



Detailed heat transfer and fluid flow investigation in a rectangular duct with truncated prismatic ribs

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ABSTRACT

The paper presents an experimental study of detailed heat transfer and flow field characteristics in a rectangular duct having different types of truncated prismatic ribs on the bottom surface. The truncated prismatic ribs are manufactured by tapering the square rib from both the sides up to the center to provide rib height at the ends of 0, 2, 4, 6 and 8 mm. Experimental heat transfer results using transient liquid crystal thermography (LCT) are reported along with the mean flow field results using particle image velocimetry (PIV) at a rib pitch-to-height ratio of 10. The heat transfer effectiveness of proposed rib configurations is evaluated by examining the surface- and spanwise-averaged Nusselt number distribution. The effect of rib configurations on the flow parameters as well as on the heat transfer augmentation, with an emphasis to overall averaged augmentation Nusselt number, friction factor ratio, and performance index factors, are studied over a wide range of Reynolds number (9400–58,850). Most of the truncated prismatic ribs provide higher augmentation Nusselt number (about 25.15%) and lower pressure penalty (about 54.65%) than those with the square ribs. The truncated prismatic ribs provide better thermohydraulic performance than the square rib, however, these values are about 25–53% higher respectively at the lowest and the highest Reynolds number. Further, the aero-thermal characteristics are studied and documented in order to enhance the understanding and to correlate the flow dynamic mechanisms with the heat transfer augmentation from the fundamental perspective for all proposed rib configurations at a fixed Reynolds number of 42,500. The combined analysis of aerothermal characteristics puts in evidence the role of fluid dynamic factors i.e. flow features, mean velocities, and the turbulence intensity in the heat transfer augmentation.

1. Introduction

A compact, reliable, economic and energy efficient heat exchanging system has played a major role in industrial applications related to heating and cooling of the thermal systems under consideration. One practical way of enhancing the thermal performance of heat exchanging system is by using convective systems and liquid coolants for heat transportation [1]. Nanofluids have recently seen as a promising option for thermal fluids which can be effectively used for heat transport. The nanofluids significantly improve the thermal performance of the heat exchange systems employed in different practical applications, for instance CPU cooler [1], annulus and plate heat exchanger [2,3], and heat sink microchannel [4,5]. Aliabadi et al. [6] reported that the heat transfer coefficient and pressure drop for the ribbed wavy heat sinks are 4–128% and 8–185% higher than those for the smooth wavy sinks, which can be further enhanced by using nanofluids instead of water.

Another way of enhancing the convective heat transfer is by using

rib arrays inside flow passages, which are often used in many industrial applications such as cooling of gas turbine blades, combustor liner cooling passages, rib roughened radiator tubes/ducts, solar collectors, compact heat exchangers, cooling of electronic components and nuclear reactor fuel elements [7–9]. In each of the applications, the design/geometry of the rib turbulators varies, and might depends upon the nature of flow and configurational requirement. For instance, the radius of curvature of the rib in radiator tubes/ducts is high, and are of the same order of magnitude as the rib height due to manufacturing constraints; while in cooling of internal passages of gas turbine blades or combustors, sharp-cornered ribs (square/rectangle) are used in practice. In heat exchangers, vortex generators (square/rectangular, plain, louver, semi-dimple, winglet etc.) are most commonly employed, while the rounded ribs have special relevance in AGR fuel elements. In general, the spanwise vortices induced by the ribs break up the boundary layer and generate turbulence due to flow separation and flow re-attachment in the inter-rib region. The high magnitude of the turbulent

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Nomenclature

C_p	specific heat capacity, (kJ/kgK)
D_h	hydraulic diameter of the test section, (m)
e	maximum rib height, (mm)
e_p	rib height at the ends, (mm)
f	friction factor for ribbed duct
f_o	friction factor for smooth duct
h	convective heat transfer coefficient, (W/m ² K)
HTC	heat transfer coefficient
k	thermal conductivity of Perspex substrate, (W/mK)
k_a	thermal conductivity of air, (W/mK)
Nu	local Nusselt number of the surface with ribs, $Nu = hD_h/k_a$
Nu/Nu_o	augmentation Nusselt number
$(Nu/Nu_o)_a$	overall averaged augmentation Nusselt number
Re	Reynolds number based on hydraulic diameter, $Re = U_r D_h/\nu$
T_a	air temperature, (K)
T_i	initial wall temperature, (K)

T_w	wall surface temperature, (K)
TI	turbulence intensity, $TI = \sqrt{u_{rms}^2 + v_{rms}^2}$, (m/s)
TLC	thermochromic liquid crystal
u, v, w	time-averaged velocity component in x, y, and z direction, (m/s)
U_{xy}	mean velocity magnitude, $U_{xy} = (\sqrt{u^2 + v^2})$, (m/s)
U_{xz}	mean velocity magnitude, $U_{xz} = (\sqrt{u^2 + w^2})$, (m/s)
U_r	average velocity at the inlet of the test section, (m/s)
x, y, z	coordinate axis indicating streamwise direction, wall normal direction and spanwise direction, respectively

Greek letters

η_1, η_2	performance index factor
ρ	density of Perspex substrate, (kg/m ³)
ρ_a	density of air, (kg/m ³)
ν	kinematic viscosity of the air, (m ² /s)
τ	time, (s)

transport provides good mixing to improve heat-exchange and thereby resulting in an increase of convective heat transfer rate. But unfortunately, the rib turbulators also increase the pressure penalty/energy consumption and thereby affecting the overall thermo-hydraulic performance of the thermal system [8–10]. Therefore, it is important to find optimal rib configuration which will produce maximum heat transfer with minimum pressure drop.

