

Numerical Simulation of Heat Transfer Enhancement due to a Gap in an Inclined Continuous Rib Arrangement in a Solar Air Heater Duct

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ABSTRACT

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 modeled and three-dimensional Navier-Stokes equation has been solved using a commercial code Ansys Fluent 14. 5 for the Reynolds number range of 3500 to 19, 000. The flow geometry of the rectangular duct has rectangular cross-section of 181 mm in width and 31 mm in height. The artificial roughness was generated using square ribs of 2 mm size having a gap with fix roughness parameters, namely relative roughness height (e/D_h) of 0. 037, relative pitch (P/e) of 8, relative gap position (g/W) of 0. 25, relative gap width (g/e) of 1. 0 and relative roughness angle (α) of 60°. The absorber plate is heated with a constant heat flux of 1000 W/m² keeping in view of the heat generated by incidence solar radiation. The effect of the roughness geometry on heat transfer and flow field characteristics of the duct has been investigated numerically. The boundary layer elements were attached near the heating wall and total hexahedral elements of around 2. 1 million are used based on grid independency analysis. 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 3-20% for Nusselt number for the range of investigation.

Keywords: Solar air heater duct, heat transfer, artificial roughness, computational fluid dynamics, 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 breaks the viscous sub-layer and detaches the flow from the wall which reattach with the wall after some distance. This results in increase in the heat transfer coefficient between absorber plate and air.

Many investigators [1-6] have studied the effect of different types of roughness geometries and their arrangements on heat transfer enhancement from the absorber plate. Gupta al. [1] developed mathematical relations for optimizing the thermo-hydraulic performance of solar air heater with roughened absorber plates. Artificial roughness increases the heat transfer coefficient but the pumping power also gets increased due to increase of friction losses. Aharwal 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 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 as 2 mm. They reported that the maximum enhancement in Nusselt number and friction factor was observed as 1. 48-2. 59 and 2. 26-2. 87 times of that of the smooth duct, respectively. Aharwal et al. [3] proposed an empirical correlation based on their experimental data. Chaube et al. [4] applied 2-dimensional computational fluid dynamics (CFD) to estimate the heat transfer augmentation and flow characteristics due to rib roughed absorber plate of a solar air heater using shear stress transport $\kappa\text{-}\omega$ turbulence model. Kumar and Saini [5] used renormalization-group (RNG) $k\text{-}\epsilon$ model for 3-dimensional simulation of flow through a solar air heater duct roughened with thin circular wire of arc shaped geometry and reported good agreement with the experimental results. Using Ansys Fluent, Karmare and Tikekar [6] have numerically optimized the geometric configuration of different shaped metal ribs for heat transfer of absorber plate of solar air heater.

In this paper, 3-dimensional numerical simulation has been carried out to study the heat transfer and friction factor for a gap in square ribs on the absorber plate of a solar air heater. The experimental data of Aharwal et al. [2, 3] have been used to validate the model. Commercial CFD code Ansys Fluent has been used for numerical analysis. Numerical results obtained with different turbulence models have been compared with the experimental results to find the best suitable model. The flow and heat transfer behavior inside the duct has been reported.

Numerical model

A numerical model of the rectangular duct used by Aharwal et al. [2, 3] has been developed in Ansys work bench as shown in Fig 1. The duct has three sections namely, entry, test and exit of lengths 800, 1200 and 600 mm respectively. The flow section has internal dimensions as 181 x 31 mm with the roughness at upper part (see Fig. 1). Square ribs of 2 mm size as roughness elements have been integrated at the

inner side of top surface of the duct. A gap of 2.0 mm at relative gap width (d/W) of 0.25 has been developed in the rib from the trailing edge. Each rib is inclined 60 degree with respect to flow direction. The relative roughness pitch is kept as 8.

