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CFD Investigation of Heat Transfer and Fluid Flow through a Rectangular Channel Having Turbulators

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Abstract- Several types of turbulators elements were used extensively to improve the heat transfer characteristics. The roughness elements of two dimensions, three dimensions and of irregular shapes were used by various investigators. This paper presents the study of heat transfer in a rectangular channel by using Computational Fluid Dynamics (CFD). The effect of Reynolds number on Nusselt number is investigated. A commercial finite volume package ANSYS FLUENT is used to analyze and visualize the nature of the flow across the duct of a solar air heater. CFD simulation results are found to be in good agreement with experimental results. It has been found that the Nusselt number increases with increase in Reynolds number.

Keywords: Heat transfer, Pressure Drop, Nusselt number, CFD.

I. INTRODUCTION

Several types of turbulators elements were used extensively to improve the heat transfer characteristics. The initial efforts on using turbulators for improving heat transfer characteristics were confided with the areas of nuclear reactors, gas turbines blades, pipes carrying fluids and compact heat exchangers. Several types of turbulators elements were used extensively to improve the heat transfer characteristics in this equipment.

The roughness elements of two dimensions, three dimensions and of irregular shapes were used by various investigators. The concept of artificial roughness was first applied by Joule [1] to enhance heat transfer coefficients for in-tube condensation of steam and since then many experimental investigations were carried out on the application of artificial roughness in the areas of cooling of gas turbine, electronic equipment, nuclear reactors, and compact heat exchangers etc.

Nunner [2] was the first who developed a flow model and likened this model to the temperature profile in smooth tube flow at increased Prandtl number. A friction correlation for flow over sand-grain roughness was developed by Nikuradse [3]. Based on law of the wall similarity, Nikuradse presented the pressure drop results in terms of roughness function R and roughness Reynolds number e+. Dipprey and Sabersky [4] developed a heat-momentum transfer analogy relation for flow in a sand-grain roughened tube and achieved excellent correlation of their data.

The concept proposed by Dipprey and Sabersky was so common and it can be applied to any roughness for which law of the wall similarity holds. Prasad and Mullick [5] were the first who introduced the application of artificial roughness in the form of small diameter wire attached on the underside of absorber plate to improve the thermal performance of solar air heater for drying purposes.

After Prasad and Mullick's [5] work a number of experimental investigations of solar air heater 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 [6-9].

Effect of various parameters on the thermo-hydraulic performance of artificially roughened solar air heater through CFD approach can be obtained in Ref. [10-19]. Ahn [20] investigated on five different types of roughness element in rectangular duct with e/DH

=0.0476, P/e=8, and W/H=2.33, to understand the comparative thermo-hydraulic performance due to these elements. They concluded that the triangular rib has the highest heat transfer capacity and Nusselt number is higher in the case of square and triangular ribs when compared to semicircular ribs. The square ribs have the highest friction factor.

Chandra et al. [21] investigated the effect with varying number of with transverse ribbed walls with the parameters Re = 10,000 to 80,000; P/e = 8; e/DH = 0.0625; L/Dh = 20 for fully turbulent flow in square channel. They concluded that one ribbed wall has the heat transfer increase of 2.43–1.78 (40% improvement) for Re = 12,000 to 75000, with two opposite ribbed walls the increment was 2.64 to1.92 (6% improvement), three ribbed walls have the increment of 2.81 to 2.01 (5% improvement) and with four ribbed walls, an increment of 2.99 to 2.12 (7% improvement). The maximum increase in the friction factor was found to be 9.50 with four sided ribbed walls and minimum with one ribbed wall of 3.14.

They also compared the performance factor {(Str/Stss)/(fr/fss)} of four cases and concluded that, it is highest at 1.78–1.17 for one wall ribbed surface. Tanda [22] investigated for heat transfer coefficient distribution in rectangular channel with transverse continuous, transverse broken and V-shaped broken ribs with the parameter's W/H = 5; α = 45 or 60.

