between red and dark blue. In an experiment with a low heat flux (lowest temperature crystal calibration-heat gun is far away) the expected color band was much wider than the band for the experiment with the highest temperature crystal (heat gun is closest to the thermocouple). All of the colors which were supposed to exist in a 1°C temperature band were forced to exhibit themselves in an extremely short spatial bandwidth (1mm) for the highest temperature crystal. However, the hue-temperature slope was sufficiently defined even with the limited number of data points available. Corresponding local intensity values are presented for all three crystals in Fig. 6(b). The intensity peaks corresponded to an extremely narrow green dominated band for all three crystals.

3.3 Transient heat transfer measurements

Forced convection heat transfer depends on the temperature change of the model surface when subjected to a transient convective heating or cooling. The transient technique, reviewed by Schultz and Jones(1973) uses the timewise variation of wall temperature as a measure of the wall heat flux (q) and the corresponding heat transfer coefficient (h). When the model has a low thermal conductivity (k), the wall temperature response is limited to a thin layer near the wall surface and the lateral conduction is very small. Therefore the heat conduction into the model may be assumed to be one dimensional into a semi-infinite medium.

Transient heat transfer into a semi-infinite medium with constant thermal properties is governed by the transient one-dimensional diffusion equation

$$\frac{\partial T}{\partial y}=\frac{1}{\alpha}\frac{\partial T}{\partial t}, \tag{1}$$

where α is thermal diffusivity. The boundary and initial conditions can be stated as follows :

$$q(t)=h(T_w-T_\infty)=-k\frac{\partial T}{\partial y} \quad \text{at } y=0, \tag{2}$$

$$T=T_i \quad \text{at } y=-\infty, \tag{3}$$

$$T=T_i \quad \text{at } t=0, \tag{4}$$

where T_w, T_∞ and T_i are wall surface temperature at time t, constant free stream fluid temperature and initial wall surface temperature, respectively.

For an impulsively starting heat transfer experiment, Eq. (1) can be solved to give the surface temperature as

$$\theta=\frac{T_w-T_i}{T_\infty-T_i}=1-\exp(\beta^2)\text{erfc}(\beta), \tag{5}$$

where β is nondimensional time defined as :

$$\beta=\frac{h}{k}\sqrt{\alpha t}. \tag{6}$$

The specific solution assumes constant free stream temperture and constant heat transfer coefficient in time for a given location. Then, a single measurement of surface temperature at a certain time enables the heat transfer coefficient to be found when the reference temperature, initial temperature and the thermal properties are known. This is the basic principle of the specific heat transfer coefficient measurement technique using the images captured on liquid crystal covered surfaces. In this approach, any spatial variation in heat transfer coefficient will generate a corresponding variation in surface temperature which varies during a transient experiment. This spatial variation of surface temperature does not cause the heat transfer coefficient to vary in time significantly as discussed by Ireland and Jones (1985).

In the present experiments, the plate material was acrylic which has low thermal conductivity. A thermophysical triple product $\sqrt{\rho ck}$ of 569 $W(s)^{0.5}/(m^2K)$ was used in the data reduction with the uncertainty band of $\mp 5\%$ as reported by Baughn et al.(1988). Then the measurements of required times to reach the known color display temperature would allow the solution of Eq. (5) for the heat transfer coefficients.

