Nomenclature

H height of the duct, mm
g/W relative gap position
W width of the duct, mm
g/e relative gap width
b width of the rib, mm
e/D_h relative roughness height
e height of the rib, mm
P/e relative pitch,
α relative roughness angle, Degree
Nu Nusselt Number
P Pitch, mm
Re Reynolds number
D_h Hydraulic Diameter, mm
Pr Prandtl Number

STUDY OF HEAT TANSFER ENHANCEMENT IN DESCRETE RIB ARRANGMENT IN A SOLAR AIR HEATER DUCT

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ABSRACT

In the present work numerical simulation has been carried out to investigate the effect of an inclined rib with a gap on the performance of a solar air heater duct. The geometry is numerically modelled and three- dimensional Navier–Stokes equation has been solved using a commercial code Ansys Fluent 14.0 for the Reynolds number ranges of 5000 to 17,000.The flow geometry of the rectangular duct has inner cross-section 181 mm in width and 31 mm in height. The artificial roughness was generated by a square rib of 2 mm size having a gap with fix the roughness parameters, namely relative roughness height (e/D_h) of 0.037, relative pitch (P/e) of 10, relative gap position (g/W) of 0.25, relative gap width (g/e) of 1.0 and relative roughness angle α 60°. The absorber plate is heated with a constant heat flux of 1000 W/m^2equivalent to incidence solar radiation. The boundary layers were attached near the heating wall and total hexahedral elements of around 2.6 million are found optimum based on grid independency analysis. The effect of the roughness geometry on heat transfer and flow field characteristics of the duct has been investigated. Different turbulent models are used and their results are compared. Realizable k- ε model with standard wall treatment showed good agreement with available experimental results. The comparison of numerical results with the experimental results shows the deviation in the range of 2-19% at different Reynolds numbers.

Keywords: Solar air heater, Heat Transfer, Artificial roughness, CFD, Turbulence

Introduction

The thermal efficiency of solar air heater is low due to the formation of a very thin viscous sub-layer at the absorber plate surface which results in low heat transfer coefficient. Artificial roughness has generally been employed as a passive technique for enhancing the heat transfer from a heated surface. Artificial roughness can break the viscous sub-layer and creating the turbulence flow which can not affect the core flow results increment in the heat transfer coefficient between absorber plate and air.
Various investigators have studied different types of roughness geometries and their arrangements. Gupta al. [1] developed mathematical relations for optimising the thermo-hydraulic performance of solar air heater with roughened absorber plates. Artificial roughness can increase the heat transfer coefficient but the pumping power was also increased due to increase of friction power. Agarwal et al. [2] conducted experimental investigation on heat transfer enhancement due to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater and found that thermo-hydraulic performance parameter and maximum enhancement in Nusselt number and friction factor was observed to be 1.48-2.59 and 2.26- 2.87 times of that of the smooth duct , respectively for the relative gap width of 1.0, the relative gap position of 0.25 and Reynolds number ranging from 3000 to 18,000 having rib height and width 2 mm. Chaube et al. [3] have computationally analysed heat transfer augmentation and flow characteristics due to rib roughness over absorber plate of a solar air heater using shear stress transport κ-ω turbulence model using 2 dimensional numerical analysis. Kumar and Saini [4] done the computational numerical analysis on a solar air heater duct provided with artificial roughness as thin circular wire in arc shaped geometry. Renormalization-group (RNG) k-ε model

were been found a good agreement and accordingly this model is used to predict heat transfer and friction factor in the duct. The heat transfer and flow analysis of the chosen roughness element has been carried out using 3-D models and constructing the mathematical model and solution domain the result was obtained, analysed and data was selected. Agarwal et al.[5] conducted experimental investigation on heat transfer and friction characteristics of solar air heater ducts having integral inclined discrete ribs on absorber plate. The roughened duct has a width to height ratio (W/H) of 5.83 Karmare and Tikekar et al.[6] carried CFD analysis on solar air heater taking metal ribs of circular, square and triangular in shape as artificial roughness and optimise it using Ansys Fluent.

