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Study of Dissimilar Surface Material Patterns on Thermal Performance of Solar Air Heater

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Abstract: *This work is concerned with a two-dimensional numerical study done to predict the influence of transverse rectangular cross-sectioned ribs on a solar air heater's convective heat transfer properties. Solar air heater is a useful device that can be utilized to augment the temperature of air by extracting heat from solar energy. It is a rectangular duct consisting of an absorber plate on its top and heat falls only on the top of absorber plate. When ribs/baffles are introduced just beneath the absorber plate, there is a considerable alteration in the thermal performance of air flowing through the rectangular duct. A comparison was made between the results of thin (high aspect ratio) and square ribs arranged in three patterns, namely, single wall arrangement, staggered arrangement and in-line arrangement on two opposite walls. The Nusselt number variation with Reynolds number range 5000-24000 was checked at a fixed rib pitch (p) and height (e) values. Computational fluid dynamics (CFD) simulations were performed using commercially available software ANSYS FLUENT v15.0. The results were compared with the existing experimental ones while performing simulations under similar conditions. Two methods were used to calculate the average Nusselt number in which one method extracted the local Nusselt number at many points and on averaging these, gave the average Nusselt number and the other method resembled the one used in the existing experimental work. The results revealed that, as compared to smooth duct, the introduction of ribs led to a considerable augmentation in heat transfer. Good agreement was found between the existing experimental results and numerical output, when the second method was adopted to calculate the Nusselt number. However, the Nusselt number calculated using method 1 yielded values lower than the existing ones. The results revealed that the thin ribs yielded better performance than the squared ones. Out of the three arrangements, the best thermal performance was given by thin inline ribs whose convective heat transfer coefficient was 1.83 times smooth duct's convective heat transfer coefficient.*

Keywords: *Solar air heater, turbulent flow, Nusselt number, ribs, Reynolds number*

1. Introduction

Augmentation of convective heat transfer of a rectangular duct with the help of baffles/ribs has been a common practice in the past few years. This concept is widely applied in enhancing the thermo-hydrodynamic efficiency of various industrial applications such as thermal power plants, heat exchangers, air conditioning components, refrigerators, chemical processing plants, automobile radiators and solar air heaters. Solar air heater is a device used to augment the temperature of air with the help of heat extracted from solar energy. These are cheap, have simple design, require less maintenance and are eco-friendly. As a

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result, they have major applications in seasoning of timber, drying of agricultural products, space heating, curing of clay/concrete building components and curing of industrial products [1-5].

The shape of a solar air heater of conventional application is that of rectangular duct encapsulating an absorber plate at the top, a rear plate, insulated wall under the rear plate, a glass covers over the sun-radiation exposed surface, and a passage between the bottom plate and absorber for air to flow in. The detailed constructional details of a solar air heater are shown in fig.1.

Solar air heaters have higher thermal efficiency when the Reynolds number of air flow through their passage is 3000-21000. In this range, the duct flow is generally turbulent. Hence, all the research work pertaining to the design of an effective solar air heater involves turbulent flow. Conventional solar air heaters with all the internal walls being smooth usually have low efficiency. The solar air heater's internal surface can be artificially roughened by mounting certain ribs/obstacles of different shapes such as circular wires, thin rectangular bars, etc. periodically on the lower side of collector plate. This results in a considerable augmentation in the heat transfer rate, but at the same time leads to increase in friction factor thereby enhancing the pumping power requirements.