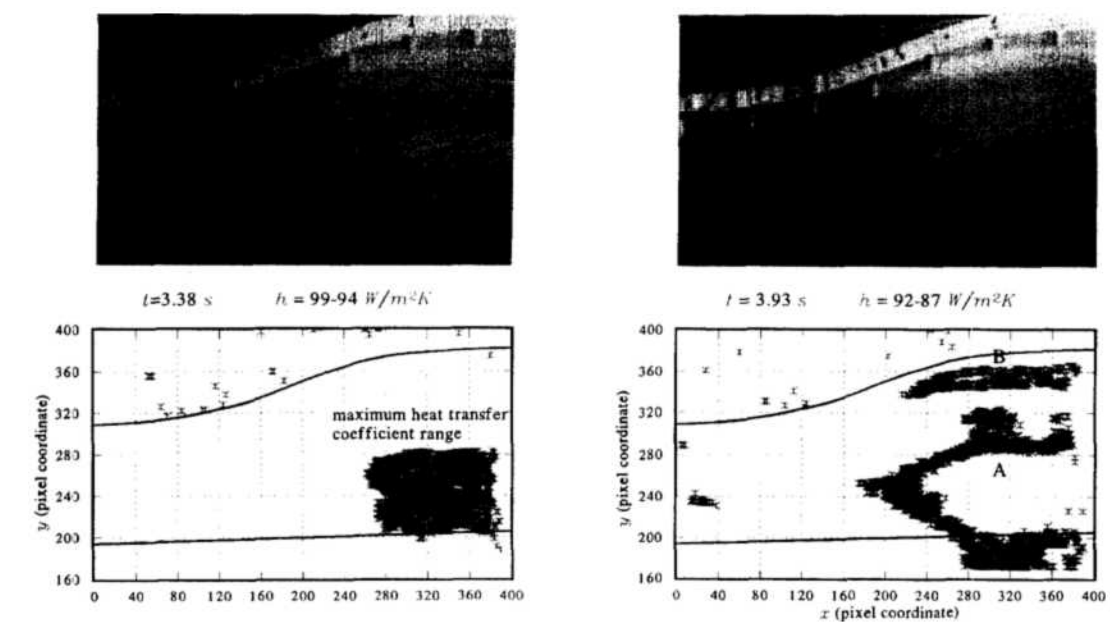
3.4 Results and discussion

Actual experiments were performed with an initially heated test section. The heater was kept active for about 5 hours prior to a transient run. This guaranteed a reasonably uniform initial wall temperature distribution just before the experiment. The experiment was initiated by connecting the test section to a large vacuum reservoir providing continuous steady flow in the test section for long durations. The heat flow direction was from the wall to the free stream due to the fact that the wall was initially at $T_i=55.7$℃ and the air entering into the bellmouth inlet was at ambient level, 28.6℃.

When the fast opening valve opened, the image from the bottom surface was completely dominated by black as an indication of a reasonably uniform initial temperature of about 55.7℃. The appearance of the first dark blue color was within the first second. The dark blue color was dominant almost uniformly all over the bottom surface. The blue content of the liquid crystal color did not change for a long time period between $t=0.0$ and 3.30 seconds because of the flat hue-temperature relation above 49℃. An almost constant hue value for this range was around 170 as shown in Fig. 6(a). The color display of the highest temperature liquid crystal was passed between 3.38 and 6.62 seconds. Within this specific time interval none of the points at the bottom surface of the duct had a temperature below 48℃. After the passage of the highest temperature liquid crystal, the medium temperature liquid crystal responded in between 13.32 and 21.39 seconds and finally the lowest temperature crystal responded in between 45.75 and 77.89 seconds. This feature avoided the mixing of colors from other liquid crystals.

The images were captured in natural color using a 24 bit **HSI** based image-processing system, controlled by a personal computer. Each captured frame was stored on the hard disk in an area having 778 Kbytes of memory. After storing an image having 512 columns and 512 rows of square pixels, hue, saturation and intensity values for each pixel were determined. It is a known fact that hue determination at low intensity values is not a stable process. Any hue value having an associated intensity value of 50 or less was discarded during the data reduction. This approach eliminated a significant amount of pixels showing some color within the range of the crystal. For example a hue value of 145 with a low intensity value may be introduced by the parts of the image which are not a liquid crystal covered surface. Applying an intensity threshold of this nature eliminated the unnecessary pixels which might come from the dark areas either from the liquid crystal image or from the background. The current data reduction scheme was searching for the pixels having a hue value between 140 and 150. This range corresponded to the higher end of the linear hue versus temperature relation. This hue band carried a color which could be described approximately by greenish-blue and corresponded to an approximate temperature range of 0.31℃ for the highest temperature crystal. During the data reduction process each pixel staying within the hue range between 140 and 150 was marked and its pixel coordinate was written into a specific file. The pixels showing a local intensity value of less than 50 were also discarded. Each one of the images shown in Fig. 7 were processed for the same hue band of 140-150. The pixels marked with the criteria described above were also presented next to each image. The actual temperature for each pixel was deduced from the hue value by using the calibration shown in Fig. 6(a). The time information was also recorded on each image accurate to 1/100 of a second. The convective heat transfer coefficient was deduced by using the transient technique.