In this paper, inclined continuous rib with a gap at an angle of 60° has been taken as roughness element. The heat transfer and flow analysis of the chosen roughness element have been carried out using 3-D models. The ribs are mounted on the absorber plate whereas other sides of the duct are kept smooth.

Duct Detail

The rectangular duct considered inner cross- section dimension of 181mm ×31 mm. The aspect ratio has been kept 5.833 while taking length of test Section, entry Section and exit Section as 1200 mm, 800 mm and 600 mm respectively as per ASHARE Standard. The long entry and exit sections have been kept to reduce the end effect of test sections and creating turbulence near the absorber plate.

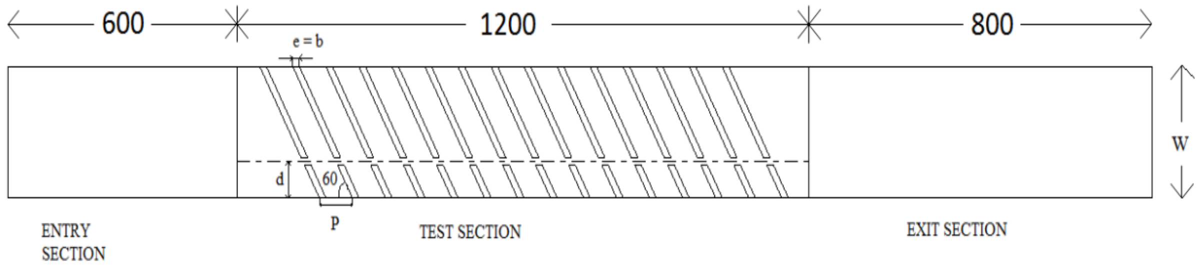

Fig.1. Artificial Roughness arrangement in absorber plate

A constant Heat flux of 1100 W/m^2 was supplied from the electrical heater placed above the absorber plate as shown in Fig.1.

CFD Analysis

Solution Domain

The arrangement of roughness elements in the form of integral discrete ribs having a gap fixed on the inner side of the absorber plate has been considered. The solution domain used for CFD analysis has been generated as shown in Fig.2. The duct used for CFD analysis having the height (H) of 31 mm and width (W) of 182 mm. Thickness of the absorber plate has been considered as 0.5 mm. A uniform heat flux of 1000 W/m^2 was considered for analysis. Roughness was considered at the underside of the top of the duct to have roughened surface while other three sides were considered as smooth surfaces.

Grid generation

Thus 3-D solution domain and grid were selected. In order to examine the flow and heat transfer critically in the inter rib regions, finer meshing at roughened rib has been done. In other regions coarser mesh has been used as shown in Fig. 3. For the present work, meshing has been done using commercially available software ANSYS FLUENT 14.0. The boundary layers were attached near the heating wall .Number of non-uniform hexahedral cells in each set of geometries varies from 2.6 to 1.6 million. The results are grid independence and well resolved. The geometry is meshed with different grid points and very less difference in the solutions noticeable. A maximal convergence criterion of 1x10^{-6} was applied.

CFD Analysis

The assumptions were made in the mathematical model:

i. The flow is study, fully developed, turbulent and three dimensional.

ii. The thermal conductivity of the duct wall and roughness material does not change with temperature.

iii. The duct wall and roughness material is homogeneous and isotropic. The working fluid, air is assumed to be incompressible for the operating range of solar air heaters since variation in density is very less.

The inlet velocity of flow is calculated using Reynolds number. The boundary conditions were taken as velocity inlet at inlet and outflow at outlet with constant heat flux through the top wall. The second order schemes and SIMPLE algorithm are used for discretising of governing equation.

