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NUMERICAL STUDY ON HEAT TRANSFER OF TURBULENT DUCT FLOW THROUGH RIBBED DUCT

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ABSTRACT

Ribs have been used as a tool to enhance heat transfer by increasing the level of turbulence mixing in the flow. Enhancing heat transfer surface are used in many engineering applications such as gas turbine blade cooling passages (i.e. channel/duct), air heater, heat exchanger surfaces, gas-cooled reactor fuel elements, ventilation equipment of micro-electronic systems and air conditioning/ refrigeration systems, hence many techniques have been investigated on enhancement of heat transfer rate and decrease the size and cost of the involving equipment especially in heat exchangers. Rib roughness on the underside of the top wall of a duct has been found to substantially enhance the heat transfer coefficient. A two-dimensional CFD investigation is conducted to study forced convection of fully developed turbulent flow in a rectangular duct having ribs on the underside of the top wall. CFD solutions are obtained using commercial software ANSYS FLUENT v12.1. The working fluid in all cases is air.

KEYWORDS: Ribbed duct, CFD, Heat transfer, Flow friction.

INTRODUCTION

Nowadays, the high cost of energy and material has resulted in an increased effort aimed at producing efficient heat transfer equipment's. The heat transfer rate can be enhanced by introducing the disturbance in the fluid flow (making and breaking thermal boundary layers) but in process industries pumping power may increase significantly and ultimately the pumping cost becomes high .Therefore to achieve the desired heat transfer rate in an existing heat exchange equipment's at an economic pumping power, several techniques have been proposed in recent years and are discussed in further sections. Heat transfer augmentation techniques refer to different method used to increase rate of heat transfer without affecting much the overall performance of the system. These techniques are used in heat exchangers. Some of the applications of heat exchangers are in process industries, thermal power plant, air conditioning equipment, refrigerators, radars for space vehicles, automobiles etc. The Heat transfer enhancement in duct flow by inserts such as twisted tape, coil inserts/spirals, ribs and dimples is mainly due to flow blockages, partitioning of the flow and secondary flow. The flow blockages increase the pressure drop and leads to increased viscous effect because of reduced fluid flow area. The blockages also increase flow velocity and in some situations it leads to a significant secondary flow. The secondary flow further provides a better thermal contact between surface and fluid as secondary flow creates swirl and this results in mixing of fluid that enhances the thermal gradient which ultimately enhances the heat transfer coefficient. In the past decade, several studies on the passive techniques of heat transfer augmentation have reported. The present paper review mainly focus on the rib turbulators heat transfer enhancement and its design modification towards the enhancement of heat transfer and saving pumping power. Enhancing heat transfer surface are used in many engineering applications such as gas turbine blade cooling passages (i.e. channel/duct), air heater, heat exchanger surfaces, gas-cooled reactor fuel elements, ventilation equipment of micro-electronic systems and air conditioning/ refrigeration systems, hence many techniques have been investigated on enhancement of heat transfer rate and decrease the size and cost of the involving equipment especially in heat exchangers. One of the most important techniques used are passive heat transfer technique. These techniques when adopted in heat transfer surfaces proved that the overall thermal performance improved significantly. Rib roughness on the underside of the top wall of a duct has been found to substantially enhance the heat transfer coefficient. Surface roughness disturbs the laminar sub-layer in the turbulent flow and promotes local wall turbulence that, in turn, increases the heat transfer from the surfaces. The augmentation in heat transfer accompanies a higher pressure drop penalty of the fluid flow. Dipprey and Sabersky [1] developed a friction similarity law and a heat momentum transfer analogy for flow in rough tubes. Webb and Eckert [2] developed the heat transfer and friction factor correlations for turbulent air flow in tubes having repeated rib roughness. Zhang et al. [3] reported that the addition of grooves in between adjacent square ribs enhances the heat transfer capability of the surface considerably with nearly same pressure drop penalty. Many experimental investigations have been carried out to determine configurations that produce optimum results in terms of both heat transfer and friction factor. Parameters involved in such experimental studies are passage aspect ratio, AR [4,6]; pitch ratio, P/e [7,8]; blockage ratio, e/Dh [8,9]; rib angle of attack, α [4,10,11]; number of ribbed walls [12]; and the manner by which ribs are positioned with respect to each other [6,13]. The previous experimental [14] studies indicated that for fully developed flow hot spots exist in the recirculating region immediately downstream the square ribs because the fluid flow is nearly stagnant relative to the mainstream in this region. The hot spots lead to lower heat transfer coefficient from the surface. Therefore, it is of interest to know the heat transfer coefficients than on the friction factor, and the influence of the rib shape on the heat transfer coefficient disappears at higher Reynolds number where the flow is in the completely rough regime. Liou and Hwang [16] investigated the fully developed flow in channels roughened with three rib shapes, namely square, semicircular and triangular cross section. The results showed that the three types of rib channels had comparable thermal performance, but the square-ribbed geometry is the most likely the one to yield hot spots behind the rib. Arman and Rabas [17] used a non-orthogonal, body fitted numerical code to predict the effect of the rib shape on the thermal-hydraulic performance in a circular tube. By investigating the effects of several different rib shapes, such as sine, semicircle, arc, and trapezoid, they reported that the increases in heat transfer were in the order of arc, semicircle, sine and trapezoid. Chandra et al. [18] studied a square channel with two ribbed walls for five different rib profiles. Their study illustrated that rib turbulators with greater number of sharp corners yield increasingly higher heat transfer coefficient as well as pressure drop. More recently, Ahn [19] studied the fully developed heat transfer and friction characteristics in rectangular duct roughened by five different rib shapes, i.e., square, triangular, circular, and semicircular geometries. He concluded that the square-shaped roughness geometry has the highest friction factor; meanwhile, the triangular-shaped rib has the highest heat transfer coefficient and efficiency index. In addition, flow measurements in the fully developed region have been obtained using LDV measurements [20]. Computational studies have also been used extensively in studying the flow and heat transfer effects in ribbed ducts. The advantage of being able to study both the flow and heat transfer in the entire flow field is worth the effort required to simulate ribbed duct flows, but the whether the channel roughened with ribs of different shape can improve the heat transfer rate. There have been attempts undertaken to overcome the adverse effect by varying the geometry of ribs. Lockett and Hwang [14] employed the non-invasive optical method of holographic interferometry to investigate the heat transfer in turbulent flow over square and rounded rib-roughness elements. They found that the heat transfer distribution depends on the Reynolds number for the rounded rib, but independent for square rib geometry. In both cases, the minimum heat transfer occurred at the base of the rear facing rib wall. This paper basically describes the characteristics of the heat transfer and friction in a square duct where various-shaped ribs are placed transversely to the main stream direction on one wall. The shapes of the ribs investigated are circular and square.

