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Transient Analysis of Transverse Ribbed Rectangular Duct by Liquid Crystal Thermography

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***Abstract*— The aim of this study was to the evaluate the Transient heat transfer from a transverse ribbed rectangular duct, by using the Liquid Crystal thermography technique. A comparative study was done for transient variation of nusselt number for smooth and the transverse ribbed roughened surface. Variation of Nusselt number with time has been observed experimentally. In this study, collection of True-Images for transient measurement of temperature and post processing has been successfully applied. It is seen that the value of Nusselt number decreases with increase in time. It is also observe that the transient Nusselt number for roughned surface is nearly four times than that of the smooth surface for beginning time duration for fixed value of Reynolds number .**

Keywords— Trnasient heat transfer, liquid crystal thermography, nusselt number

INTRODUCTION

In the last decade the visualization of temperature has been getting a great success by emerging Liquid crystal thermography as optical method. The liquid crystal is anisotropy fluid which changes in colour with experiencing the thermal load at a certain temperature range. A colour corresponding to this temperature range is called bandwidth. Response of liquid crystal is reversible for a certain bandwidth.

Spatial and temporal analysis of heat transfer from the surface of solar air heater required temperature information on the location of interest and in desired time duration. Conventional method of temperature measurement uses thermocouple. Major problem to measure a thermal filed (temperature information) of the surface by thermocouple is that a large number of thermocouples are needed. Also, they individually acquire some contact region, and hence one has to tack spatial average of temperatures. That will give the average temperature of the surface not at local basis. Liquid crystal thermography is best suited method here, to measure the temperature at local basis, it can even give the temperature at a pixel level of an image.

A significant amount of study have been done in the last few decades on enhancement of heat transfer in solar air heater. In which one of the effective method is applying artificial turbulence promoters inside the channel. Researchers have observed the change of heat transfer coefficient by measuring the average surface temperature of the absorber plate of solar air heater with the help of thermocouples. In the present study Nusselt number (convective heat transfer coefficient) at transient basis has been measured with the help of LCT. This study will be helpful to understand the actual mechanism of heat transfer of solar air heater.

Responses of Liquid crystal to temperature change

Responses of liquid crystal materials with temperature change may about bands of 0.5 ^{o}C to 20 ^{o}C, and working temperature of –30 ^{o}C to above 120 ^{o}C. These colour changes are repeatable and reversible as long as the TLC's are not physically or chemically damaged. The response time of TLC's may equals about 10 ms [1]. Liquid crystals (LCs) may be in the form of liquid, powder or sheet and specified by coding like "R35C5W". Specification of liquid crystal is given on the response phenomena of colour change. Initially LCs maintains black colour at room temperature around 25 ^{0}C. Here in specification R35 refer to starting temperature value (35^{0}C) corresponding to red (colour) start of LC sheet, 'C' refers to temperature unit 'centigrade'. On experiencing of high temperature LC sheet responds, from event point

NOMENCLATURE			x, y, z	Coordinate axes	
A	Area ………………………………......(m2)		e	Rib height …………………………….. (m)	
h	Heat transfer coefficient ………... (W/m2K)		P	Rib pitch …………………….……… (m)	
D	Hydraulic diameter of channel ………. (m)		L	Length ……………………………..… (m)	
c	Specific heat …………………….. (J/kg-K)		α	Thermal diffusivity (m2/s)	
k	Thermal conductivity ………. . . ...(W/m.K)		ρ	Density (kg/m3)	
Nu	Nusselt number		μ	Dynamic viscosity (Pa-s)	
Re	Reynolds number		*Subscripts*		
q	Heat flux ……………….………..… (W/m2)		a	Air	
T	Temperature ……………………..… (°C)		avg	Average	
ΔT	Temperature difference …………….... (°C)		∞	Ambient	
V	Air velocity in channel………………... (m)		o	Initial	
			s	Smooth plate	

red, then yellow, green, cyan, blue, magenta and back to black.