Examination of the video images from the



(a) (b)

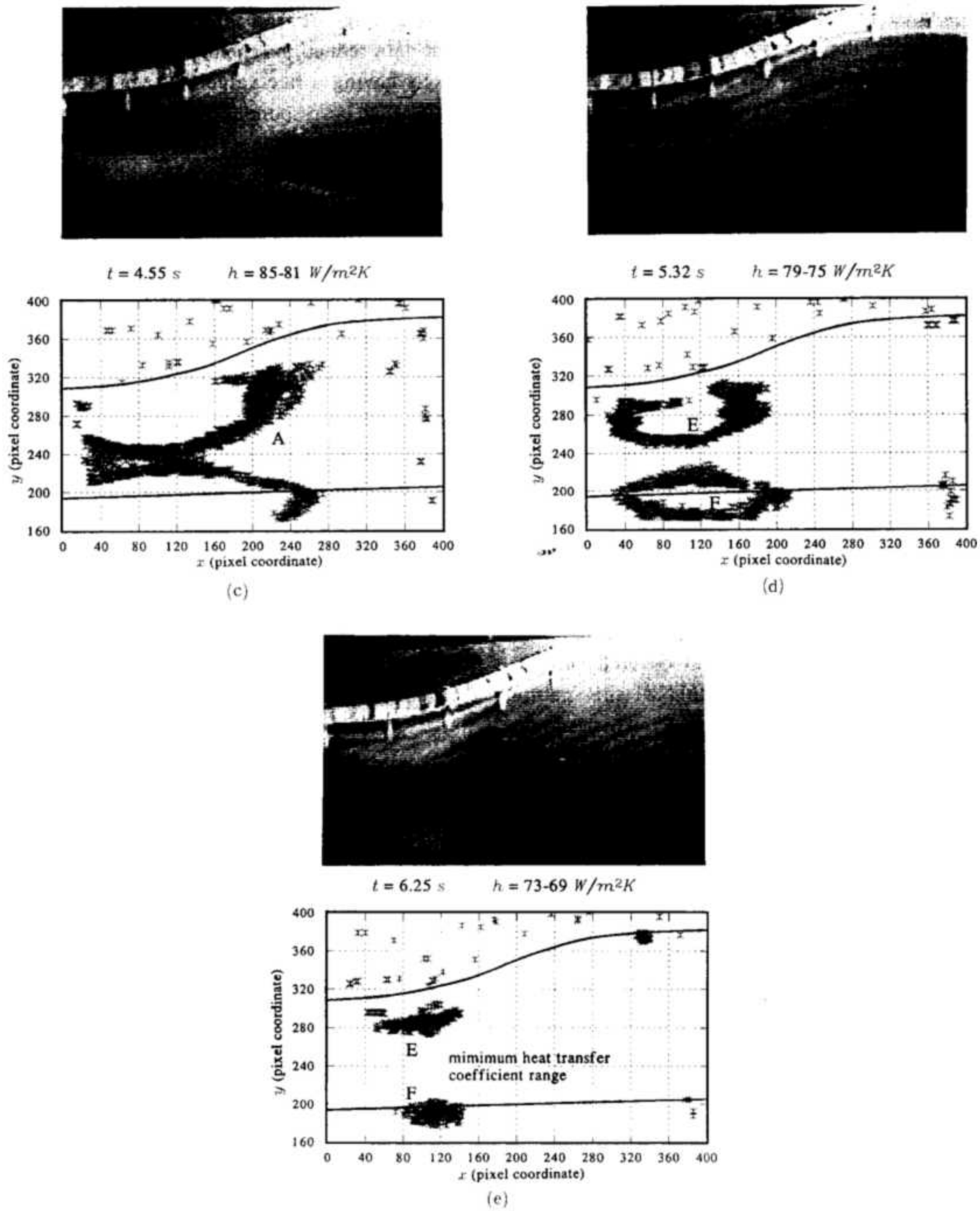


Fig. 7 Convective heat transfer coefficient map at the bottom surface of the transition duct