Results and Discussion

Selection and validation of model

Different models namely Standard k- ε model, Renormalization group (RNG) k-ε model, Realizable k- ε model and Shear Stress Transport (SST) k-ω have been tested for smooth duct to find out the validity of the models. The results obtained by different models have been compared with Dittus–Boelter empirical correlation for Nusselt number given below for smooth duct

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

Fig.4 shows the comparison of results obtained by different model to standard equations and Realizable k-ε model are in good agreement with standard results.

Effect of Heat transfer and friction factor

Fig.5 shows variation of Nusselt number for different value of Reynolds number over smooth plate. The Nusselt number seems to increase with increase in Reynolds number due to increase in turbulence intensity caused by increase in turbulence kinetic energy. The another reason is secondary flows which can stick with the leading edge of the rib while flowing along it and when mix with the primary flows create turbulence near the rib which leads to increase in heat transfer coefficient resulting increment in Nusselt number. As the velocity increases the turbulence increases which tend to breaking of viscous sub-layer and the heat transfer increases with some contribution of vortices generated near the rib.

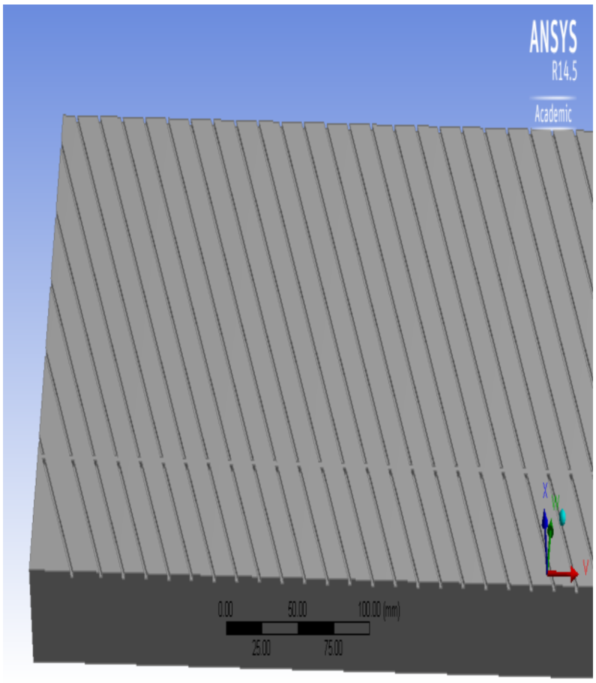

Fig.2 Domain for CFD analysis

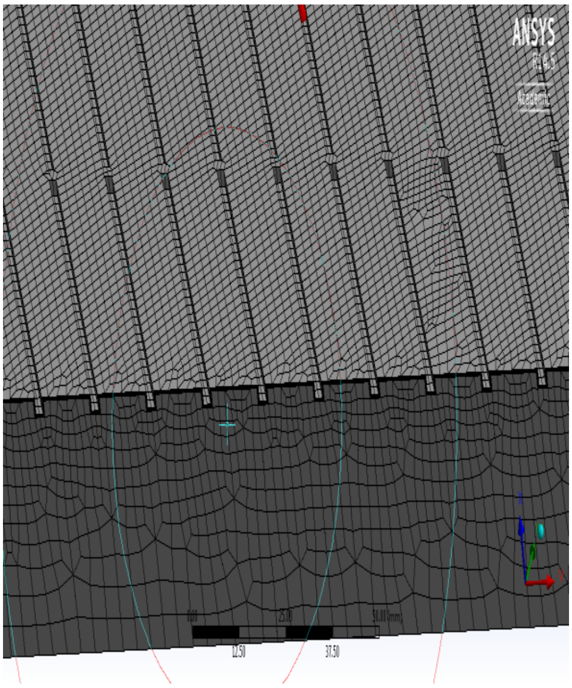

Fig3 Meshing domain of CFD analysis

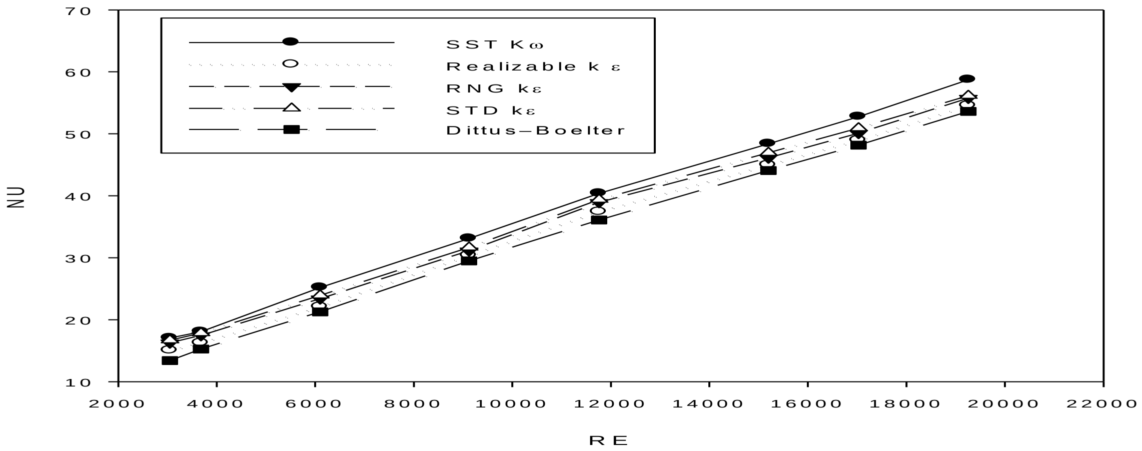

Fig.4 Comparison between Nusselt number predictions of different CFD models

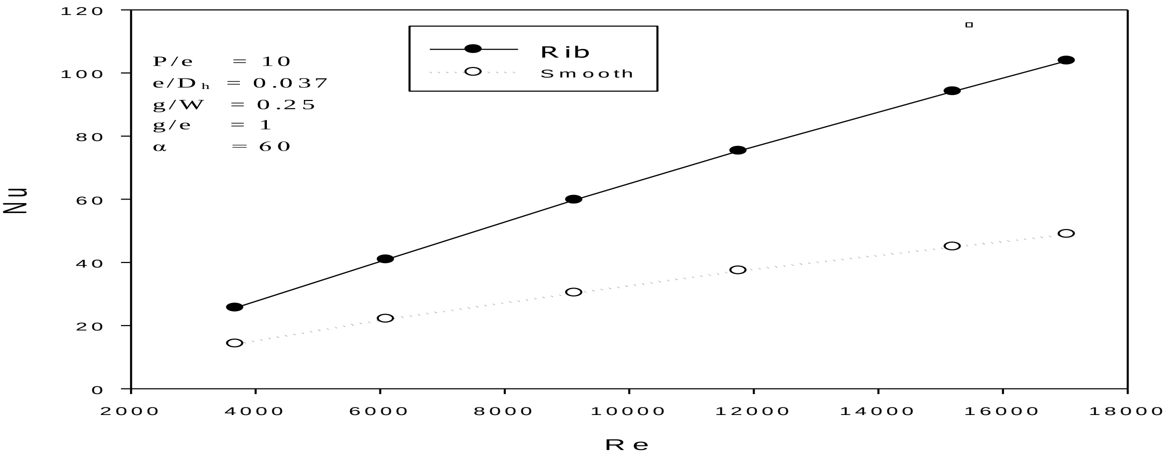

Fig. 5 Comparison of Nusselt number of Rib roughened duct over smooth duct

Conclusion

The average enhancement in Nusselt number values over smooth duct are found 2.05 times.

The comparison of numerical results with the experimental results shows the deviation in the range of 2-19% at different Reynolds numbers

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