Liquid crystal thermography was applied to the study of heat transfer from the ribbed surface. He found the maximum performance of continuous transverse ribs, 45 V-shaped ribs and 60 V-shaped ribs at the optimum value of P/e = 13.3, transverse broken ribs with P/e = 4 and 8 give the higher heat transfer augmentation. Transverse broken ribs with P/e = 4 and 13.3 gives best thermal performance and transverse continuous ribs again with P/e = 4 and 8 gives lesser heat transfer increment.

Andallib et al. [23] investigated the heat transfer and flow characteristics in the entrance section of a rectangular channel with one and two solid ribs at the bottom surface. They used hot wire anemometry (HWA) and resistance thermometry (RTD) for measuring the velocity and temperature and Liquid crystal thermography (LCT) to trace temperature profiles, heat transfer coefficient evaluation and Nusselt number calculation. The various parameters used are Re = 2.09 x 104; P/e = 10.

They compared the results of experimentation and theoretical energy balance and found similar performance under the given range of data selected.

Won and Ligrani [24] compared the thermo-physical characteristics in channels with parallel and cross rib turbulators on two opposite surfaces with the parameters Reynolds number based on channel height = 480 to 18300; W/H = 4; α = 45; e/D = 0.078; P/e = 10. They found that Nusselt number is almost same for crossed and parallel-ribs, local.

Nusselt number for parallel-ribs is significantly higher than crossed-rib and pressure loss is higher in central part of the channel.

Wang and Sunden [25] performed investigation of heat transfer and fluid flow in rectangular channel with broken V-shaped up ribs using crystal thermography (LCT) and particle image Velocimetry (PIV) techniques using the parameters e/Dh of 0.06; P/e was kept to 10; α = 60; W/H = 1/8. They concluded that the performance in heat transfer is higher than the continuous ribs bur with more friction loss.

Liu et al. [26] investigated on heat transfer increment in a solar air heater with the absorber plate roughened by extended surfaces geometry. Several other types of turbulators elements were used extensively to improve the heat transfer characteristics [57-85]. The aim of present study is to analyze CFD investigation of ribbed rectangular channel on the flow and heat transfer."

II. CFD ANALYSIS

Computational Fluid Dynamics (CFD) is the science of determining numerical solution of governing equation for the fluid flow whilst advancing the solution through space or time to obtain a numerical description of the complete flow field of interest.

The equation can represent steady or unsteady, Compressible or Incompressible, and in viscid or viscous flows, including non-ideal and reacting fluid behavior. The particular form chosen depends on intended application. The state of the art is characterized by the complexity of the geometry, the flow physics, and the computing time required obtaining a solution.

The 2-D computational domain used for CFD analysis having the height (H) of 20 mm and width (W) 100 mm and length of 640 mm as shown in Fig. 1. In the present analysis, a 2-dimensional computational domain of artificially roughened solar air heater has been adopted which is similar to computational domain of Yadav and Bhagoria [11].

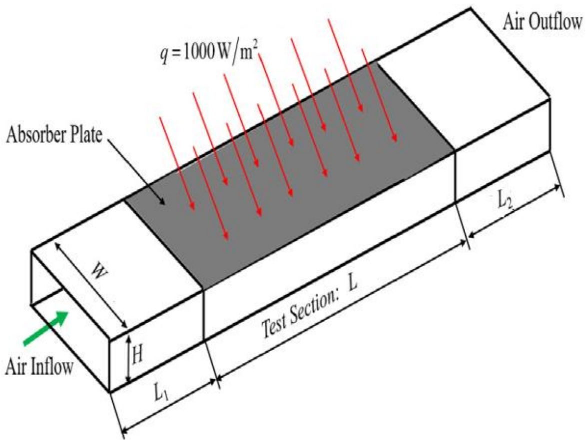

Fig 1. Computational Domain.

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 (Fig. 2).