highest temperature crystal showed that there were about 97 subsequent frames available for processing at a frame-capturing rate of 30 frames per second. The present study showed that even a small fraction of 97 available frames from the highest temperature crystal were more than enough to generate a very clear mapping of heat transfer coefficient islands. Figure 7 presents only five of these video images and the associated quantitative heat transfer islands after processing.

The five consecutive images recorded during the passsage of the colors from the highest temperature liquid crystal are shown with their associated time measured from the beginning of the experiment. A typical image shown in Fig. 7 is for one half of the bottom surface of the duct due to the symmetry. The centerline of the duct is indicated with a solid line close to the horizontal axis. The reduced data is presented in the pixel coordinate system of the image processor. Although the bottom surface was slightly curved, this method of presentation using pixel coordinates was found the most suitable.

The heat transfer coefficient island shown in the image at $t=3.38$ seconds was calculated from the actual local temperature at each pixel location by using the transient theory. As a result of the selection procedure, this island corresponded to the local temperatures between 48.25 and 48.56℃. The calculated heat transfer coefficient limits for the specific hue range, at $t=3.38$ seconds were between 99 and 94 W/m^2K. The estimated experimental uncertainty on the heat transfer coefficient was within 5.72% using standard uncertainty prediction method of Kline and McClintock (1953). The specific heat transfer coefficient island shown at $t=3.38$ seconds corresponded to the coldest zone of the duct bottom surface at this time. This island generated the highest heat transfer coefficient, as the most successfully cooled region of the duct. It should be noted that the experiment was performed in cooling mode. If an experiment were designed with initially cold walls and a heated free stream, this island would be the first to show up during the experiment, marking the most severely heated region.

In the specific experiment, as the time passed, the cold front (48.25～48.56℃) diffused more into the duct starting from its initial location at the lower right corner of the image. At $t=3.93$ seconds the cold front was not any more in the form of a single closed island. This image provided the heat transfer coefficients between 92 and 87 W/m^2K. At this time, the cold front was more spread out in a form which complemented the island representing the heat transfer coefficients between 99 and 94 W/m^2K. In addition to this island marked as (A), a narrow band of the same cold front (B) was marked by the flow field close to the upper right corner of the image. In the mean time, the island (A) and (B) started to move closer to each other. At $t=4.55$ seconds, (A) and (B) completely merged into each other and moved further into the square inlet section of the duct. The heat transfer coefficient range for this island was starting from 85 to 81 W/m^2K. The image recorded at $t=5.32$ seconds indicated that the island (A) was split into two distinct islands marked as (E) and (F). The image obtained at $t=6.25$ marked the continuously decreasing heat transfer coefficient values. The final image recorded at $t=6.25$ seconds showed an extremely small island (E), marking the heat transfer coefficient range between 73 and 69 W/m^2K near the upper left corner of the duct.

After $t=6.62$ seconds the hue range between 140 and 150 never occurred on the bottom surface. The surface first assumed the dark blue of the medium temperature crystal for a while. At $t=13.32$ seconds a very similar passage of the hue band (140～150) started to occur. The last heat transfer coefficient island was generated at $t=21.39$ seconds. The lowest temperature crystal exhibited its hue range between 140 and 150 between $t=44.75$ and 77.89 seconds. The heat transfer coefficient islands obtained from the medium temperature and the lowest temperature crystals compared well with the information generated using the highest temperature crystal.

