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Thermal Analysis on Solar Air Heater Duct

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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 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.*

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 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 .

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 cover over the sun-radiation exposed surface, and a passage between the bottom plate and absorber for air to flow. The detailed constructional details of a solar air heater are shown in fig. 1.1

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.

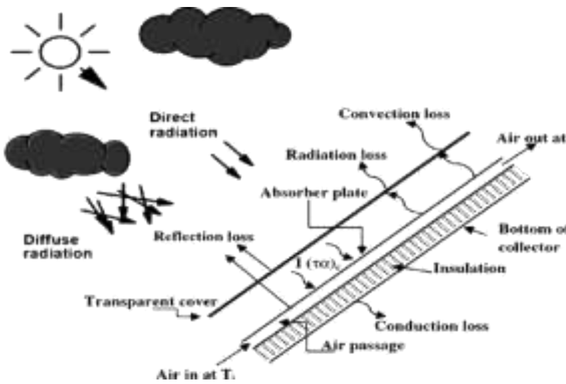

Fig. 1.1 Solar air heater constructional details [3]

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. 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

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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.

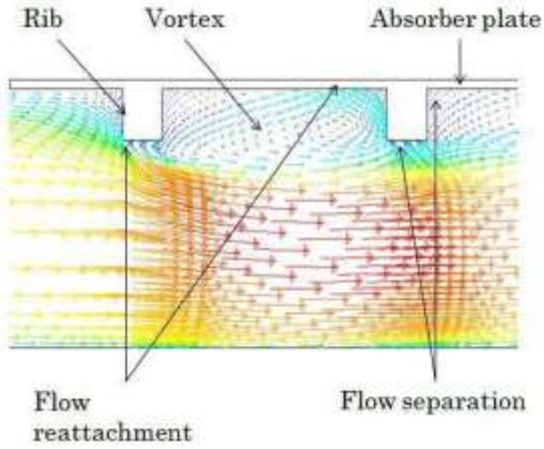

Fig. 1.2 Mechanism of augmentation of convective heat transfer by the introduction of ribs

As compared to experimental activities being carried on solar air heaters, very less numerical work has been done in this field. 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 softwares are saving of time and less costs required to complete the work. Some commercially available CFD software packages are FLUENT, FLOVENT, CFX, STAR- CD and PHOENICS.

2. Numerical Simulation

2.1 Computational domain - A rectangular section was considered. It consisted of three sections, test section of length L_2, entrance section of length L_1 and exit length of length L_3. The domain on which numerical simulations were performed was two-dimensional. It is because Chaubet al. 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 rectangular duct. Their rectangular duct was of length 2000 mm, width 300 mm and 30 mm with a test section length of 440 mm.

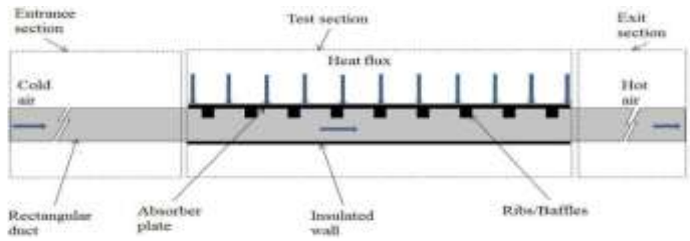

Fig. 3.1 Sketch of computational domain

The different rib arrangements employed for simulation are indicated in Fig. 3.2.

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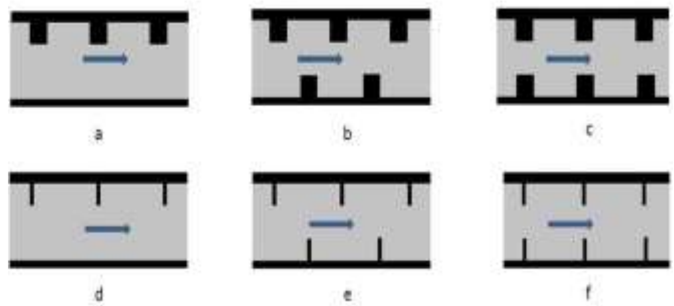


Fig. 3.2 Different arrangement of ribs namely (a) single square ribs, (b) staggered square ribs, (c) in-line square ribs, (d) single thin ribs, (e) staggered thin rib and (f) in line thin ribs

2.2 Operating and Geometrical parameters used for CFD analysis

Operating and Geometrical parameters	Value / Range
Test length of duct, L_2	440 mm
Entrance length of duct L_1	500 mm Exit
Length of duct L_3	240 mm Duct
Height, H	30 mm
Duct width, W	300 mm
Duct hydraulic diameter, D_h	54.54mm
Aspect ratio of duct, W/H	10
Constant heat flux, q"	100 W/m²
Range of Reynolds number	5000-23000

2.3 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 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, as shown in fig. 3.3

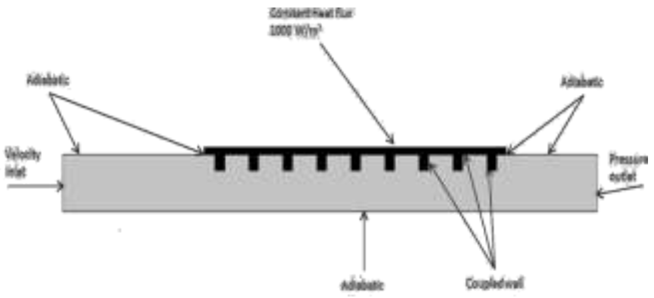


Fig. 3.3 Different boundary conditions assigned to edges of computational domain

2.4. C F D Modelling:

Commercially available ANSYS v 15.0 was the CFD software employed to solve the concerned general differential equations numerically. This software numerically simulates using FINITE VOLUME METHOD

2.5. Construction of geometry:

The geometry was constructed in commercially available software ANSYS v15.0. Firstly, an outline of the geometry without ribs was created in x-y plane with appropriate dimensions (in mm) and then surface was generated from the "built sketches" option. Then another sketch that involved the interface between absorber plate and fluid was developed. The surface initially created was split into two faces with the help of "face-split" option by choosing the second sketch as the tool geometry. The face-splitting option was followed by the generation of surfaces from the faces with the help of "create surface from faces" option. Finally, all the edges and surfaces were named accordingly.