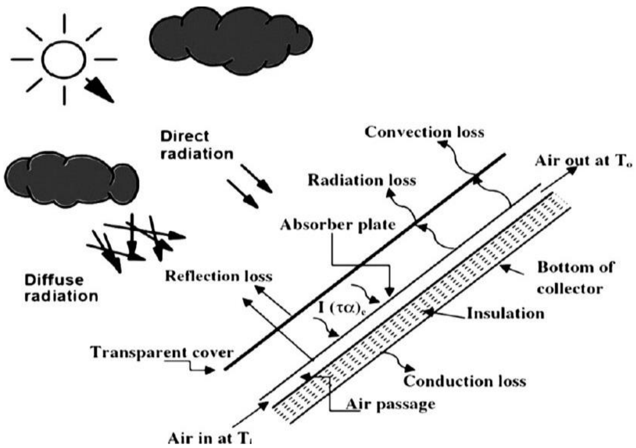

Fig. 1 Solar Air Heater Constructional Details

It is a well-known fact that the friction factor and convective heat transfer coefficient of turbulent flow are highly dependent on the surface roughness of the duct through which they pass [6]. Hence, artificially roughened solar air heaters must be designed in such a manner that their performance yields higher convective heat transfer rates from absorber plate to air low roughness to air flow. Extensive research is being conducted in this field by many authors, whose work generally involves performing experiments or carrying out numerical simulations with different types, sizes and patterns of ribs/ baffles and finding the right parameters at which the heater gives optimal performance (minimum friction loss and maximum heat transfer). Some scientists, after performing research work on solar air heaters, develop a set of correlations for calculating Darcy's friction factor and Nusselt number in terms of operating and roughness parameters.

The mechanism by which heat transfer, between air and roughened absorber plate, increases is breakage of laminar sub-layer. The introduction of ribs leads to local wall turbulence and breakage of laminar sub-layers leading to periodic flow reattachment and separation. Vortices are formed near these baffles, which leads to a significant rise in Nusselt number.

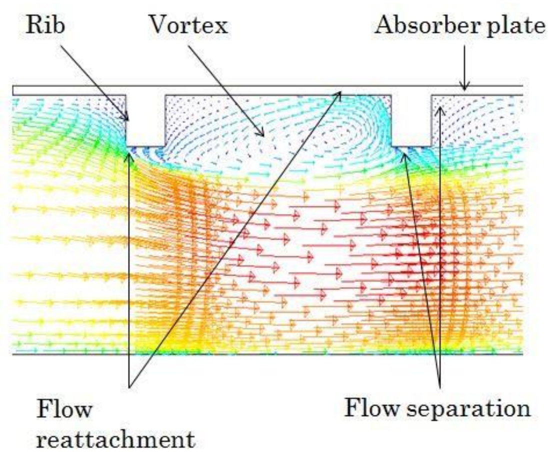

Fig. 2 Mechanism of Augmentation of Convective Heat Transfer By The Introduction of Ribs

As compared to experimental activities being carried on solar air heaters, very less numerical work has been done in this field [7]. Numerical study of solar air heaters using CFD software is an excellent method to understand in detail how flow behaves under the presence of obstacles in solar air heaters. CFD results are more accurate as compared to experimental results. Other benefits of using CFD software's are saving of time and less costs required completing the work. Some commercially available CFD software packages are FLUENT [8], FLOVENT [9], CFX [10], STAR- CD [11] and PHOENICS [12].

1.1 Objectives

The performance of solar air heaters are greatly altered by changing parameters such as flow velocity of air and the duct's internal surface roughness. The average Nusselt number is strongly dependent on these parameters. Hence this concept can be used in a positive way to enhance, between air flowing inside the duct and the absorber plate, convective heat transfer. For this reason, there has been an intense research in this field in the past. However most of these projects have been experimental and very less numerical work has been done. Numerical study of solar air heaters using CFD software is an excellent method to understand in detail how flow behaves under the presence of obstacles in solar air heaters. CFD results are more accurate as compared to experimental results. Other benefits of using CFD software are saving of time and lesser costs are required to complete the work. Hence, the objective of this work is to prove that CFD can be effectively used to design solar air heaters based on their thermal performance. This work deals with numerical study on the effect of transverse rectangular cross-sectioned thin baffles (high aspect ratio ribs). A detailed literature concerning work done on solar air heaters is presented in the next chapter. Moreover, it will be seen in open literature that no such work has yet been conducted. The present work motivation commences from the review so that the void in the literature can be filled. Hence, keeping in mind wide range of applications of solar air heaters and turbulent flow in the field of engineering, a dedicated work is required to understand the thermo-hydraulic behavior of these devices so that their efficiency can be improved such systems can be accurately designed.

2. Review of Literature

Priestet al [2020] It is now easy to improve the tribological performance by surface texturing technique, which includes decrease in friction parameter, increases life, load capacity and lowers the energy consumed by producing the micro dimples on bearing surface. The technology of surface texturing is expected to be a very sufficient in future because it improves tribological properties of component.

Petterson and Jacobson [2019] determine the behavior of wear and friction properties of boundary lubricated textured surfaces. In this they determine how lubricant can be supplied to the interface and how to separate wear particles according to their sizes, shapes and orientation. Series of surface textures of parallel grooves or square depression of various characteristics have been produced by various techniques such as anisotropic etching of silicon wafers and lithography.