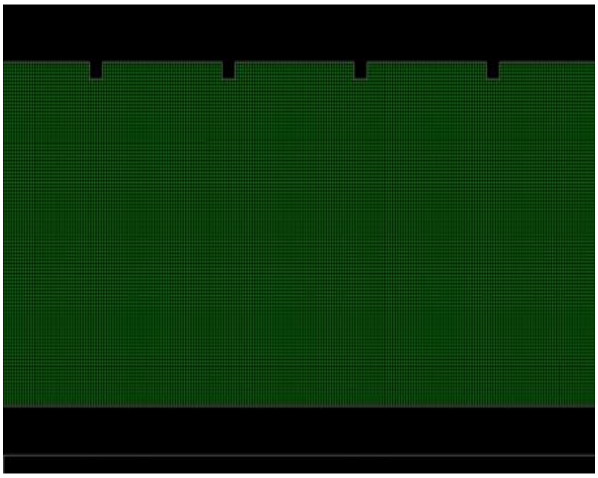

Fig 2. Meshing of computational Domain.

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.

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.

III. RESULTS AND DISCUSSIONS

The effects of relative roughness pitch 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 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 kinetic energy.

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 decreases with the increase in relative roughness pitch (P/e) for fixed value of roughness height (e).

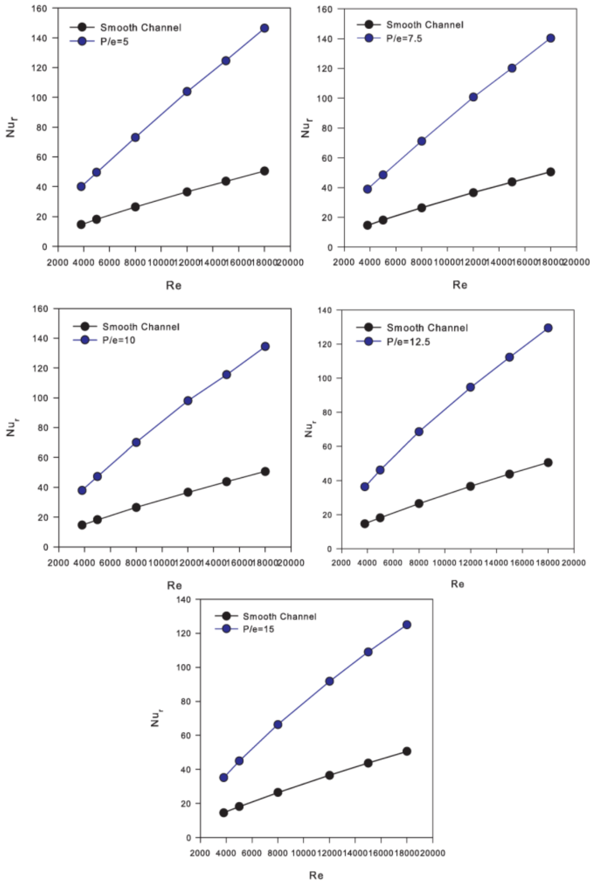

Fig. 3 Nusselt number Vs. Reynolds number.

This is due to the fact that with the increase in relative roughness pitch, number of reattachment points over the absorber plate reduces. The roughened duct with relative roughness pitch of lowest value provides the highest Nusselt number. The roughened duct with highest value of relative roughness pitch provides the lowest Nusselt number.

IV. CONCLUSION

A 2-dimensional CFD analysis has been carried out to study heat transfer and fluid flow behavior in a ribbed rectangular duct with one roughened wall having square transverse 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:

- The use of turbulators on a surface is an effective technique to enhance heat transfer to fluid flowing in the duct. Artificially roughened channels have enhanced rate of heat transfer as compared to the smooth channel.
- 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 decreases with the increase in relative roughness pitch (P/e) for fixed value of roughness height (e).
- The roughened duct with relative roughness pitch of lowest value provides the highest Nusselt number.
- The roughened duct with highest value of relative roughness pitch provides the lowest Nusselt number.

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