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Experimental investigations of heat transfer enhancement from rectangular duct roughened by hybrid ribs

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ABSTRACT

Heat transfer and flow friction measurements were conducted for a fully developed turbulent flow in a rectangular duct with its bottom wall ribbed with three different rib geometries (semi-circular, rectangular and hybrid ribs of the two). The test duct was designed with an aspect ratio of 1:4 and its bottom wall was made of a rectangular removable brass plate of 320 mm by 120 mm. Brass ribs of 3 mm height, 6 mm width and 120 mm length were used. Experiments were carried out based on a Reynolds number in the range between 12,500 up to 86,500 and a range of rib pitch to height ratio from 6.6 to 53.3 for the three different rib geometries. It was found that the enhancement in heat transfer (Nu/Nu_s) was achieved in whole investigated cases, varied between 1.3 and 2.14 corresponding to a friction factor ratio (f/f_s) of 1.8 and 4.2. Also, the hybrid ribs provide mostly higher values for the efficiency indices compared with those of the rectangular and semi-circular ribs cases. New correlations for (Nu/Nu_s), (f/f_s) and $(Nu/Nu_s)/(f/f_s)^{1/3}$, were obtained as functions of Re and p/e ratio for all investigated geometries and configurations.

1. Introduction

Enhancing the heat transfer rates in several thermal systems is an importunate request for saving power consumption. This is particularly paramount in the engineering applications of elevated temperatures. Different enhancement techniques have technically been categorized for heat transfer augmentation, including; roughened surfaces, extended surfaces, twisted tapes and wire-coiled tubes inserts. The appropriate type of heat transfer enhancement technique can be selected by considering the level of enhancement, available pressure drop, complexity and cost. Most of the heat transfer augmentations provide extended heat transfer surface area, interrupt boundary layer development, and boost the turbulence level. These often result in extra flow resistance and higher pressure drop and hence, extra pumping power is required [1]. Therefore, it is a real challenge for investigators to find a new roughness geometry that can augment heat transfer with a minimum rise in the flow friction. For many years, artificially roughened surfaces have been used to enhance the thermal performance of compact heat exchangers, cooling systems of gas turbine blades, fuel elements for advanced gas-cooled nuclear reactors, cooling systems for electronic equipment, cooling of scram-jet engine inlets and electric utility devices. The basic idea of the heat transfer enhancement is not only to disturb the velocity and temperature profiles close to the walls, but also to create a secondary flow pattern. This secondary flow pattern improves the fluid mixing properties due to the generated vortices which in turn increases the local heat transfer coefficient.

The roughness of boundary surfaces influences the rate of diffusion of properties through the adjacent fluid so that the degree of local heat and momentum transfer to the fluid depends on the way in which the roughened surface affects boundary layer development. Stake-holders, in the form of ribs, have been showing interest among other enhancement with different geometries and orientations. Heat transfer is enhanced by two mechanisms due to the existence of ribs. First, by disturbing the wall sub layer, flow turbulence, separation and reattachment are created resulting in a higher heat transfer coefficient. Second, by increasing the heat transfer surface area due to the presence of the ribs. It is important to know the hydrodynamic and thermal flow characteristics in the boundary layer adjacent to the heated walls for purposely enhancing the heat transfer.

A number of previous theoretical and experimental studies were

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Nomenclature

C_p	Specific heat at constant pressure, J/kg. K
D_H	Hydraulic diameter of the duct, m
e	Rib height, m
H	Test duct height, m
h	Heat transfer coefficient, W/m^2. K
k	Air thermal conductivity, W/m. K
L	Test-section length, m
$\dot{m}$	Air mass flow rate, kg/s
p	Rib pitch, m
P	Pressure, Pa
q''	Net heat flux, W/m^2
T	Temperature, K
U	Flow mean velocity, m/s
W	Test-duct width, m
x	Axial distance measured from inlet, m

Greek letters

Δ	Difference
ν	Air kinematic viscosity
ρ	Air density

Subscripts

m	Mean value, bulk flow
s	surface, case of smooth duct
x	local value
x-Δx	test zone inlet

