Applied Thermal Engineering 128 (2018) 415–425

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental and numerical investigation of heat and fluid flow in a square duct featuring criss-cross rib patterns

Prashant Singh [a,*], Yongbin Ji [b], Srinath V. Ekkad [a]

[a] *Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA, USA*
[b] *Department of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China*

HIGHLIGHTS

- Detailed HTC reported for unique combination of criss-cross ribs using TLCT.
- Numerical results reported on heat transfer (HT) enhancement mechanism.
- HT enhancement varied from 2.7 to 3.1 for Reynolds number from 30,000 to 60,000.
- *THP* varied from 1.25 and 1.5 for Reynolds number from 30,000 to 60,000.

ARTICLE INFO

Article history:
Received 24 May 2017
Revised 25 August 2017
Accepted 7 September 2017
Available online 9 September 2017

Keywords:
Rib turbulators
Criss-cross
Liquid crystal thermography
Thermal hydraulic performance

ABSTRACT

This paper presents findings from experimental and numerical study of heat and fluid flow in a straight square duct featuring rib turbulators in a criss-cross pattern formed by 45° angled rib turbulators. Two ribbed configurations with criss-cross pattern – Inline and staggered, have been studied where the baseline case was smooth duct with no heat transfer enhancement feature. Detailed heat transfer coefficients were calculated using transient liquid crystal thermography by employing 1-D semi-infinite conduction model. Heat transfer and pressure drop measurements were carried out for Reynolds number ranging from 30,000 to 60,000. For understanding of heat transfer enhancement mechanism, numerical investigations were carried out using SST k-ω turbulence model. Numerical predictions of near-wall fluid dynamics and turbulent transport has been presented in conjunction with experimentally obtained detailed heat transfer coefficients to demonstrate the heat transfer characteristics of ribbed duct. Nusselt numbers normalized with respect to Dittus-Boelter correlation for developed turbulent flow in circular duct varied between 2.7 and 3.1 for inline and staggered configurations and the thermal hydraulic performance varied between 1.2 and 1.5 for the range of Reynolds number investigated.

1. Introduction

Applications of heat transfer enhancement concepts can be found in gas turbine airfoils, solar air heaters, electronic cooling, etc. A common technique to enhance heat transfer is by installing turbulence promotors (“rib turbulators”) on the smooth walls. The rib turbulators generate secondary flows which increase near-wall shear in the vicinity of the ribs and these secondary flows also interact with channel side walls to increase turbulent transport of energy from relatively hotter walls by forming vortex or vortices. One application of rib turbulators as heat transfer enhancement technique is found in gas turbine airfoils. The gas turbine airfoils are subjected to elevated heat loads on both pressure and suction side walls. Hence rib turbulators are installed on pressure and suction side internal walls to increase heat transfer in order to increase the heat transfer rates between internal walls and coolant. Rib turbulators also result in increase in wetted surface area which enhances the overall conductance. Several studies have been carried out in the past on heat transfer enhancement by various cooling designs, such as, ribbed channel with bleed holes, ribbed channel with grooves, rib dimpled compound channels, jet impingement, jet impingement with effusion holes, dimpled channel, jet impingement onto dimpled target surface etc. [1–11]. The use of artificial roughness on a surface is an effective technique to enhance heat transfer coefficient also has good application in design and development of efficient solar air heaters. Many investigations [12–21] have demonstrated the effects of different rib configurations on heat transfer coefficient between absorbers plate

---

[*] Corresponding author at: 445 Goodwin Hall, 635 Prices Fork Rd, Blacksburg, VA 24061, USA.
E-mail address: psingh1@vt.edu (P. Singh).

http://dx.doi.org/10.1016/j.applthermaleng.2017.09.036
1359-4311/

Nomenclature

c	specific heat capacity of solid
d_h	channel hydraulic diameter
e	rib height
f	friction factor
f_0	friction factor from modified Blasius correlation
h	heat transfer coefficient
k_s	thermal conductivity of solid
k_f	thermal conductivity of air
L	length of the test section
Nu	local Nusselt number
Nu_0	Nusselt number (D-B correlation)
$\overline{Nu}$	globally averaged Nusselt number
p	rib pitch
Δp	pressure drop across test section
Re	Reynolds number, ud_h/υ
T_i	initial wall temperature
t	time
T_w	wall temperature
T_m	mainstream temperature
THP_0	thermal hydraulic performance
u	average coolant velocity in the duct

Greek symbols

ρ	density of air
υ	kinematic viscosity of air

Subscripts

s	smooth surface

Abbreviations

D-B	Dittus-Boelter correlation
HT	heat transfer
LC	liquid crystal
LN_2	liquid nitrogen
M	million

and air flowing in solar air heaters, numerically and experimentally, in order to improve the heat transfer capability of solar air heater ducts.