Literature review

At last, two decade liquid crystal thermography has been widely used in the visualization of transient Phenomenon of heat transfer through internal duct flow. Author [1] visualized temperature field by using LCT and velocity field by particle image velocimetry. They gave a map of thermal field in their form of colour change during natural convection over a vertical surface, and also provided a relative investigation between steady and transient method to determine convective heat transfer coefficient. Transient study on smooth and the transverse ribbed surface was done in [1], [3], and [4]. In [2] TLCs with constant bandwidth of different temperature range 28-33, 33-38, 38-43 and 45-50 °C were used the temperature changes micro circular channel flow, at level of uncertainty of ± 0.4 °C. Hue-temperature calibration is the important part of LCT literature [1] and [5] show full details of calibration. Hue temperature curve plot at different polynomial fits are investigated in the literature. It was found that the calibration curve may get differing on changing of experimental setup or equipped instruments of imaging. Both the literature assures the variation of hue, value increases with increasing of surface temperature. Variations of hue with temperature at different location have been found in [2] and [4]. Transient analysis was done by [3] in turbine cooling by impingement jet on transverse roughened duct. Studies were made of continuous and discrete ribs in different position of inclination. Transient response of temperature was successfully found by liquid crystal thermography. From the above literature review it is observed that studies were made of to measure the temperature variation with time in transient condtions using liquid cryatel thermo graphy techniques and efforts have not been made to measure the variation of Nusselt number with time of artificially roughened surface under transient conditions. Therefore in the present work experimental facility has been design and developed to measure the variation of Nusselt number of artificially roughned surface using LTC.

TEST FACILITY AND IMAGE ACQUISITION

Experimental setup

In the present work an experimental facilty has been designed and fabricated figure to measure the Nusselt number of smooth as well as artificial roughned surface. Fig (2) shows the schematic diagram of experimental set-up. It consists of heating element, test section, blower, illuminating system, camera, data logger and computer. Test section was a rectangular channel with aspect ratio of 5 (0.04 m height and 0.2 m wide), and length 1.5m, made of 8 mm thick Cast Acrylic sheet. The bottom plate of the test section made of 8 mm Aluminium sheet. A heater with temperature sensing element was used to warm up incoming air.

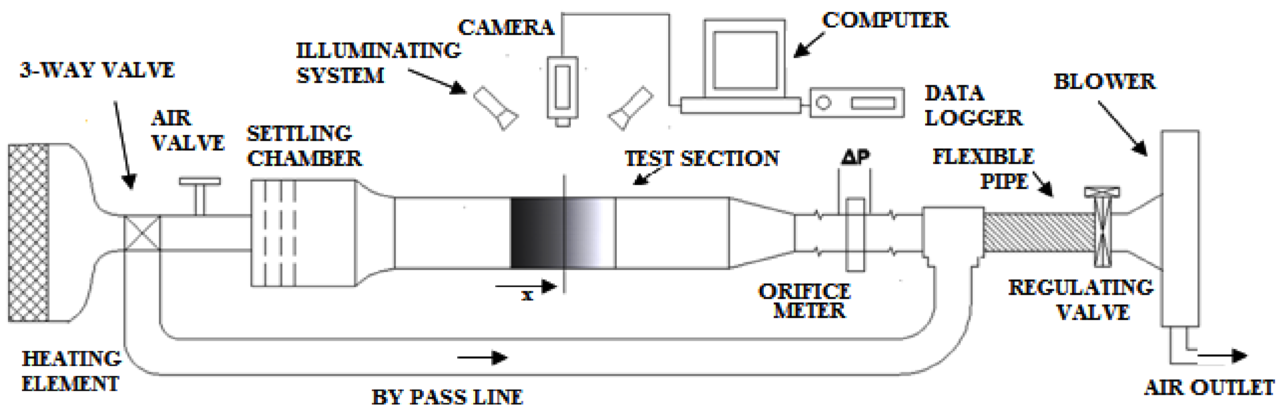

Figure 2: Schematic of the experimental setup

The heating power of the heater regulated with the help of variable AC drive. Liquid crystal sheets, with specification R35C5W, manufactured by *Hallcrest. Inc* were applied over the inside surface of aluminium plate. Fine-gauge T-type thermocouples were inserted at the inlet and outlet portion of the test section to measure mean air temperature. A data logger was used to record temperature information over the time .