Dimensionless terms

p/e	Rib pitch to height ratio
f	Darcy friction factor
Nu	Nusselt number
Re	Reynolds number
Nu/Nu_s	Nusselt number enhancement ratio
f/f_s	friction factor ratio
η_i	Efficiency index, based on pumping power

revised here. Ichimiya [2], conducted experiments to examine the effect of different roughness elements on the insulated upper wall on the heat transfer of the opposite wall in a parallel plate duct. The experiments were based on the variation of space between upper and bottom plate (20–40 mm) and pitch of roughness elements (20–200 mm) while the roughness elements were square of 10 mmx10 mm. The results showed that for large pitch, separation-reattachment flow pattern was produced. Also, it was found that with decreasing pitch, recirculating closed vortex flow pattern was domineering. Moreover, the results showed that friction factors are 9–60 times greater in magnitude than that of a small duct for medium pitches, which were optimum on heat transfer for each space. Liou et al. [3] studied numerically and experimentally turbulent heat transfer for a periodic fully developed flow in a channel rib-roughened with one surface. The computation was confined within a unit module of the duct with a resultant economy of computational effort. In experiments, the time-dependent temperature profiles of the ribbed duct flows were obtained by using real-time holographic interferometry. In general, the regions susceptible to the hot spots were identified. Aliaga et al. [4] conducted heat transfer measurements on two ribbed plates, heated with constant heat fluxes using an infrared (IR) thermography technique. The tests were conducted for two roughness heights (e/D_h = 0.052 and 0.093). The results showed that a pattern of separation-reattachment flow was observed over the plate with a pitch ratio (p/e) of 12 and a pattern of trapped vortex flow between ribs for a (p/e) of 5. Also, the average heat transfer coefficient showed a declining trend outwards the leading edge, becoming nearly constant downstream. Acharya et al. [5] performed an experimental study heat transfer and pressure loss of a flow in a periodically ribbed duct at two Reynolds numbers, 3400 and 24,000. The bottom wall was roughened with square ribs of a pitch to rib height ratio of 20. It was noticed two local maxima of Nusselt number found in each inter-rib module, with the large occurring in the local zones of the reattachment downstream of the rib, and smaller peak occurring in the rib upstream corner, as a result of a small counter-rotating eddy. Young and Vafai [6] studied the convective cooling of a heated obstacle placed on a channel wall. The results showed that local Nusselt number distributions on the left and right surfaces of the obstacle are dramatically different, with much greater values near the upper corners. Tauscher and Mayinger [7] investigated the performance (heat transfer and pressure loss) in plate heat exchanger with rib-roughened surfaces of different rib shapes and dimensions. Holographic interferometry and laser Doppler Velocimeter were used in measurements. The results showed that the local heat transfer continuously had maximum value before the top of a rib, minimum behind the rib and, further local maximum was observed inter-rip space depending on Reynolds number. Also, it was found that turbulence intensity was increased when the number of ribs, passed by the fluid flow, were increased and at higher flow rates, few ribs were adequate to cause flow disturbance. Abdel-Moneim et al. [8] carried out measurements to investigate the enhancement in the heat transfer and the influence of the flow friction in a rectangular channel using periodic zigzag (multiple V-shaped) ribs affixed, in tandem, on the bottom surface of the channel for a range of Reynolds number from 15,000 to 75,000, rib-to-pitch (e/p) ratio between 0.0375 and 0.15, and for three rib angles (α) of 30, 45 and 60deg. It was found that multiple v-shaped ribs cause secondary flow that interacts with the main flow over the ribbed wall of the duct. This promotes turbulence and yields a significant enhancement in the heat transfer ($Nu/Nu_s > 1.0$) and in the same time increases the flow friction. Lee and Abdel-Moneim [9] developed a model to investigate heat transfer and flow characteristics of turbulent flow over an array of transverse ribs mounted on a horizontal heated surface. The predictions showed that the decrease in the rib pitch, intensity of ribs, strongly reduces the local values of the heat transfer coefficient, especially at the inter-rib spaces. Khan et al. [10] conducted an experimental study on forced convection heat transfer in developing region through a ribbed square duct with rib pitch to height ratio of 16 and Reynolds number range of 4.6×10^4 to 5.2×10^4. The results showed that the mean temperature of flow for the ribbed duct increases 1.81% over that of the smooth duct and the Nusselt number increases 6.24% over that of the smooth duct with corresponding increase of 3.32% in the pressure drop. Gradeck et al. [11] performed an experimental study of the effects of the hydrodynamic conditions on heat transfer enhancement to a single phase water flow. A test section composed of two opposite corrugated plates instrumented with thermocouples was heated electrically. The results showed that higher temperatures were recorded behind the top of the corrugation than those on the top due to the effect of reverse flow. Also, the local heat