Numerous experimental and numerical studies have established the significant effect of channel, rib, and flow features on heat transfer and friction factor characteristics [8–16]. The locally deteriorated heat transfer immediately behind the ribs, where the possibility of hot spot formation is the highest, has been reported along with higher pressure drop [8–10,15]. These local hot spots in the inter-rib region have found to be detrimental to the material structure and resulting in thermal failure of the thermal systems (like gas turbine blade, combustor liner etc.).

The ribbed duct flow is highly complex and unsteady; therefore, detailed spatial and temporal information is required to understand the flow physics and heat transfer mechanisms. Investigations with point-wise based measuring tools are unable to identify instantaneous flow structures and provide discrete regional averaged information due to their restricted spatial resolution by the size and nature of the probes [17–19]. In recent years, the progress in computational and hardware capabilities, mainly focussed towards advancement in optical techniques i.e. liquid crystal thermography (LCT), infrared thermography (IR), particle image velocimetry (PIV) etc., permit the researchers working in the pertinent area of rib roughened ducts to acquire high resolution temporal and spatial data of temperature and flow fields. Several researchers have implemented these sophisticated experimental optical diagnostics in order to study local heat transfer distribution and flow field characteristics inside ducts with ribs of rectangular/square cross-section [8–11,15,20–23]. However, some researchers provided permeability in the rib that allows the flow to go through the rib, and resulting in successful manipulation of the large-scale vortical structures inside the reattaching shear layer [24–28]. These investigations concluded that permeable-ribbed ducts have an advantage of higher local heat transfer coefficient immediately behind the rib resulting in the removal of hot spots, and lower pressure penalty when compared with the duct with solid ribs.

Apart from providing permeability, attempts have also been made to alleviate the problems of low heat transfer, high-pressure drop and hot spots formation by modifying the geometry of rib cross-section [17,29–33]. Using LCT, Wang and Sunden [29] found that the trapezoidal ribs with decreasing height in the flow direction provide the

highest heat transfer augmentation and friction factor among the square, triangular, and trapezoidal-ribs with both decreasing height and increasing height in the flow direction and could be helpful in obviating the local hot-spots formation. Ali et al. [30] investigated the effect of changing the trapezoidal angle (5°, 10°, 15° and 20° of the trapezoidal rib with decreasing height in flow direction on flow structures, and its consequent effect on the heat transfer augmentation at Reynolds numbers of 9400, 27,120, 44,600 and 61,480 using PIV and LCT techniques. It has been observed that the size of secondary recirculation bubble diminishes at higher Re and higher trapezoidal angle, and thereby leading to the removal of hot spots in immediate downstream of the rib. Moon et al. [31] numerically studied sixteen rib configurations of different cross-sectional shape and found the boot-shaped rib turbulators provides the maximum heat transfer performance with comparable pressure penalty to that of the square rib. The authors also reported that the slope of the front surface of the rib as a critical factor for determining the heat transfer performance because it directly affects the size of the recirculating zone.

Effect of three different rib geometries (semi-circular, rectangular and hybrids of the two) on heat transfer and flow friction characteristics have been investigated by Alfarawi et al. [32]. The flow velocity, the turbulent intensity as well as rib pitch to height ratio (p/e) are significantly altered the heat transfer augmentation, thereby leading the maximum heat transfer at $p/e = 6.6$ for the hybrids ribs and at $p/e = 13.3$ for remaining configurations. Recently, Sharma et al. [33] studied the effects of varying pentagonal angle (5° to 20°) and rib pitch to height ratio (6–12) on the local heat transfer and friction factor characteristics inside a rectangular duct roughened with pentagonal ribs one principal wall. LCT has been used to measure surface temperature distribution and finally to demonstrate the local HTC over the ribbed surface at different Re (9400–58,850). At higher Re and pentagonal angle, a significant improvement in augmentation heat transfer immediately behind the pentagonal ribs has been observed and thereby leading to obviation of the hot spots.

The literature confirms the three-dimensional nature of the flow field within the ribbed duct even for the simplest rib configuration due to manipulation of vortical structures in the inter-rib region [8–10,20–22]. The ribs having a variable cross-sectional area along the width span of the duct, like delta-wing vortex generator (VG)/profiled ribs, referred as three-dimensional ribs hereafter, have also been gained significant interest from the research community [34–39]. The three-dimensional ribs are not only strongly disturbed the boundary layer by the associated secondary flow, but also generated longitudinal vortices which persist over longer stream-wise distances. Using LCT and LDV,

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