



Nusselt number-friction characteristic for a twisted rib roughened rectangular duct using liquid crystal thermography

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ABSTRACT

Liquid crystal thermography technique is applied over a wide wall of a rectangular channel having twisted rib roughness to evaluate heat transfer distribution. The temperature distribution can be easily visualized easily as color pattern obtained by a CCD camera. The captured color pattern is digitized and converted to HIS (Hue, Saturation and Intensity) from RGB (red, Green and Blue). In this study the effect of different roughness parameters such as relative roughness pitch, twist ratio and rib inclination angle on heat transfer coefficient and friction factor are investigated. The range of Reynolds number and aspect ratio of the duct is selected those are most suitable for solar air heater. It is observed that relative roughness pitch of 8 shows the maximum heat transfer while friction factor decreases with increase in relative roughness pitch. The effect of twist ratio is to create the jet formation on the downstream side of the ribs, which creates vigorous mixing to increase in heat transfer. The increase in twist ratio decreases the number of jets formed and the Nusselt number, while friction factor increases. The rib inclination to the main flow generates secondary flow, increases turbulence level as well as Nusselt number. The secondary flow increases with increase in inclination angle to create maxima in Nusselt number at an angle of 60°. The friction factor increases with increase in rib inclination angle.

1. Introduction

The implementation of rib roughness over a surface is one of the passive techniques such as solid rib, wire coils, dimples, and fins as an insert to promote heat transfer. The periodic ribs placed transverse to the flow direction mainly generate turbulence at the vicinity of the surface and breaks laminar sub layer, causes good mixing with the core flow to augment heat transfer coefficient. Artificial roughness of different shapes is being applied over the absorber plate of solar air heater. However, the use of artificial roughness increases the turbulence intensity to increase in pressure loss also [1]. Therefore, it becomes essential to search an artificial roughness and its parameters needs to be optimized to provide maximum heat transfer argumentation with minimum pressure drop penalty. A liquid crystal thermography (LCT) technique is being applied to study the temperature distribution over a surface in a duct of air flow. The liquid crystals sheets are organic compounds having properties of reflecting different color depending upon temperature. Gao et al. [2] used LCT technique to study the effect of rib roughness in heat transfer and fluid flow in a rectangular duct. Wang et al. [3] obtained inter rib Nusselt number distribution using LCT for continuous and truncated ribbed surface and reported that a surface having continuous ribs provides better thermo-hydraulic

performance compared to discrete ribs. Tanda [4] has applied LCT technique to study the Nusselt number distribution over a surface having V-shaped turbulators. Cavallero et al. [5] uses LCT technique to study of heat transfer along a channel with various combinations of transverse, continuous, discrete and inclined ribs. Tariq et al. [6] studied the Nusselt number distribution and fluid flow over a surface having chamfered ribs. The author studied the variation of thermal boundary thickness, skin friction, velocity profiles and temperature distribution with the help of LCT technique. Tariq et al. [7] applied silted ribs and obtained the optimal Nusselt number for the surface. Ali et al. [8] investigated heat transfer and fluid friction inside a rectangular channel for flow over trapezoidal rib roughened surface using LCT technique. Reddy et al. [9] observed that heat transfer augmentation under steady state condition in a vertical rectangular fin using LCT technique and used Golden Section Search Algorithm to retrieve natural convection. Rashidi et al. [10] studied the effect of baffles, twisted tape, vortex generators, and wire coil inserted inside the heat exchanger and concluded the twisted tapes yields the maximum heat transfer. In this present work, the study is carried out for the Nusselt number distribution over a heated surface with twisted ribs arrangement inside a rectangular duct to represent solar air heater. The major objective of this study is:

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Nomenclature

A_o	orifice plate area, m^2
A_p	area of heated plate, m^2
C_d	coefficient of discharge of orifice plate
C_{pa}	specific heat of air, $J/kg\ K$
d_o	orifice plate diameter, m
d_p	pipe diameter, m
D	duct depth, m
D_h	hydraulic diameter, m
fr	friction factor, dimensionless
g	acceleration due to gravity, m/sec^2
h	heat transfer coefficient, $W/m^2\ K$
Δh_o	change in limb height, m
HSI	hue, saturation, intensity
k_a	thermal conductivity of air, $W/m\ K$
L	duct length, m
LCT	liquid crystal thermography
m	mass flow rate, kg/s
Nu	Nusselt number, dimensionless
ΔP_o	pressure drop across orifice plate, N/m^2
ΔP_d	pressure drop across the duct, Pa
Pr	Prandtl number, dimensionless
P/e	relative roughness pitch, dimensionless