COMPUTATIONAL MODEL

The configuration of various-shaped ribs used in this study is shown in Fig. 1. The rib height, e, varies from 1mm to 2 mm and rib pitch-to-height ratio, P/e, is equal to 10. The effects of these various-shaped ribs on Heat Transfer and Flow Friction Characteristics are studied. The solution domain is a horizontal duct with circular and square rib roughness on the absorber plate at the underside of the top of the duct while other sides are considered as smooth surfaces. After defining the computational domain, uniform and 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 plate. All internal edges of rectangle 2D duct are defined as turbulator wall. Meshing of the domain is done using ANSYS ICEM CFD V12.1 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 k-ε 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.

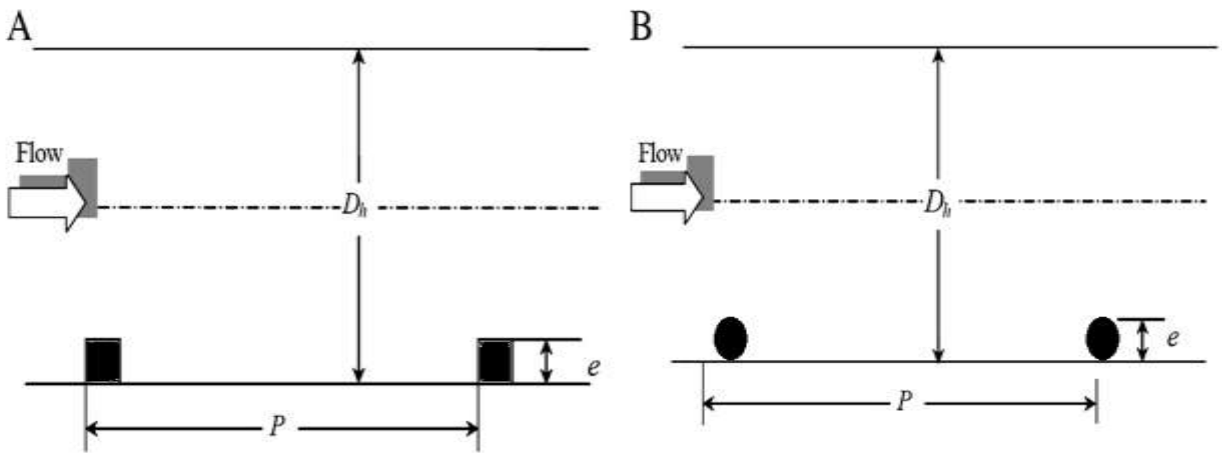

Figure 1. Configuration of various-shaped ribs

RESULTS AND DISCUSSION

Fig. 2 shows the effect of Reynolds number on average Nusselt number for different values of relative roughness height (e/D) and fixed value of roughness pitch (P). 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.