Siripuram et al. [2019] there are various types of shapes of microstructures such as spherical, cylindrical, hemi spherical, triangular cross-section, square etc. and according to his experimental results square asperities gives the largest leakage rate and triangular asperities gives the smaller leakage rate.

Kovalchenko et al. [2017] have studied laser texturing expanded the contact parameters in terms of speed and load of hydrodynamic lubrication. Laser surface texturing technique is more efficient at higher loads and speed provided that viscosity of lubricant should be high.

Mehenny et al. [2017] had done a theoretical analysis to determine the influence of circumferential waviness of the journal in automotive engine on the lubrication of bearing. Assumption was made that surfaces of bearing and shafts have to be rigid and lubricant is viscous.

Ronen et al. [2016] provided the way to improve the tribological characteristics of the reciprocating automotive components by studying the micro-surface structure in the form of micro pores. He found that surface texturing on the surface of system can be used effectively to maintain hydrodynamic effects even with nominally parallel surface, and the optimum surface texturing improves the tribological characteristics in reciprocating automotive components.

Brizmeretal.[2015]demonstrated the use of laser surface texturing in parallel thrust bearing. It is found that the characteristics of textures may affect characteristics of bearing. The effects of texturing will be positive and it will improve the performances of journal bearing. Values of friction torque, maximum pressure, minimum film thickness, axial film flow, and rupture film angle for both the surfaces (smooth and textured) are compared for different texture area fraction δ2.

3. Research Methodology

3.1 Problem Formulation

The present work is concerned with carrying out two-dimensional simulations on an artificially roughened solar air heater, through which air of air flows. The air heater internal surface was roughened with the help of transverse-square and thin (high aspect ratio) ribs. The ribs were arranged in different patterns namely one wall only, staggered and in-line on both lower and upper faces.

3.2 Computational Domain

A rectangular section was considered. It consisted of three sections, test section of length L2, entrance section of length L1 and exit length of length L3. The domain on which numerical simulations were performed was two-dimensional. It is because [13] performed numerical simulations on their solar air heater of aspect ratio 7.5. They compared two dimensional results with three dimensional results on the same geometry and did not find any considerable difference between the two. They explained their observation by claiming that for continuous transverse ribs, the secondary flow effect was negligible at higher duct aspect ratios. The geometry taken is similar to that of Skullong et al's [1] rectangular duct. Their rectangular duct was of length 2000 mm, width 300 mm and 30 mm with a test section length of 440 mm.

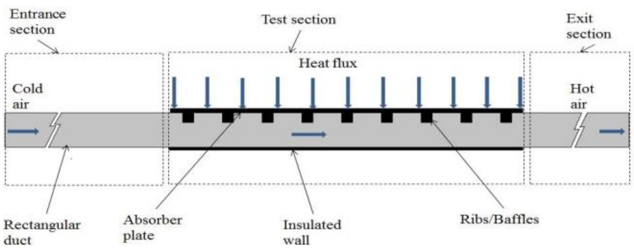

Fig. 3 Sketch of Computational Domain

Hence our domain test section length was 440 mm and its entrance and exit length dimensions were selected on the basis of ASHRAE recommendations, according to which an exit length more than $2.5\sqrt{WH}$ and entrance length more that $5\sqrt{WH}$ were compulsory to establish a fully developed flow in the test domain. The geometry of the computational domain [14]. The different rib arrangements employed for simulation are indicated.

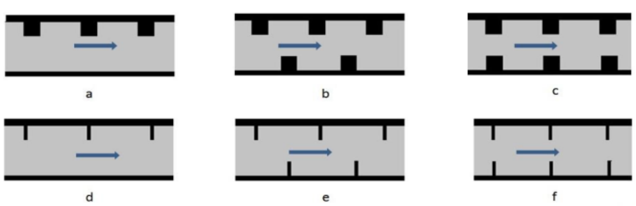

Fig. 4 Different Arrangement Of Ribs Namely (A) Single Square Ribs, (B) Staggered Square Ribs, (C) In-Line Square Ribs, (D) Single Thin Ribs, (E) Staggered Thin Rib And (F) In Line Thin Ribs