Figure 8 shows the islands generated at $t=3.38$, 3.93, 4.55, 5.32 and 6.25 seconds. Reducing five out of 97 available frames from the passage of the highest temperature secured the full coverage of the heat transfer islands on the bottom surface. The density of useful heat transfer information from the highest temperature crystal was extremely high. The corresponding heat transfer coefficient islands are marked very distinctly without any significant overlapping as far as the h bandwidths are concerned. The blank areas which are not filled with symbols also automatically generated extra heat transfer islands in between the marked areas. As an overall result, the highest convective heat transfer coefficients were induced

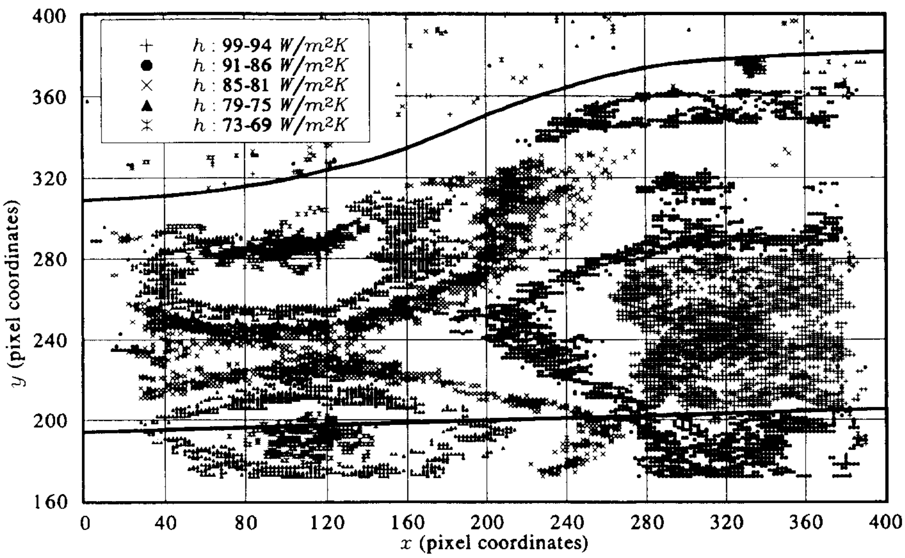


Fig. 8 Convective heat transfer coefficient map at the bottom surface of the transition duct

near the exit section of the bottom surface. A region of about one third of the duct length was spread around the centerline of the duct on the bottom surface. This area corresponded to a flow zone where the duct width was maximum in the horizontal plane minimum in the vertical plane, near the exit section. The highest heat transfer coefficient island corresponded to an area where there was a strong main flow impingement on the curved bottom surface. The lowest level of the convective heat transfer activity was observed near the entrance section of the duct. The lowest heat transfer islands were organized along the first one third of the duct length. One island was located just on the symmetry line (F) and a second separate island was formed near the upper curved boundary (E). The flow and its corresponding convective heating activity is expected to occur in a symmetrical fashion in the transition duct. The areas very near the corner flow (near the curved boundary) also experienced minimal convective heating activity.

4. Concluding Remarks

The recently developed hue-capturing technique was implemented for obtaining heat transfer coefficients in a transition duct. The transition duct was used as a heat transfer model representative of a curved geometry. The true color digital image-processing approach provided an extremely high data rate in terms of generating two dimensional heat transfer coefficient islands on surfaces with complex curvature. A complete heat transfer coefficient mapping of the bottom surface was possible with an excellent spatial resolution, using only five image frames out of 97 available frames from an almost three second long color passage of a liquid crystal. The reduced data in the form of convective heat transfer coefficient islands were presented with their associated natural image captured through the image processor for each specific time. Excellent consistency of the method in terms of marking the pixels within a predetermined narrow temperature band was proved. As a result of a set of experiments, it has been shown that the new hue-capturing technique implemented in a transient heat transfer model is an accurate and powerful tool in mapping surface heat transfer coefficients with high resolution. High resolution isothermal mapping was completed in a very time efficient manner. The method is non-intrusive and the overall uncertainty on convective heat transfer coefficient from the specific technique is estimated to be 5.72%.

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