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Computational Investigation on Thermo-Hydraulic Performance Characteristics of Ribbed Passage with Turbulence Generators

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Abstract:

Ribs of different geometrical shapes are used on the surface for heat transfer enhancement.Computational study was carried out to determine average heat transfer coefficients and friction factors for turbulent flow through rectangular ducts. A commercial finite volume package Ansys Fluent is used to analyze and visualize the nature of the flow across the ribbed duct. The fluid in the duct was air, and the average heat transfer coefficients were determined by measuring the overall heat transfer coefficients of the duct. To attain fully developed conditions at the entrance and exit, the duct was built with additional lengths before and after the test section. The results are presented in dimensionless form, in terms of Nusselt numbers and friction factors as functions of the Reynolds number. It was found that the ribs increase both the heat transfer and the pressure drop compared with a smooth duct.Thermal enhancement factor (TEF) isdetermined for all geometry and configurations of ribs pattern.

Keywords **—Nusselt Number, Heat transfer, Pressure Drop, CFD**

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I. INTRODUCTION

Various techniques are applied to improve the heat transfer performance in channels, such as fin, protrusion, dimple, vortex generator, groove, and ribs. The rectangular duct geometry is commonly employed in engineering applications, such as compact heat exchangers, solar collectors, and others. A survey of the available published literature on the heat transfer and pressure drop characteristics of rectangular ducts reveals a great lack of information about turbulent conditions. With regard to laminar heat transfer and pressure drop, the situation is better. Turbulent heat transfer and fluid flow characteristics of air in rib-roughened tubes, annuli, ducts and between parallel plates have been studied extensively because of their important applications. Such a heat transfer enhancement method is widely used in cooling passages of gas turbine blade, compact heat exchangers, fuel elements in advanced gas-cooled reactor electronic cooling devices, etc. Taking the cooling passages is usually approximated by a rectangular duct with a pair of opposite rib-roughened walls.

The ribs shape, size, and arrangement are important parameters that affect significantly thermo-hydraulic performance in a channel flow. Various studies are available in the literature for thermal performance of channel roughened with different geometry of ribs. Applications of heat transfer enhancement concepts can be found in gas turbine airfoils, solar air heaters, electronic cooling, etc. 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. 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 have demonstrated the effects of different rib configurations on heat transfer coefficient between absorbers plate 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 the past, researchers have studied the flow characteristics of ribbed duct, both, experimentally and numerically. Some studies focused on the relative arrangement of ribs, e.g. parallel, staggered, and criss-cross. Several investigations have been carried out in the past on rib turbulator as a method of enhancing heat transfer.

From the literature, it shows that the geometry and spacing of ribs has a significant effect on hydraulic and thermal performance in the channel flow. Ribs of different geometrical shape are used on the surface for heat transfer enhancement. However, the combination of different geometry of ribs on the heat transfer surface is found fewer in literature. As summarized above, many researchers have investigated internal cooling channels having a variety of ribs over the last few decades. However, the heat transfer performances of many other rib shapes have not yet been reported. In the present work, the flow structures, heat transfer characteristics, and thermal performances of rib-roughened rectangular channels were evaluated using three-dimensional RANS analysis; new rib shapes—fan shaped, house-shaped, reverse cut-trapezoidal, cut-trapezoidal, reverse boot-shaped, boot-shaped, reverse pentagonal, pentagonal, and reverse right-angle trapezoidal—were compared against the rib shapes that have already been tested in previous works—square, isosceles triangular, reverse right-angle triangular, right-angle triangular, right-angle trapezoidal, isosceles trapezoidal, and semi-circular. It is well known that in a turbulent flow a laminar sub-layer exists in addition to the turbulent core. The rib roughness on heat transfer surface breaks up the laminar boundary layer of turbulent flow and makes the flow turbulent adjacent to the wall. The rib roughness that results in the desirable increase in the heat transfer also results in an undesirable increase in the pressure drop due to the increased friction; thus the design of the flow channel and absorber surface of channel should, therefore, be executed with the objectives of high heat transfer rates and low friction losses. It is therefore desirable that the turbulence must be created only in the region very close to the heat transferring surface i.e. in the viscous sub-layer only where the heat transfer takes place and the core flow should not be unduly disturbed so as to avoid excessive friction losses. This can be done by keeping the height of the roughness elements to be small in comparison with the channel dimensions. Numbers of investigations involving roughness elements of different shapes, sizes and orientations with respect to flow direction have been carried out in order to obtain an optimum arrangement of roughness element geometry.[1-44]