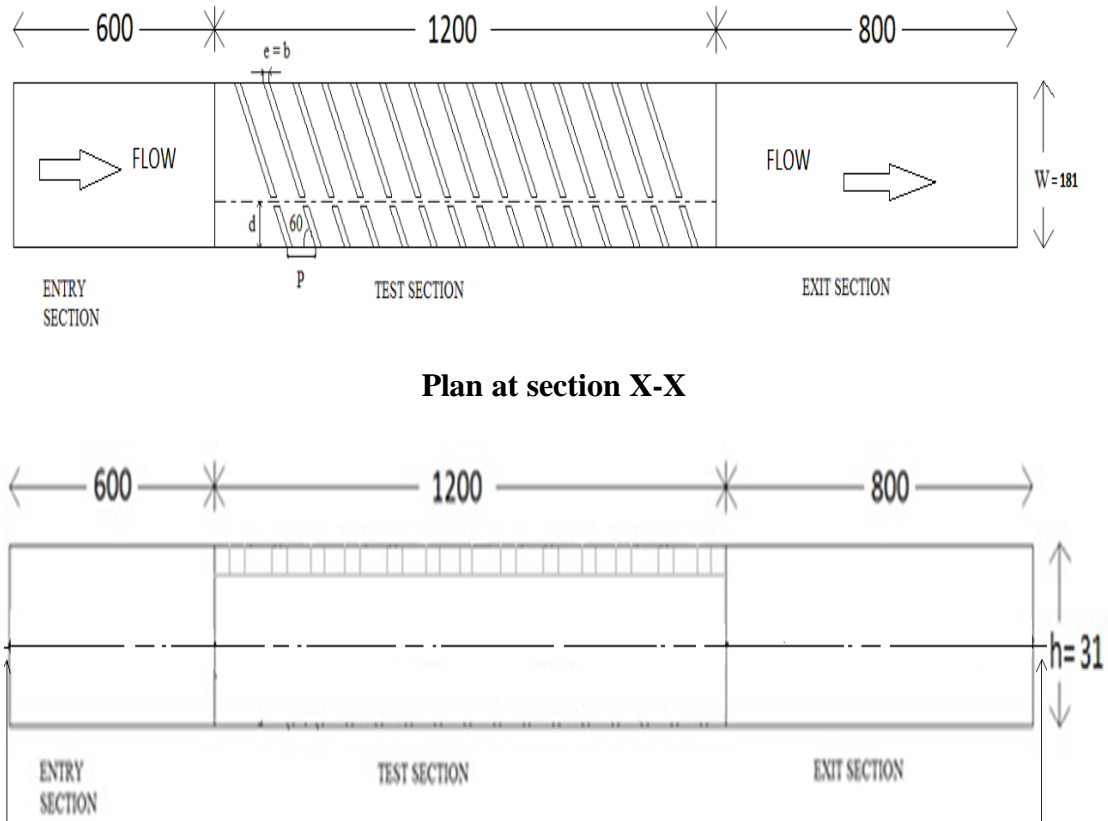


Fig. 1: Artificial Roughness arrangement in absorber plate

3-dimensional elements have been used to discretize the numerical domain. 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. 2. For the present work, meshing has been done using commercially available software Ansys Fluent 14.5. The boundary layers were attached near the heating wall.

Boundary layer elements of five rows have been attached at the roughened wall. Grid independency test has been carried out and the total number of non-uniform hexahedral cells for the optimized mesh is 2.1 million. Thus the results are grid independence and well resolved. The minimum orthogonal quality of mesh is 0.263. The convergence criterion of 1×10^{-5} was applied for mass, momentum and energy

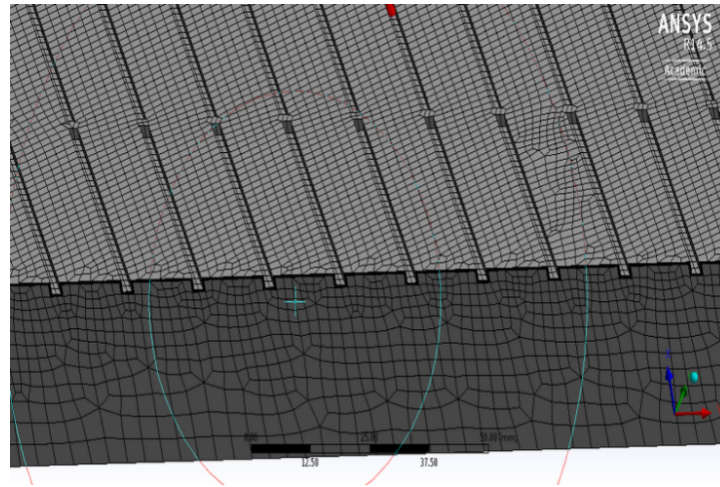


Fig. 2: Meshed elements in the solution domain and conservation.