Table 1: Operating and Geometrical Parameters Used For CFD Analysis

Operating and Geometric parameters	Value / Range
Test length of duct, L2	440 mm
Entrance length of duct L1	500 mm
Exit length of duct L3	240 mm
Duct height, H	30 mm
Duct width, W	300 mm
Duct hydraulic diameter, D	54.54 mm
Aspect ratio of duct, W/H	10
Constant heat flux, q''	1000 W/m2
Range of Reynolds numbe	5000-23000

Repeated square ribs (tt = 6 mm) and thin ribs (tb = 0.5 mm) with an axial pitch of p = 40 mm characterized the roughness parameters of the test duct. Re was varied from 5000-23000 as this is the range in which solar air heaters particularly have higher efficiencies. Constant heat flux of value approximately 1000 W/m2 was supplied only on the upper wall of the absorber plate. Simulations were performed assuming the flow to be steady. The operating and geometrical parameters used for computational analysis are listed [15-18].

3.3 Governing Differential Equations

Continuity equation

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

Momentum Equation

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right)$$

Energy equation

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_j}\left[(\Gamma + \Gamma_t)\frac{\partial T}{\partial x_j}\right]$$

Where

$$\Gamma = \mu / \Pr \quad \text{and} \quad \Gamma_t = \mu_t / \Pr_t$$

3.4 Boundary Conditions

On all the walls (including the roughened one) of the rectangular duct, no-slip boundary conditions were assigned. Constant heat flux of 1000 W/m^2 was decided to be the boundary condition at the upper wall of the absorber plate. At the inlet, uniform velocity with an inlet temperature of 300 K and at the exit, invariable pressure (atmospheric pressure) boundary conditions were assigned. All the other edges were assigned as walls with insulated boundary conditions [19].

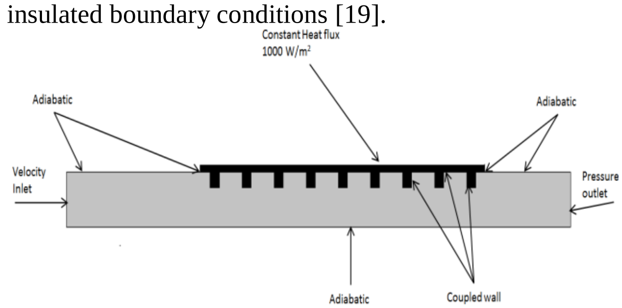

Fig. 5 Different Boundary Conditions Assigned To Edges Of Computational Domain

4. Results

In this project, a computational model was constructed to measure a solar air heater's thermal performance. It consisted of baffles/ribs just below its absorber plate. This section presents detailed results of the average convective heat transfer characteristics.

4.1 Selection of Most Appropriate Turbulent Model

For the smooth duct, the number of mesh cells was varied from 26280 to 186880 at a Reynolds number of 22500. It was observed in simulation results using SST-k-omega and RNG-k-epsilon turbulent model, there was less than 2% alteration in average Nusselt number after 143080 number of mesh cells. When the turbulent model was Realizable-k-epsilon, there was less than 2% alteration in average Nusselt number after 105120 number of mesh cells. Hence further simulations for different Reynolds number were performed using 143080 mesh cells with SST komega and RNG-k-epsilon turbulent models and 105120 with Realizable-k-epsilon turbulence model. The Grid independence test results are represented in Fig. 6

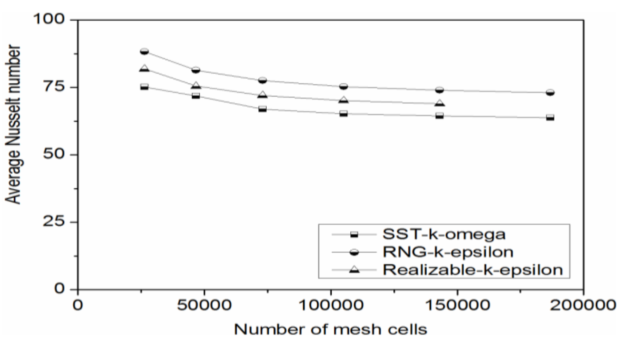

Fig. 6 Grid Independence Test Results For Selection Of Most Appropriate Turbulence Model

Fig. 7 shows that as the Reynolds number incremented, the average Nusselt number increased for all the three turbulent models. The reason why this trend was observed was that as the Reynolds number increased, the flow became more turbulent (more dominance of inertial effects over viscous effects) and hence the heat transfer rate increased. Furthermore, it could be seen that the turbulent model that was the closest to output and theoretical results in the best manner was SST-k-omega. The error associated was less than 3 %. Hence, SST-komega turbulent model was used for simulating the roughened ducts.

