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Heat Transfer Analysis of Advanced Solar Collector

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Abstract*: *A 2-dimensional CFD analysis has been carried out to study heat transfer and fluid flow behavior in a rectangular duct of a solar air heater with one roughened wall having circular and square 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 (Re = 3800–18,000). It is found that the thermal enhancement factor values vary between 1.4 and 1.7 for circular rib and between 1.5 and 1.7 for square rib.

Keywords*: *Ansys, CFD, Fluent, Heat Transfer, Rib

I. INTRODUCTION

Due to a growing world population and increasing modernization, global energy demand is projected to more than double during the first half of the twenty-first century and to more than triple by the end of the century. Presently, the world's population is nearly 7 billion, and projections are for a global population approaching 10 billion by midcentury. Future energy demands can only be met by introducing an increasing percentage of alternative fuels. Incremental improvements in existing energy networks will be inadequate to meet this growing energy demand. Due to dwindling reserves and ever-growing concerns over the impact of burning carbon fuels on global climate change, fossil fuel sources cannot be exploited as in the past [1-10]. A solar collector is a special kind of heat exchanger, which collects solar radiant energy, and transfers it to a fluid- usually water or air. It converts solar radiation to thermal energy of fluid and delivers the heated fluid for use. A conventional solar air heater generally consists of an absorber plate with a parallel plate below forming a passage of high aspect ratio through which the air to be heated flows. However, the value of the heat transfer coefficient between the absorber plate and air is low and this result in lower efficiency. For this reason, the surfaces are sometimes roughened or longitudinal fins are provided in the airflow passage. A roughness element has been used to improve the heat transfer coefficient by creating turbulence in the flow. However, it would also result in increase in friction losses and hence greater power requirements for pumping air through the duct. In order to keep the friction losses at a low level, the turbulence must be created only in the region very close to the duct surface, i.e. in laminar sub layer. A further disadvantage associated with the use of solar air heater is that large volume of fluid has to be handled. As a result, the pressure becomes an important parameter and has to be kept in prescribed limits. Air density is 0.001th of water, and thus for the same energy input, air can be heated covering much greater volumetric flow rate [11-35]. Solar air heaters, because of their inherent simplicity, are cheap and most widely used as collection device. The thermal efficiency of solar air heaters has been found to be generally poor because of their inherently low heat transfer capability between the absorber plate and air flowing in the duct. In order to make the solar air heaters economically viable, their thermal efficiency needs to be improved by enhancing the heat transfer coefficient. This is accomplished by breaking up the laminar sub-layer that forms in the vicinity of the absorber plate, and by introducing artificial roughness to the heat-transferring surface, which causes the flow at the heat-transferring surface to become turbulent. Many different types of roughness geometries and their arrangements have been investigated by a variety of researchers [36-45].The heat transfer between the absorber surface (heat transfer surface) of solar air heater and flowing air can be improved by either increasing the heat transfer surface area using extended and corrugated surfaces without enhancing heat transfer coefficient or by increasing heat transfer coefficient using the turbulence promoters in the form of artificial roughness on absorber surface. The artificial roughness on absorber surface may be created, either by roughening the surface randomly with a sand grain/sand blasting or by use of regular geometric roughness. It is well known that in a turbulent flow a laminar/viscous sub-layer exists in addition to the turbulent core. The artificial roughness on heat transfer surface breaks up the laminar boundary layer of turbulent flow and makes the flow turbulent adjacent to the wall. In order to achieve high heat transfer rates while minimising friction losses, the flow duct and absorber surface of solar air heaters should be designed with the goals of high heat transfer rates while minimising friction losses in mind; as a result, the design of the flow duct and absorber surface of solar air heaters should be executed with the objectives of high heat transfer rates while minimising friction losses in mind [46-76].This work basically describes the characteristics of the heat transfer and friction in a square duct where circular-shaped ribs are placed transversely to the main stream direction on one wall. The objectives of this paper are to fulfill two aspects; i.e., to provide detailed information of average heat transfer and flow friction characteristics in ribbed passages, and to compare the thermal performance of different configurations of ribbed duct.

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It is the specific objectives of this paper to develop a computational model and solve the governing equations on a computational domain, and then to compare the thermal performance of various configurations of ribbed ducts.

II. CFD ANALYSIS

The 2-dimensional solution domain used for CFD analysis has been generated in ANSYS version 19 (workbench mode) as shown in Fig. 1. 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.