The boundary conditions were taken as velocity inlet at the duct inlet and outflow at the duct outlet with constant heat flux through the top wall. A constant heat flux of 1000 W/m^2 was supplied through an electrical heater placed above the absorber plate in the test section.. The second order schemes and SIMPLE algorithm are used for solution of governing equations.

Following assumptions were made:

- 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.

Results and Discussion

The variation of Nusselt number at different Reynolds number has been determined numerically for smooth duct using different turbulence models and compared with Dittus-Boelter empirical correlation as below.

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

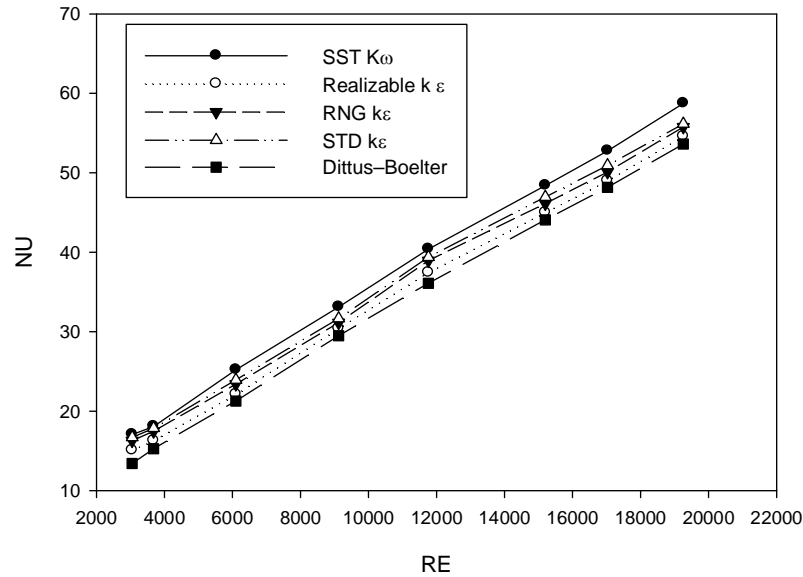


Fig. 3: Comparison between Nusselt number predictions of different CFD models

It is observed that the numerical results obtained with Realizable $k\text{-}\epsilon$ model are more close to the other turbulence models namely, standard $k\text{-}\epsilon$ model, renormalization group (RNG) $k\text{-}\epsilon$ model and shear stress transport (SST) $k\text{-}\omega$ model. The maximum deviation of the numerical values of Nusselt number is within 2% of the values from eq. (1) for Realizable $k\text{-}\epsilon$ model and the latter is, therefore, used in the further analysis.

The numerical values of Nusselt number has been calculated from the CFD analysis and compared with the experimental values of Aharwal et al. [2] at different Reynolds numbers in Fig. 4 along with that of the smooth duct.

It is seen that the value of Nusselt number increases with increase in the Reynolds number and is higher for roughened plates as compared to the smooth plate at all Reynolds numbers. The comparison of experimental and numerical values of roughened plate shows maximum deviation of 3-20 %. Further the trend of both the results is similar. During experiments, the walls are not perfectly insulated and there is a possibility of some heat loss though these walls. This heat loss increases with increase in Reynolds number and therefore the deviation in the numerical and experimental values also increases with increase in Reynolds number.

Fig. 5 shows the comparison of friction factor obtained numerically and experimentally for roughened plate along with that of the smooth plate. It is seen that the friction factor values of roughened plate is higher than the smooth wall in both the cases. However the deviation between the experimental and numerical values of friction factor is significantly high. It seems that the turbulence model selected is not suitable to predict the pressure loss. Also the entrance length is small which may have not resulted in fully developed flow before it enters to the test section.