Heat transfer enhancement due to rib turbulators is affected by several parameters such as rib angle-of-attack, channel aspect ratio, rib pitch-to-height ratio, blockage ratio, and rib shape. Investigations on these aspects of rib turbulator design have been reported in [22–31]. In the past, researchers have studied the flow characteristics of ribbed duct, both, experimentally and numerically [32–37]. Some studies focused on the relative arrangement of ribs, e.g. parallel, staggered, and criss-cross [38–40]. Gao and Sunden [38] used particle image velocimetry to reveal the flow characteristics in rectangular channels with aspect ratio of 1:8. Six different rib configurations were experimentally investigated, namely staggered parallel ribs, staggered-single parallel ribs, inline parallel ribs, crossed ribs, V-ribs pointing downstream, and pointing upstream. Ekkad and Han [39] performed a detailed study on heat transfer characteristics with all rib parallel to each other in a non-rotating square channel using transient liquid crystals technique. Lee et al. [40] used naphthalene sublimation technique to measure detailed heat transfer enhancement contours using heat-mass transfer analogy. They tested continuous V shaped ribs and discrete V shaped ribs. Several investigations have been carried out in the past on rib turbulator as a method of enhancing heat transfer.

In past, several numerical investigations have been carried out to understand turbulent heat and fluid flow in rib roughened ducts. Murata and Mochizuki [41] carried out numerical investigation of laminar and turbulent heat transfer in a square duct featuring angled rib turbulators. Lu and Jiang [42] carried out experimental and numerical study on a rectangular channel featuring angled rib turbulators. The authors concluded that the SST $k-\omega$ turbulence model was more suitable for the prediction of turbulent heat transfer compared to RNG $k-\varepsilon$ model. Al-Qahtani et al. [43] used Reynolds Stress turbulence model in conjunction with near-wall second –moment turbulence closure to study heat transfer in rotating rectangular channels with rib turbulators. Eiamsa-ard and Promvonge [44] studied four turbulence models for prediction of heat transfer in a rectangular duct featuring grooves. The authors carried out computations using standard $k-\varepsilon$, RNG $k-\varepsilon$, standard $k-\omega$, SST $k-\omega$ turbulence models and found that the $k-\varepsilon$ model was better than the other turbulence models. For computations of heat transfer in a square duct roughened by discrete V-shaped ribs, Promvonge et al. [45] used RNG $k-\varepsilon$ model. Acharya et al. [46] compared nonlinear and standard $k-\varepsilon$ models for prediction of periodically developed heat and flow transfer in ribbed duct and concluded that the nonlinear model predicted realistic Reynolds stresses in the core flow region than the standard model. Peng et al. [47] studied different rib shapes numerically using SST $k-\omega$ turbulence model. Sewall and Tafti [48] carried out Large Eddy Simulations (LES) on a two-pass rib roughened duct featuring 90° rib turbulators and demonstrated that LES predicted flow and heat transfer was very accurate. However, LES comes at a significant computational cost. In order to maintain a balance between computational accuracy and cost, SST $k-\omega$ turbulence model was used in the present study. Further, the choice of the turbulence model in the present study is based on relative comparisons of heat transfer predictions by four other turbulence models and experimentally obtained heat transfer data.

The present study reports a new ribbed configuration which has shown promise in terms of heat transfer and overall thermal hydraulic performance. Detailed heat transfer measurements have been carried out using transient liquid crystal thermography. The ribs were installed periodically in a single pass channel with aspect ratio of unity. The ribbed channel was constructed by aligning ribs at an angle of attack of 45° in a unique pattern, which is called as "criss-cross" in this paper. Two such ribbed configurations were studied – inline and staggered. Heat transfer experiments were also carried out on smooth duct with no heat transfer enhancement features in order to characterize the inlet conditions and its effect on the downstream heat transfer distribution. Heat transfer and static pressure measurements were carried out for Reynolds number ranging from 30,000 to 60,000. Heat transfer measurements have been presented as detailed contours, region-wise averaged Nusselt numbers normalized with D-B correlation and globally averaged Nusselt number ratios. Numerically predicted fluid flow has been used to explain the heat transfer enhancement characteristics of the configurations. Thermal hydraulic performance of the channel has also been reported along with the frictional losses in the channel due to the ribs. Detailed discussion on flow physics has been presented for better understanding of heat transfer in rib roughened duct.