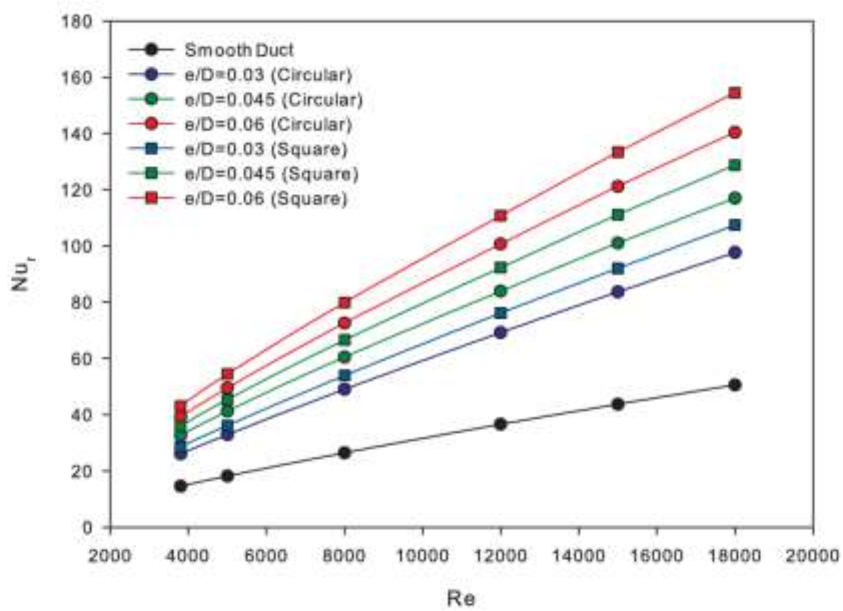

Figure 2. Nusselt number vs Reynolds number

It can be seen that the enhancement in heat transfer of the roughened duct with respect to the smooth duct 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 (e/d) for fixed value of roughness pitch (P). This is due to the fact that heat

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transfer coefficient is low at the leading edge of the circular wire rib and high at the trailing edge. Higher relative roughness height produced more reattachment of free shear layer which creates the strong secondary flow. The roughened duct having circular rib with highest relative roughness height provides the highest Nusselt number at a higher value of Reynolds number. The roughened duct having square rib with highest relative roughness height provides the highest Nusselt number at a higher value of Reynolds number. Square sectioned rib provides higher value of enhancement in average Nusselt number as compared to circular rib at a higher value of Reynolds number.The heat transfer phenomenon can be observed and described by the contour plot of turbulence kinetic energy. The contour plot of turbulence intensity is shown in Fig. 3. The intensities of turbulence are reduced at the flow field near the rib and wall and a high turbulence 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.

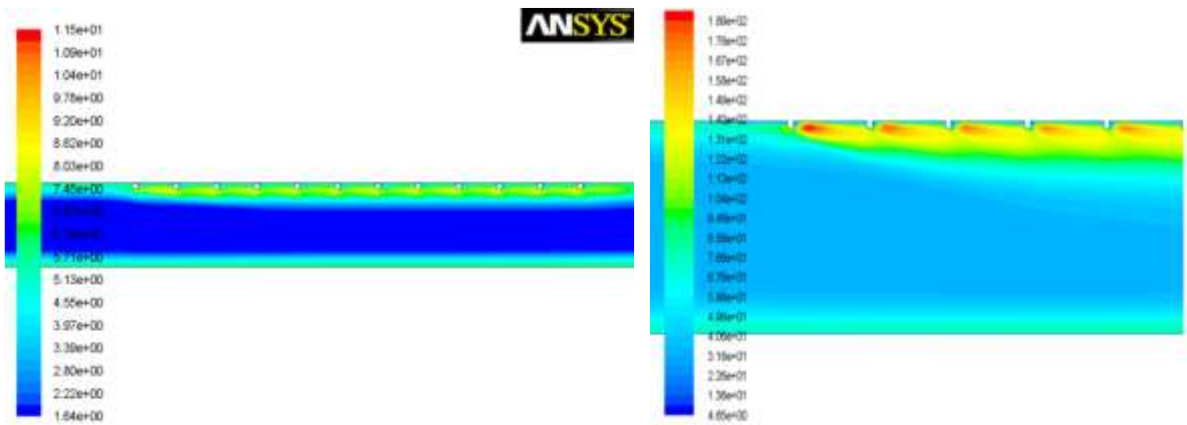

Figure 3. Contour plot of turbulence intensity

CONCLUSION

The flow over two-dimensional ribs of different shapes is studied to examine the heat transfer characteristics as well as the friction characteristics. A 2-dimensional CFD analysis has been carried out to study heat transfer and fluid flow behavior in a rectangular ribbed duct two different wire rib roughness. The effect of Reynolds number and relative roughness pitch on the heat transfer coefficient and friction factor have been studied. In order to validate the present numerical model, results have been compared with available experimental results under similar flow conditions. CFD Investigation has been carried out in medium Reynolds number flow. The following conclusions are drawn from present analysis:

1. There is a definite increase in heat transfer in ribbed duct with increase in friction to the flow when its surface is roughened. However the different investigators find different values of increment in heat transfer and friction factor for each type of rib geometry used.
2. The roughened duct having circular rib with highest relative roughness height provides the highest Nusselt number at a higher value of Reynolds number. The roughened duct having square rib with highest relative roughness height provides the highest Nusselt number at a higher value of Reynolds number.
3. Square sectioned rib provides higher value of enhancement in average Nusselt number as compared to circular rib at a higher value of Reynolds number.This fragment should obviously state the foremost conclusions of the exploration and give a coherent explanation of their significance and consequence.

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