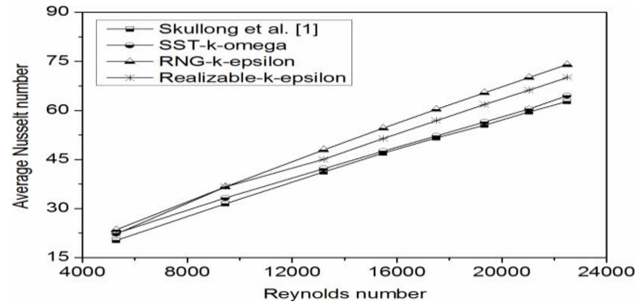

Fig. 7 Comparison Of Smooth Duct Results For Different Turbulent Models

4.2 Numerical Simulations On Ducts With Different Shaped Ribs

This section presents detailed results of average convective heat transfer characteristics of the heater, for different shaped ribs.

Grid Independence test results for all the different geometries

Figure 8 shows the results of grid independence tests conducted on different geometries. The turbulent model used was SST-k-omega for all the cases, since in the previous section it was proved that SST-k-omega most accurately simulated a solar air heater. The best mesh size was extracted from the Grid Independence test when there was less than 2 % variation in results onfurther increasing the number of mesh cells after this mesh size. Table 1 gives the range in which the number of mesh cells was varied and the most appropriate number of mesh cells for each configuration.

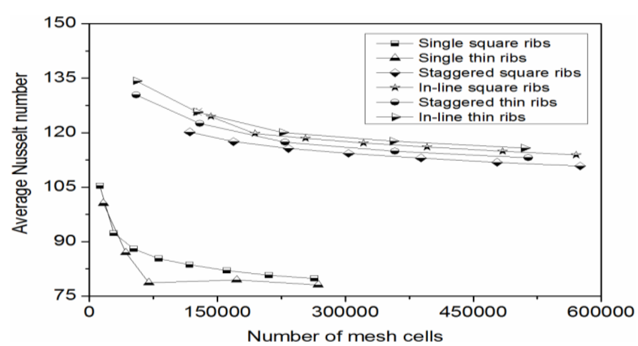

Fig. 8 Grid Independence Test Results For Different Rib Arrangements

5. Conclusion

A two-dimensional numerical study was done to predict the influence of transverse rectangular cross-sectioned ribs on a solar air heater's convective heat transfer properties. A rectangular duct was constructed and numerical analysis was carried out on square and thin (high aspect ratio) rib shapes arranged in different fashion, namely single wall, staggered and in-line ribs arranged on two opposite walls including the absorber plate. Air was the working fluid and constant heat flux was applied only on the absorber plate's top surface. The output of numerical simulations drew the following conclusions

- On comparing simulation results, pertaining to smooth duct's average Nusselt number, for different turbulent models, it was found that SST-k-omega can best predict the thermal performance of the solar air heater.
- For all the cases considered in this study, increase in Reynolds number leads to augmentation in Nusselt number.
- When ribs/baffles are introduced just beneath the collector plate, there was a considerable alteration in the heat transfer coefficient of air.
- Two methods were used to calculate the average Nusselt number in which one method extracted the local Nusselt number at many points and on averaging these, gave the average Nusselt number and the other method resembled the one used in the existing experimental work. Good matching between existing experimental results and numerical outputs was spotted, when the second method was adopted to calculate the Nusselt number, thereby proving that CFD can be effectively applied for the design of solar air heaters. However, the Nusselt number calculated using first method yielded values lower than the existing ones.
- The staggered ribs gave lower Nusselt number than the in-line ones.
- Out of the three arrangements, the best thermal performance was given by thin inline ribs whose convective heat transfer coefficient was 1.83 times that of smooth duct.

Since, it was observed that high aspect ratio ribs allow higher convective heat transfer, hence it would be interesting to conduct research work on triangular shaped ribs having very low apex angles. The present work is expected to be very helpful for carrying out the new future project.

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