A Computational Fluid Dynamics Investigation of Solar Air Heater Duct Provided with Inclined Circular Ribs as Artificial Roughness

Manish Kumar and Varun

Abstract--- This paper presents a Computational Fluid Dynamics (CFD) analysis of solar air heater duct to estimate its thermo-hydraulic performance. On the inner side of absorber plate, inclined circular ribs are provided to create artificial roughness. The roughness parameters were studied in the present work are inclination angle (α) of ribs 45° and 60° and roughness height (e) 1mm and 2mm at a constant roughness pitch (p) of 20mm. Reynolds number (Re) in the range of 6000 to 15000 and constant heat flux (I) having a value of $1000W/m^2$ on absorber plate were used as operating parameter during the analysis. Renormalization group (RNG) $k-\epsilon$ turbulence model is selected for the analysis from the different turbulence model after comparing the results of these models with empirical correlation results for smooth duct, as RNG $k-\epsilon$ model results was found in good agreement. The effect of different roughness parameters has also been compared on the basis of overall enhancement ratio to obtain the optimum roughness parameters.

Keywords--- Artificial Roughness, CFD, Solar Air Heater, Heat Transfer

NOMENCLATURE

H	Height of the solar air heater duct, mm
W	Width of the solar air heater duct, mm
D	Hydraulic diameter of duct, mm
e	Roughness height or rib diameter, mm
e/D	Relative roughness height
α	Inclination angle, $^\circ$
$\alpha/90$	Relative inclination angle
p	Pitch, mm
I	Heat flux, W/m^2
Nu_r	Nusselt number for roughened duct
Nu_s	Nusselt number for smooth duct

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f_r	Friction factor for roughened duct
f_s	Friction factor for smooth duct
Pr	Prandtl number
Re	Reynolds number

I. INTRODUCTION

AS there is a continuous increase in the energy demand, which encouraged us to think new ways to fulfil this demand. Among all source of energy, solar energy is freely available to curb this demand. In order to harness solar energy efficiently, the efficiency of solar collector should be high. As we know that the efficiency of solar air heater is poor, which can be improved by enhancing the heat exchanging process using efficient conversion and utilization technique. So to enhance the heat transfer between absorber plate of solar air heater and air, artificial roughness is provided in the air passage. As we know when the flow takes place there is a formation of laminar sub layer which acts as insulation and prevents heat transfer from the surface. By providing artificial roughness laminar sub layer breaks down, this further causes flow to be turbulent near the roughened surface. Due of this changed flow pattern, colder air gets in contact with absorber plate surface again and again, and heat transfer rate gets increase. This turbulence leads to increase friction in the flow which leads to increase in pumping power.

In early systematic investigation, Nikuradse [1] had experimentally investigated the effect of roughness in a pipe flow and had reported that the increase in friction factor with the increase of roughness Reynolds number and roughness height. Dipprey and Sabersky [2] had developed analogy for the calculation of heat transfer coefficient in flow through tubes having sand grain roughness. Taslim et al. [3] had been carried out an experimental investigation on channels roughened with inclined ribs, V-shaped ribs. the inclination of ribs generate secondary flow vortices as fluid enters at the leading end of the inclined rib and exits at trailing end of the rib. These vortices increase the heat transfer rate at the leading end but relatively low heat transfer at trailing end. V-shaped rib has two leading ends (higher heat transfer rate location) and one trailing end (lower heat transfer rate location), which results in higher overall heat transfer rate in V-shaped ribs. Han and Zhang [4, 5] also reported high heat transfer rate with parallel, inclined, inclined broken, V-shaped and V-shaped broken ribs.

A number of experimental investigations had been carried out to analyse the performance of solar air heater duct having roughened absorber surface. Prasad and Saini [6] had investigated the effect of height and pitch of the roughness elements on the heat transfer rate and friction, and it had been found out that with the increase in relative roughness height Nusselt number and friction factor in the roughened duct increase, and the decrease in Nusselt number and friction factor in the roughened duct with the increase in relative roughness pitch. Gupta and Solanki [7] had been investigated the effect of inclined continuous ribs in solar air heater with parameters, relative roughness height and inclination of rib, and reported maximum heat transfer rate and friction factor for the inclination angle 70° . Aharwal et al. [8] reported that heat transfer enhancement due to the gap in inclined broken rib as the main flow joins the vortices at the location of gap and accelerates it, which leads to higher heat transfer rate. Varun et al. [9] had developed a correlation of Nusselt number and friction factor for the solar air heater duct having roughness element as a combination of inclined and transverse ribs. Yadav et al. [10] had investigated the effect of roughness in solar air heater, provided in the form of protrusions which are arranged in an arc pattern and found out significant increase in the heat transfer through roughened duct. Prasad [11] had investigated thermal performance of solar air heater having artificial roughness and found out that the thermal performance is a strong function of mass flow rate, higher the mass flow rate higher the value of thermal efficiency.