In this paper, circular ribs is used for thermo-hydraulic performance analysis of channel. The present research was undertaken to determine average heat transfer coefficients and friction factors for turbulent flows in ribbed duct. Computational study was performed by using a ribbed duct. The thermal boundary conditions were constant temperature over the surfaces of walls the second wall being insulated. The Fluent software

solves the mathematical equations which governs fluid flow, heat transfer and related phenomena for a given physical problem.

II. MODELING AND ANALYSIS

The 2-dimensional solution domain used for CFD analysis has been generated in ANSYS version 16 (workbench mode)as shown in Fig. 1. The solution domain is a horizontal channel with circularrib roughness on the underside of the top of the channel while other sides are considered as smooth surfaces.

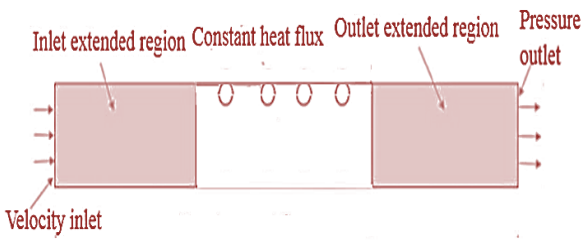

Fig. 1 Computational Domain

The following assumptions are imposed for the computational analysis.

(1) The flow is steady, fully developed, turbulent and two dimensional.

(2) The thermal conductivity of the duct wall, absorber plate and roughness material are independent of temperature.

(3) The duct wall, absorber plate and roughness material are homogeneous and isotropic.

(4) The working fluid, air is assumed to be incompressible for the operating range of solar air heaters since variation in density is very small.

(5) No-slip boundary condition is assigned to the walls in contact with the fluid in the model.

(6) Negligible radiation heat transfer and other heat losses.

The computational domain used for CFD analysis is a simple rectangle. After defining the computational domain, non-uniform mesh is generated. In creating this mesh, it is desirable to have more cells near the plate because we want to resolve the turbulent boundary layer, which is very thin compared to the height of the flow field. After generating mesh, boundary conditions have been specified. We will first specify that the left edge is the duct inlet and right edge is the duct outlet. Top edge is top surface and bottom edges are inlet length, outlet length and solar plate. All internal edges of rectangle 2D duct are defined as turbulator wall. Meshing of the domain is done using ANSYS ICEM CFD V16 software. Since low-Reynolds-number turbulence models are employed, the grids are generated so as to be very fine. To select the turbulence model, the previous experimental study is simulated using different low Reynolds number models such as Standard k-ω model, Renormalization-group k-ε model, Realizable -kε model and Shear stress transport k-ω model. The results of different models are compared with experimental results. The RNG k-ε model is selected on the basis of its closer results to the experimental results. The working fluid, air is assumed to be incompressible for the operating range of duct since variation is very less. The mean inlet velocity of the flow was calculated using Reynolds number. Velocity boundary condition has been considered as inlet boundary condition and outflow at outlet. Second order upwind and SIMPLE algorithm were used to discretize the governing equations. The FLUENT software solves the following mathematical equations which governs fluid flow, heat transfer and related phenomena for a given physical problem.

The geometrical and operating parameters for roughened duct are listed in Table 1.

Table 1
Range of parameters for CFD analysis.