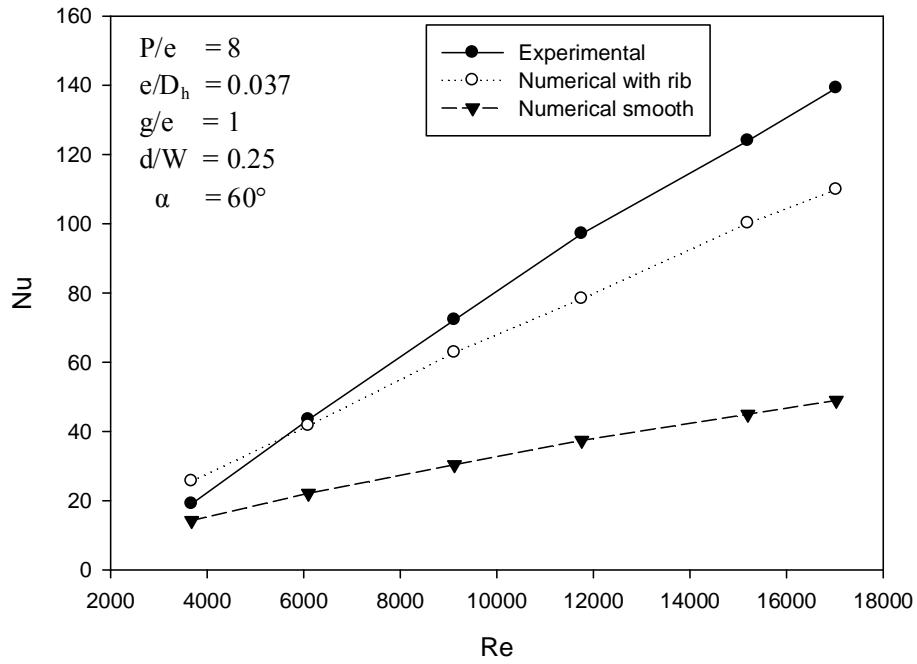


Fig. 4 Comparison of Nusselt number of Rib roughened duct and experimental results

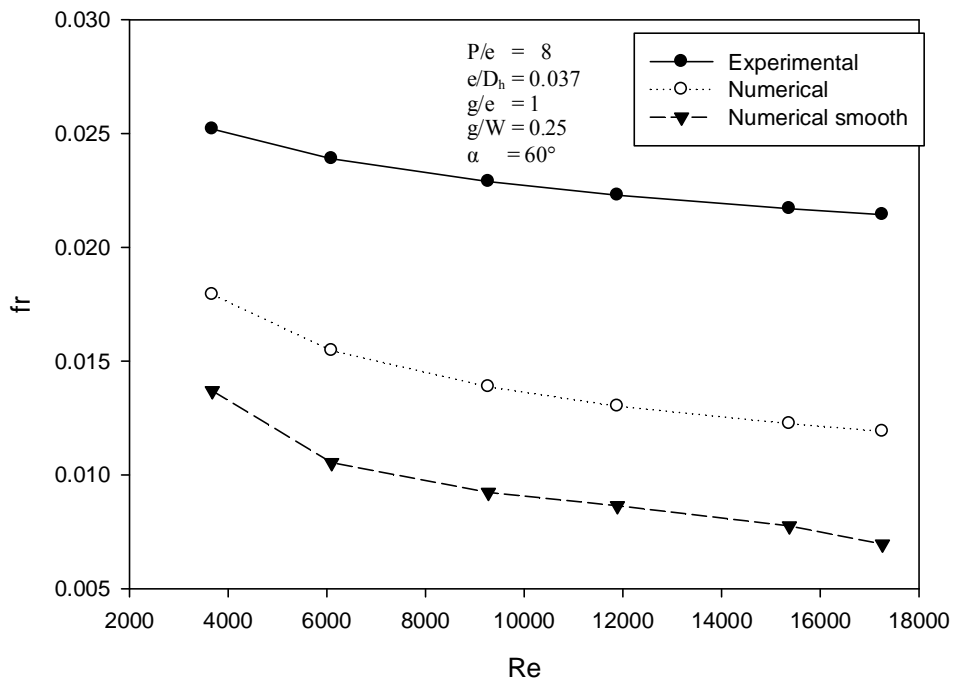


Fig. 5: Comparison of friction factor of Rib roughened duct and experimental results

Concluding Remarks:

Numerical simulation of three dimensional flow through a rib roughened duct had been carried out. It is observed that the numerical results with Realizable k- ϵ model compares well with the values obtained through Dittus-Boelter equation for the smooth duct. The same model predicts the Nusselt number of the roughened plate in close agreement with the experimental results. However the model fails to predict correctly the friction factor of the roughened plate.

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