Few numerical studies had been carried out to analyse the heat transfer and flow characteristics of solar air heater provided with artificial roughness on absorber plate. A 3-D CFD based performance analysis of solar air heater duct provided with arc shaped roughness geometry on absorber plate had been done by Kumar and Saini [12]. In this study Renormalization Group (RNG) $k-\epsilon$ turbulence model had been found to have good agreement with Dittus-Boelter empirical relation for smooth duct and used this model for analysis of roughened duct. Chaube et al. [13] did a 2-D computational analysis of solar air heater duct having rib roughness on absorber plate using SST $k-\omega$ turbulence model for nine different types of rib-shapes. It had been found out that the highest heat transfer rate was with chamfered shape ribs and also found the best performance index with rectangular shape rib of size 3×5 mm. Karmare and Tikekar [14] performed a 3-D CFD analysis of fluid flow and heat transfer in a solar air heater duct with metal grit ribs as roughness elements employed on one broad wall of a solar air heater.

Till now very less numerical studies has been done to analyse the effect of artificial roughness on solar air heaters. This motivated the present work to carry out. In the present work, inclined circular ribs have been used to create roughness on absorber plate of solar air heater duct. A 3-D Computational Fluid Dynamics (CFD) analysis has been done to analyse the effect of roughness height and inclination angle on heat transfer rate and friction factor.

II. DETAILS OF SOLUTION DOMAIN AND MESHING

The inclined circular rib shape roughness elements were fixed on the inner side of the absorber plate. Other three sides of test section except absorber plate were considered as smooth surfaces. The solution domain used for CFD analysis is shown in figure 1. The duct used for CFD analysis having the height (H) of 20 mm and width (W) of 200 mm. The aspect ratio of the duct has been kept 10 in this study. The flow domain consists of 100 mm long entry section, 150 mm long test section and 50 mm long exit section. The entry and exit length of the flow have been kept to reduce the end effects.

As the roughness geometry is inclined in transverse direction, secondary flows are bound to happen, thus 3-D flow domain and mesh was selected. In order to examine the flow and heat transfer accurately in the inter-rib regions, finer meshing at these locations has been done. In other regions coarser mesh has been used. For the present work, meshing has been done using component system 'Mesh' of commercially available software ANSYS 13.0. To ensure that all results reported here are grid independent, grid independence test has been performed using the mesh size of 1.5 times and 2 times the base mesh size (521887 nodes). No noticeable differences in the solution were observed. This base mesh size or similar density mesh was used in all simulations.

Figure 1: Solution Domain

III. SIMULATION PARAMETERS

Circular shape ribs of diameter (e) 1 mm and 2 mm were used to make inclined artificial roughness element on the inner-side of the absorber plate. Three values of inclination angle (α) 45° and 60° were used with 2 mm rib diameter. 20 mm pitch (p) value was used between the ribs. Hydraulic diameter (D) of duct was 36.36 mm. Solar air heaters normally operate in the range of Reynolds number (Re) 6000 to 15,000, so this range has been used to analyse the effect on heat transfer and friction factor. A uniform heat flux of 1000 W/m^2 was applied on the absorber plate.

IV. ASSUMPTIONS AND BOUNDARY CONDITIONS

Commercial code ANSYS FLUENT Version 13.0 was used for computational analysis of solar air heater duct in the present study. To do simulation of fluid flow and heat transfer 3-D model has been used instead of 2-D model as the secondary flows occur in the duct. The assumptions made

while doing the simulations are, fluid flow is fully developed, steady, and turbulent; the remaining duct walls except absorber plate are considered adiabatic; and the air (working fluid) is incompressible for the operating range of solar air heaters. These assumptions were made with respect to experimental investigation done on solar air heater by other investigators.