Geometrical and operating parameters	Range
Entrance length of duct, 'L_1'	245 mm
Test length of duct, 'L_2'	280 mm
Exit length of duct, 'L_3'	115 mm
Width of duct, '*W*'	100 mm
Depth of duct, '*H*'	20 mm
Hydraulic diameter of duct, '*D*'	33.33 mm
Rib height, *'e'*	2 mm
Rib Pitch, *'P'*	5-30 mm
Reynolds number, *'Re'*	3800-18000 (6 values)

III. RESULT AND ANALYSIS

The computational model studied in the present study includes a segment of the inlet plenum and the test section. Inlet for the computational domain is the inlet to the domain, so that more realistic flow with entry effect can be simulated for the test section. The flow is assumed to leave the test section to ambient with a zero static pressure boundary condition at the outlet.

Fig. 2 shows the effect of Reynolds number on average Nusselt number for different values of relative roughness pitch (P/e) and fixed value of roughness height (e). The average Nusselt number is observed to increase with increase of Reynolds number due to the increase in turbulence intensity caused by increase in turbulence kinetic energy and turbulence dissipation rate. The heat transfer phenomenon can be observed and described by the contour plot of turbulence intensity.

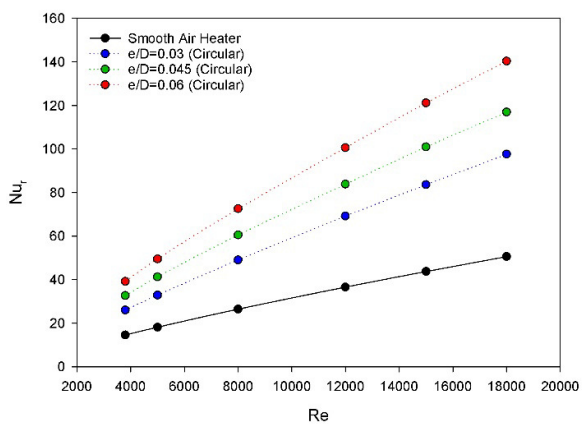

Figure 2 Nusselt number vs Reynolds number

It can be seen that the enhancement in heat transfer of the roughened channel with respect to the smooth channel also increases with an increase in Reynolds number. It can also be seen that Nusselt number values increases with the increase in relative roughness height for fixed value of roughness pitch. The roughened channel with higher relative roughness height provides the highest Nusselt number.

The heat transfer phenomenon can be observed and described by the contour plot of turbulence intensity. The intensities of turbulence are reduced at the flow field near the rib and wall and a high intensity region is found between the adjacent ribs close to the main flow which yields the strong influence of turbulence intensity on heat transfer enhancement. (Fig. 3)

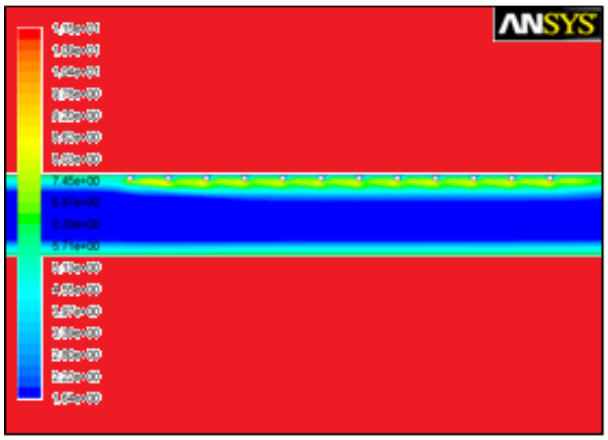

Figure 3 Contour plot of turbulence intensity

IV. CONCLUSIONS

The following conclusions are drawn from present analysis:

1. The use of artificial roughness on a surface is an effective technique to enhance heat transfer to fluid flowing in the duct. Artificially ribbed ducts have enhanced rate of heat transfer as compared to the smooth duct.
2. The RNG k-ε turbulence model gives very close results to the experimental results. RNG k-ε turbulence model has been validated for smooth duct and grid independence test has also been conducted to check the variation with increasing number of cells.
3. Nusselt number increases with an increase of Reynolds number.
4. The maximum value of average Nusselt number is found to be at maximum value of relative roughness height at a higher Reynolds number.

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