Image acquisition

A 3CCD camera of Toshiba™ was used to capture images of thermal field (test zone). Light sources 4 LED lamps (each of 20W power) were used for illuminating the test zone. Each lamp was Individually arranged in mid of the axis of a rectangle having diagonal 934 mm and the distance from the test plate was 40 mm above as shown in

figure (2). Positioning of the camera was 23 mm above the test plate. Image grabbing and storing in PC was done by installing software SAPERA LT. Software stores the images in the form of array of frame of video. Images are separate out with by image processing.

Image processing

Image processing in Liquid crystal thermography included the conversion of true RGB image to HSV image. Here RGB stands for primary colours Red, Green, and Blue, while HSV for colour parameters Hue, saturation and Value.

The hue value H actually describes the angle on the HSV cone and is calculated from:

$$if\ R > B\ and\ R > G\ H = \frac{G - B}{6(R - \min(R, G, B))}$$

$$else\ if\ G > B\ \ H = \frac{2 + B - R}{6(R - \min(R, G, B))}$$

$$else\ H = \frac{4 + R - G}{6(R - \min(R, G, B))} \quad (1)$$

Above formula, gives the hue value H ranges from 0 to 1 which corresponds to 0 to 360 in degree.

Experimental procedures

LCT technique is used to measure temperature distributions in duration of transferring heat from hot air to test the surface. Transient heating method was used to determine convective heat transfer coefficient. To correctly apply the TLC transient technique, the test model must be kept at constant (room) temperature, then quickly exposed to high temperature air coming from the heater. The air temperature was maintained within the thermo sensitivity region of the LC sheet by an auto control type heater. At the moment when the temperature of the air was maintained constant at the event temperature of LC

The poly fitted curve was obtained from the hue - temperature chart as shown in figure (3). Polynomial order 3 and 5 were used in curve fitting, in which 5 was the best suited is shown in figure (6). Hue –Temperature curve obtained in calibration process is somewhat identical with that of in [5]

Heat Transfer Measurement

Non dimensional semi-infinite assumption has been taken for finding convective heat transfer coefficient at transient basis. The convective heat transfer coefficient may be determined by using following relationship [3].

sheet, then air was allowed to pass through main test section, and during this by-pass line was maintained closed by operating three- way valve. Thermocouple readings and the LC images were recorded for the complete bandwidth of Liquid crystal.

Data were recorded to measure the temperature distribution over the surface. The colour change pattern was recorded in AVI Video files by 3CCD camera. Number of frames in a video may be obtained by the frame rate of camera × time of recording in seconds. All frames are in RGB (Red, Green, and Blue) Images and stored in tiff file, which were converted into HSV (Hue, Saturation, and Value) form by using image processing technique. In the HSV form of an image of LC sheet, hue is the important parameter; their changing of numeric value can be directly correlated with temperature. Temperature information was obtained from these images by applying Hue Temperature Calibration.

Calibration of Liquid crystal Thermography

Previous many authors have indicated that such factors as lighting angles and image processing technique can influence the TLC hue-temperature calibration curves. [Yu] Hence In-situ calibration was performed so that identical lighting and camera conditions exist during calibration and experiment. The local wall temperature response with Hue can be determined from a calibrated Hue-value. The figure shows the variation of temperature with Hue value.