At the inlet of the solution domain velocity boundary condition has been used and pressure outlet boundary condition at the outlet. Reynolds number was used to calculate mean inlet velocity of fluid flow. Turbulence intensity and hydraulic diameter was used to specify the turbulence. Constant heat flux wall boundary condition was applied on absorber plate. Discretization of the governing equations was done using second order upwind numerical scheme and SIMPLE (semi-implicit method for pressure linked equations) algorithm.

V. SELECTION AND VALIDATION OF MODEL

To select the appropriate turbulence model for the computational analysis and to validate the model, the predictions of different turbulence model namely Renormalization group (RNG) $k-\epsilon$ model, Realizable (Rlz) $k-\epsilon$ model, Standard (Std) $k-\epsilon$ model and Shear stress transport (SST) $k-\omega$ model for smooth duct having same cross section were compared with Dittus-Boelter empirical correlation [15] for Nusselt number for smooth duct

Dittus-Boelter correlation for smooth duct –

$$Nu = 0.024 Re^{0.8} Pr^{0.4} \quad (1)$$

Figure 2: Comparison of Nusselt Number Predicted by Different Model with Dittus-Boelter Relation for Smooth Duct

The prediction of RNG $k-\epsilon$ turbulence model was found to have good agreement with the results of Dittus-Boelter empirical correlation and modified Blasius equation. Figure 2 shows the variation of Nusselt number with the Reynolds

number for smooth duct predicted by different turbulence model and compared with the Dittus-Boelter correlation results. Results obtained using SST $k-\omega$ turbulence model have the highest deviation from the empirical correlation results. Rlz $k-\epsilon$ model and Std $k-\epsilon$ model have less deviation compare to SST $k-\omega$ model and gave almost same results. For the low Reynolds number flow RNG $k-\epsilon$ model predicts the almost same values of Nusselt number as given by Dittus-Boelter empirical correlation and for high Reynolds number flow RNG $k-\epsilon$ model results showed very less deviation, which was in an acceptable limit. Therefore after this validation RNG $k-\epsilon$ model was selected for the CFD analysis of solar air heater duct.

VI. RESULT AND DISCUSSION

A. Heat Transfer in Duct Roughened with Inclined Ribs

In the roughened duct flow behavior gets changed compare to smooth duct, viscous film of air adjacent to the wall get disturbed and due to this changed characteristics of flow heat transfer rate from absorber plate to air get increased. Figure 3 shows the variation of Nusselt number in the inter-rib region in the direction of flow.

Figure 3: Variation of Nusselt Number in the Inter-rib Region along the Direction of Flow

As the flow approaches to the vicinity of the rib or the immediate upstream of the rib Nusselt number start decreasing and decrease to its lowest value. This may be happen due to two reasons, one is that, heat transfer from absorber plate takes place due conduction from plate to rib and another reason may be that, in this region air gets trapped and makes a thick film of still air which creates a thermal barrier for the heat flow, hence causes the decrement in the heat transfer rate and Nusselt number. Further downstream past the rib Nusselt number starts increasing. When flow past the rib flow separation occurs but at immediate downstream flow creates vortices as secondary flow, which is dominating flow behavior in this region. So in this region flow separation decrease the

Figure 4: Velocity Vector along the Mid Plane of the flow in Inter Rib Region for the Value of Reynolds Number 9000, Relative Roughness Height 0.055 and Relative Inclination Angle 0.833

Heat transfer but secondary flow in form of vortices force the cooler air to come in contact with the absorber plate and this result in increase in heat transfer and Nusselt number in this region. Further downstream the effect of vortices gets diminishing and due to that heat transfer starts decreasing but at the point of flow reattachment it stops decreasing and after that again starts decreasing to its minimum value near the next rib. As the Reynolds number increase heat transfer rate and Nusselt number also increase in the inter rib region but near the rib in its immediate upstream and downstream location Nusselt number have the same value as it was for low Reynolds number.

Figure 4 shows the velocity vector along the mid plane of the flow in inter rib region for the value of Reynolds number 9000, relative roughness height 0.055 and relative inclination angle 0.833. Figure 4 clearly captures the vortices at immediate downstream of the rib, separation of flow and after that reattachment of flow. Increase in relative inclination angle and Reynolds number increase the density of vortices, thus increase heat transfer rate and Nusselt number.