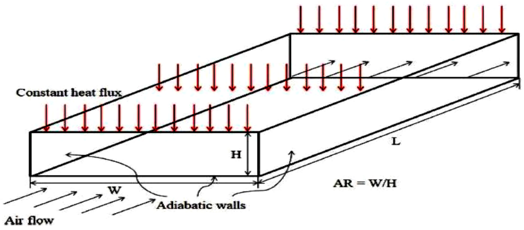

Fig. 1 Solution domain

Complete duct geometry is divided into three sections, namely, entrance section, test section and exit section. A short entrance length is chosen because for a roughened duct, the thermally fully developed flow is established in a short length 2–3 times of hydraulic diameter. The exit section is used after the test section in order to reduce the end effect in the test section. The top wall consists of a 0.5 mm thick absorber plate made up of aluminum. Artificial roughness in the form of small diameter galvanized iron (G.I) wires is considered at the underside of the top of the duct on the absorber plate to have roughened surface, running perpendicular to the flow direction while other sides are considered as smooth surfaces. For the purposes of computational analysis, a uniform heat flux of 1000 w/m^2 is assumed. The domain meshing is completed with the help of the ANSYS ICEM CFD V19 software. (Fig. 2).

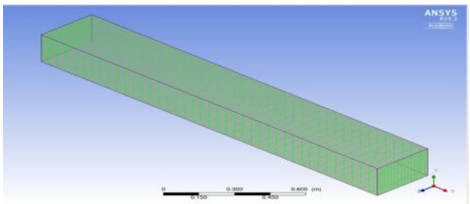

Fig. 2 Meshing

In the current simulation, the finite volume approach is used to solve the governing equations of continuity, momentum, and energy in the steady-state domain of the simulation. The numerical method used in this study is a segregated solution algorithm with a finite volume-based technique. The governing equations are solved using the commercial CFD code, ANSYS Fluent 19. A second-order upwind scheme is chosen for energy and momentum equations. The SIMPLE algorithm (semi-implicit method for pressure linked equations) is chosen as scheme to couple pressure and velocity. The convergence criteria of 10^{-3} for the residuals of the continuity equation, 10^{-6} for the residuals of the velocity components and 10^{-6} for the residuals of the energy are assumed. A uniform air velocity is introduced at the inlet while a pressure outlet condition is applied at the outlet. Adiabatic boundary condition has been implemented over the bottom duct wall while constant heat flux condition is applied to the upper duct wall of test section.

III. RESULT AND DISCUSSION

The effects of relative roughness height and Reynolds number on the heat transfer and friction characteristics for flow of air in a roughened rectangular duct are presented below. The results have been compared with those obtained in case of smooth ducts operating under similar operating conditions to discuss the enhancement in heat transfer and friction factor on account of artificial roughness. Fig. 3 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). When the Reynolds number is increased, it is seen that the average Nusselt number increases. This is due to an increase in turbulence intensity induced by an increase in both the turbulence kinetic energy and the turbulence dissipation rate.

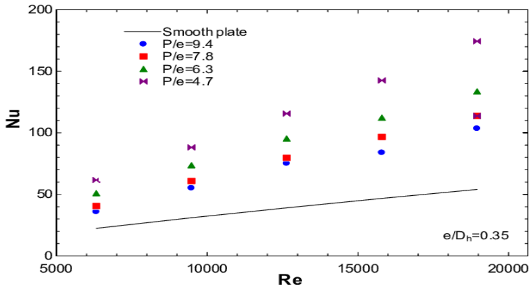

Fig. 3 Effect of Reynolds number

Effect of the relative roughness height (e/d) on heat transfer is also shown typically in Fig. 3. 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 transfer coefficient is low at the leading edge of the 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 heat transfer phenomenon can be observed and described by the contour plot of turbulence intensity. The contour plot of turbulence intensity for circular rib is shown in Fig. 4 (a, b and c). Temperature transfer is greatly enhanced by high levels of turbulence in the flow field along the wall and between two neighbouring ribs close to the main flow, which reduces turbulence intensity.

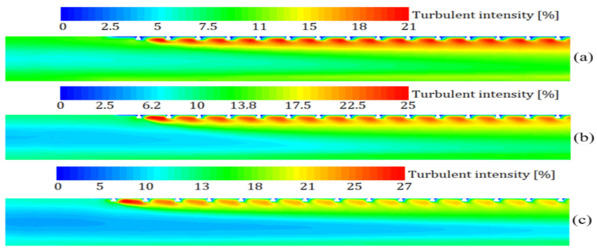

Fig. 4. Contour plot of turbulence intensity

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IV. CONCLUSION

The following conclusions are drawn from the CFD analysis: -

1. The Renormalization-group (RNG) k-ε turbulence model predicted very close results to the experimental results, which yields confidence in the predictions done by CFD analysis in the present study. 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.

2. The roughened duct having circular rib with relative roughness height of 0.06 provides the highest Nusselt number at a Reynolds number of 18000. The roughened duct having square rib with relative roughness height of 0.06 provides the highest Nusselt number at a Reynolds number of 18000.

3. It is found that the thermal enhancement factor values vary between 1.42 and 1.74 for circular rib and between 1.51 and 1.762 for square rib.

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