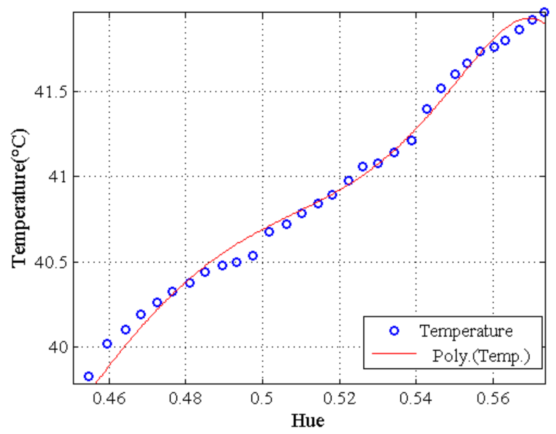

Figure 3: Calibration curve of LC

$$\frac{T(s) - To}{Ta - To} = 1 - exp\left(\frac{h^2 \alpha t}{k^2}\right) erfc\left(\frac{h\sqrt{\alpha t}}{k}\right) \quad (1)$$

Air temperatures at the inlet and outlet of test section were recorded by the data logger with information about time history of individual temperature value. Ta is the mean air temperature that was the function of time and space. At a particular time and location mean air temperature can be determined by interpolation of inlet and outlet temperature. Ts also the function time and space, which may be determined by the mean hue value and calibrating equation. h is the heat transfer coefficient, α and k are the thermal diffusivity and conductivity of the wall material, respectively.

The Nusselt and Reynolds number may be explained by following formula:-

$$Nu = h \times D/k \quad (2)$$

$$Re = (\rho \times V \times D)/\mu \quad (3)$$

Thermal conductivity k and dynamic viscosity μ of air were calculated at the film temperature.

RESULTS AND DISCUSSION

Heat transfer measurement for the smooth channel

Before doing experiments on the ribbed channel, heat transfer coefficient and nusselt number measured for the smooth channel. The results obtained from the experiment in the channel of hydraulic diameter 66.67 mm and length 1500 mm are discussed. Data were recorded at two regions of interest positioning stream wise direction X/D=6 and X/D=10 along the length of the channel. X was measured from the entrance point of the test section. Reynolds number (Re=8070) and mass flow rate were kept constant for all tests. The variation of nusselt number for both the positions is shown in figure (4-5). From fig. 4 – 5, it is seen that at the beginning (0- 10 seconds) the value of nusselt number is higher, and decreases with increasing in time. This is due to the fact that at the beginning the temperature difference between hot air and the test plate is high and it decreases with increases in time. Therefore the maximum value of Nu is observed at the beginning.