B. Effect of Relative Inclination Angle on Nusselt Number

Figure 5 shows the variation of Nusselt number for the different values of relative inclination angle and for the same value of relative roughness height 0.055. Nusselt number increases with the increase in relative inclination angle of the rib. This increase in Nusselt number attributes to generation of stronger and high intensity vortices with the increase in relative inclination angle. For the all values of relative inclination angle Nusslet number increases with the increase in Reynolds number. At high Reynolds number flow; there is less effect of inclination angle on Nusslet number as it gives the almost same value of Nusselt number.

Figure 5: Variation of Nusselt Number with Reynolds Number for Different Values of Relative Inclination Angle

C. Effect of relative Inclination Angle on Friction Factor

Changed characteristics of the fluid flow in roughened ducts causes the change in the value of pressure drop along the direction of flow, thus change in the resultant friction factor. Figure 6 shows the variation of friction factor for the different valves of relative inclination angle for a same value of relative roughness height 0.055. There is increase in friction factor with the increase in relative inclination angle and with the increase in Reynolds number, the value of friction factor decreases for all the values of relative inclination angle.

Figure 6: Variation of Friction Factor with Reynolds Number for Different Values of Relative Inclination Angle

D. Effect of relative Roughness height on Nusselt number

Figure 7 shows the variation of Nusselt number for the different values of relative roughness height for a particular value of relative inclination angle 0.666. As the relative roughness height increases Nusselt number also increases but at high Reynolds number flow ($Re=15000$) the value of Nusselt number is almost same in each case of relative roughness height. For all values of relative roughness height Nusselt number increases with the increase in Reynolds number.

Figure 7: Variation of Nusselt Number with Reynolds Number for Different Values of Relative Roughness Height

E. Effect of Relative Roughness Height on Friction Factor

Figure 8 shows the variation of friction factor for the different values of relative roughness height at the same value of relative inclination angle 0.666. Friction factor increases with the increase of relative roughness height and with the increase of Reynolds number friction factor decreases for all the values of relative roughness height.

Figure 8: Variation of Friction Factor with Reynolds Number for Different Values of Relative Roughness Height

F. Overall Performance of Duct with Different Roughness Geometries

As the artificial roughness on absorber plate of solar air heater duct increases the Nusselt number but it also increases the friction factor and pressure drop in the direction of flow. This increased friction in the flow requires more pumping power to pump the flow in the duct. So to compare the overall performance of the duct, an expression is defined overall enhancement ratio which is given below [15].

$$\text{Overall enhancement ratio} = \frac{Nu_r / Nu_s}{(f_r / f_s)^{1/3}} \quad (2)$$

Figure 9 shows the variation of overall enhancement ratio with Reynolds number for the different roughness geometries. High value of this ratio represents the high performance of the solar air heater duct. For the value of Reynolds number 6000 to almost 8000, the value of overall enhancement ratio is greater than 1. For all different type of roughness geometry, the value of overall enhancement ratio is highest at Reynolds number 6000 and after that it decreases sharply up to Reynolds number 9000 and further there is a slight increase after that very less decrement in overall enhancement ratio from Reynolds number 12000 to 15000. Solar air heater gives the best performance with roughness geometry having relative inclination angle 0.666 and relative roughness height 0.0275.

VII. CONCLUSION

A Computational Fluid Dynamics (CFD) analysis of solar air heater duct having inclined roughness rib on absorber plate has been done. The results of Dittus-Boelter empirical correlation was compared to Validate the turbulence model used for CFD analysis and it was found that Renormalization Group (RNG) $k-\epsilon$ turbulence model results show good agreement with the Dittus-Boelter empirical correlation results.

Figure 9: Variation of Overall Enhancement Ratio with Reynolds Number for the Different Roughness Geometries

Use of roughness geometry in solar air heater duct increases the Nusselt number and the friction factor. With the increase in Reynolds number, the Nusselt number increases and the friction factor decreases for all combination of roughness geometry. Heat transfer rate and friction factor increases with increase of both relative inclination angle and relative roughness height.

Roughness geometry having relative inclination angle 0.666 and relative roughness height 0.0275 was found to have best overall enhancement ratio.

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