Q	heat transfer rate, W
Re	Reynolds number, dimensionless
RGB	red, green, blue primaries
T_i	air inlet temperature, K
T_o	air outlet temperature, K
T_{mf}	air mean temperature, K
T_{TLC}/T_{mp}	TLC sheet/plate mean temperature, K
TLC	Thermo-chromic liquid crystal
V	air Velocity through duct, m/s
W	duct width, m
y/e	twist ratio, dimensionless

Greek characters

α	rib inclination angle, degree
ρ_a	air density, kg/m^3
ρ_w	water density, kg/m^3
μ	dynamic viscosity of air, $N/m^2\ sec$
ν	kinematic viscosity of air, m^2/sec

subscript

r	roughened plate
s	smooth plate

1. To observe the influence of roughness parameters of twisted rib roughness and Reynolds number on friction factor and Nusselt number using LCT technique.
2. To observe the distributions of Nusselt number over the roughened surface.

2. Experimentation methodology**2.1. Experimental details**

Fig. 1, indicates the details of the roughened surface with twisted rib roughness along with a pictorial view. The roughness is represented by the non-dimensional roughness parameters; i.e. relative roughness pitch (P/e), twist ratio (y/e) and rib inclination angle (α). Experimentation is carried out on 38 roughened plates varying roughness parameters and wide range of Reynolds number most suitable for solar air heater. The range of roughness and operating parameters considered for a present investigation are demonstrated in Table 1.

The schematic diagram of experimental set up along with a duct specification is depicted in Fig. 2. The experimental set up is fabricated by wooden block consisting of test section followed by a bell-mouthed entry section following ASHRAE standards [11] where minimum length for inlet section and outlet section are advised to be $5\sqrt{WD}$ and $2.5\sqrt{WD}$ respectively. The test section is a rectangular channel of $160\ mm \times 40\ mm$ of which lower surface is made of 3-mm aluminum

plate of 1280 mm in length and divided into two-halves to reduces conduction effects in the stream-wise direction. The top surface of the channel is covered with a transparent plexi-glass of 6 mm thickness to get access for image acquisition. Thermo-chromic Liquid Crystal (TLC) sheets are provided over the roughened surface and ribs are glued over it. A steady heat flux of $800\ W/m^2$ is provided from the opposite side of the roughened plate by an electrical heater connected to variac of single phase AC source supply. The blower is switched ON and the set-up required approximately 2–2.5 h for achieving steady state condition. The resultant TLC sheet images are captured by a CCD video camera (0.8 MP and 15 fps) (Sony™ model-DFK31AU03) which is kept normal to the sheet at a distance of 230 mm from upper end of rectangular duct and its position remains undisturbed for the entire experimentation [12]. Four 15W cool white light are placed above the test section to illuminate and to maintain same light intensity for the entire experimental investigation. In order to minimize, Infrared heating of the TLC sheets, the lamps are putted ON only at the time of image acquisition [13]. The image acquisition software (imaging source) is used to capture the colored pattern of TLC sheets over the heated surface with a resolution of 1368×768 pixel in JPG file format. In order to record the air temperature for the inlet section and exit section, calibrated T type thermocouple (24 SWG) with accuracy resolution of $0.25\ ^\circ C$ are used and connected to a data acquisition system. The pressure drop due to the presence of roughness in the test section is measured by Fluke™ digital micro-manometer. The experimental facility is shielded with

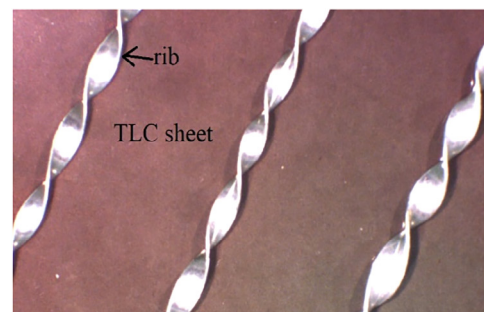
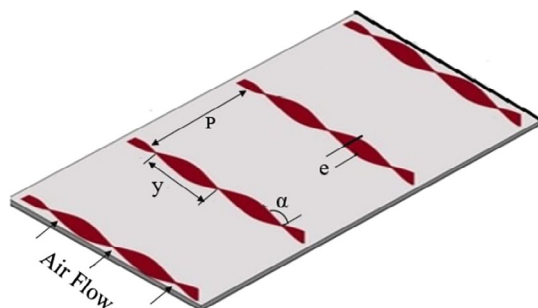


Fig. 1. Details of the twisted rib roughened surface with a pictorial view.

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