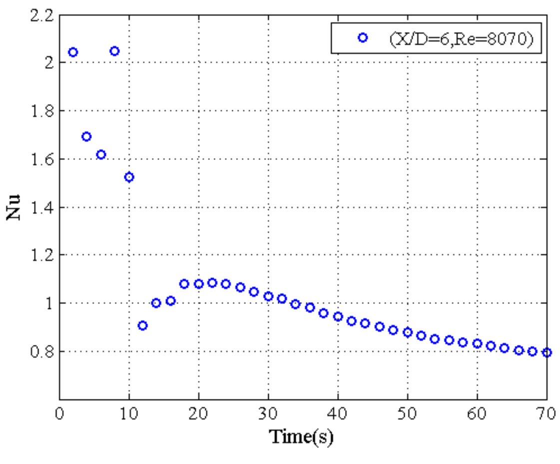

Figure 4: Variation of Nusselt number with time

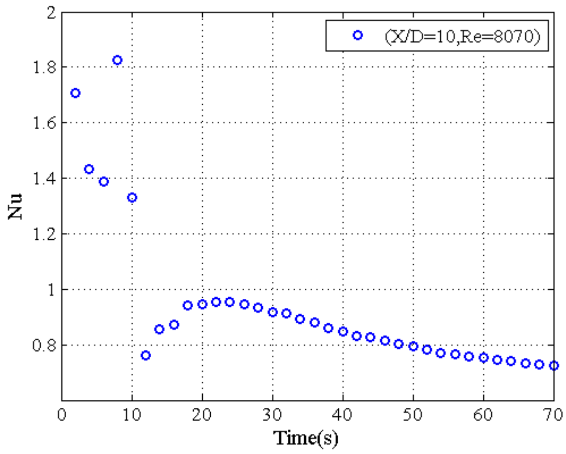

Figure 5: Variation of Nusselt number with time

Heat transfer measurement for the transverse ribbed channel

To measure the variation of Nusselt number of roughened surface the transverse rib geometric configuration has been tested. Aluminum plate of 8mm thick was machined by CNC machining to obtain accurate rib configuration (2×2 mm cross-section of each rib) over the surface of the plate. A picture of transverse ribbed surface is shown in figure (6). LC sheet was pasted between spacing portion of two consecutive ribs. Under the influence of heat sheet reflect colour in contrast of Red, Blue and green colours as shown in figure (7).

Figure 6: Unheated ribbed plate

Figure 7: Heated ribbed plate with LC on surface

Figures (8-9) shows the distribution of transient Nusselt number of transverse rib roughened test surface a function of temperature. It is seen that at the beginning (0- 10 seconds) the value of nusselt number is higher, and decreases with increasing in time. This is due to the fact that at the beginning the temperature difference between hot air and the aluminium plate is high, and it decreases with increases in time. Therefore the maximum value of Nu observed at the beginning.

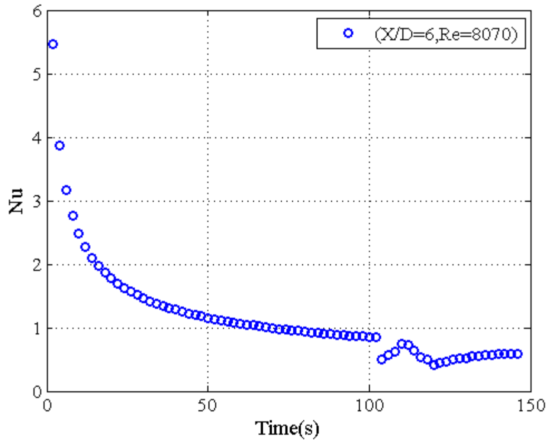

Figure 8: Variation of Nusselt number with time

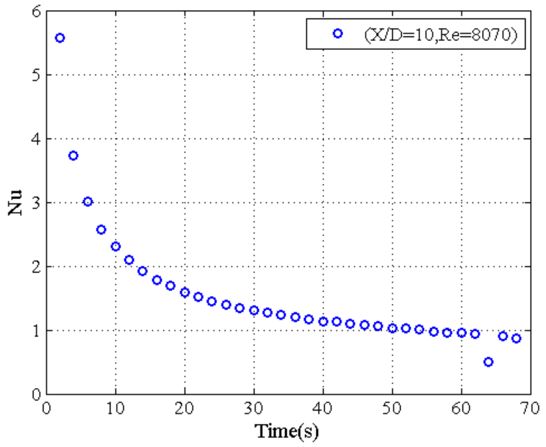

Figure 9: Variation of Nusselt number with time

Further, it is clear from the above study that by useful the artificial roughness the enhancement in the heat transfer is nearly four times as compare to that of the smooth surface.

CONCLUSIONS

The Liquid Crystal Thermography technique was successfully applied to determine the local Nusselt number at transient basis. In-situ calibration technique was used to calibrate Liquid crystal in order to minimize the errors induced by camera position, camera angle, lighting sources, etc. Convective heat transfer co-efficient in transient condition was measured at the two test position (X/D=6) and (X/D=10) in the channel. All the experiments were performed at Re=8070. The study gives the significant data for the variation of the Nusselt number with time.

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