2.6. Meshing of the domain:

The meshing work was accomplished on commercially available ANSYS meshing software. The geometry created was imported in ANSYS meshing. The required number of divisions and the type of "bias" were assigned to each edge. In order to obtain regular rectangular shaped mesh cells with the best orthogonal quality, mapped facing option was activated. Finally, mesh was generated by clicking on "Generate Mesh" button. Fig. 3.4 shows the meshed domain for different cases.

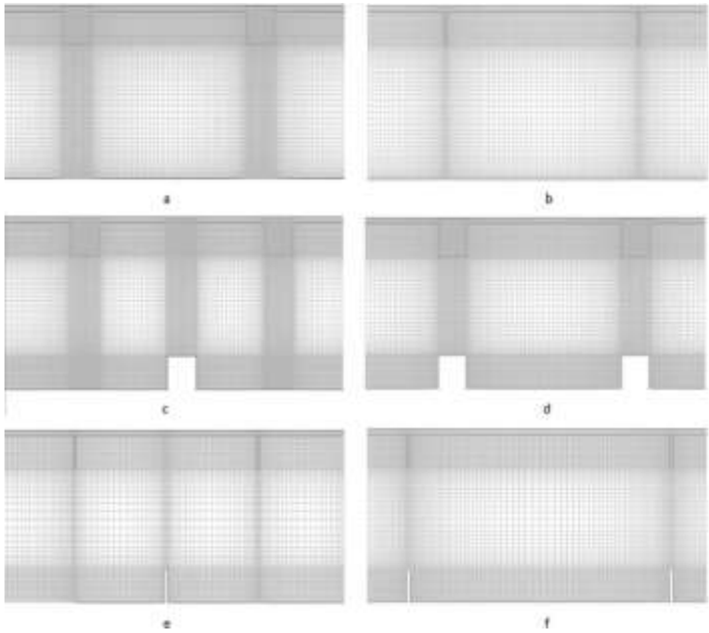


Fig. 3.4 Details of two-dimensional meshing of (a) single square ribs, (b) single thin ribs, (c) staggered square ribs, (d) in-line square ribs, (e) staggered thin ribs and (f) in-line thin ribs.

Properties	**Working Fluid(air)**	**Absorber Plate (aluminum)**
Density, Kg/m3	1.1767	2719
Viscosity, Kg/m-s	1.8582 e-05	-
Specific heat(constant pressure), J/kg-K	1006.6	871
Prandtl number	0.714	-
Thermal conductivity, W/m-K	0..262	202.4

3. Result

3.1 Selection of most appropriate turbulent model

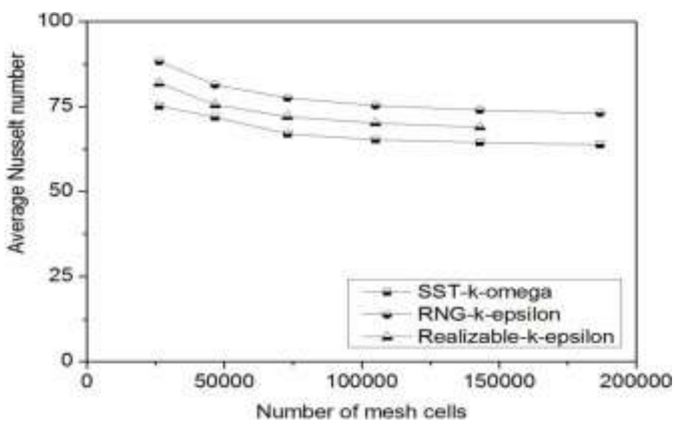


Fig. 4.1 Grid independence test results for selection of most appropriate turbulence model

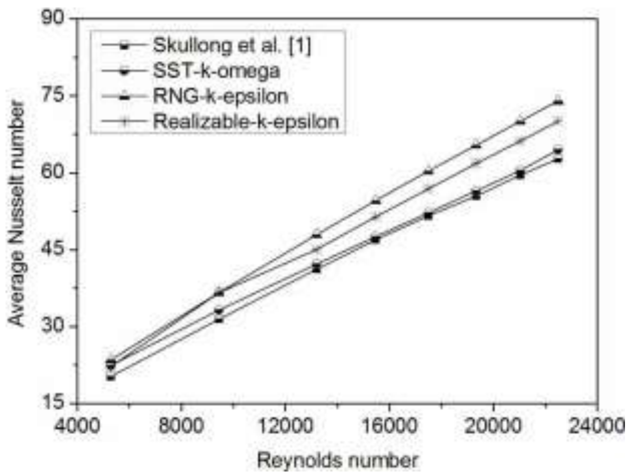


Fig. 4.2 Comparison of smooth duct results for different turbulent models

3.2 Grid Independence test results for all the different geometries

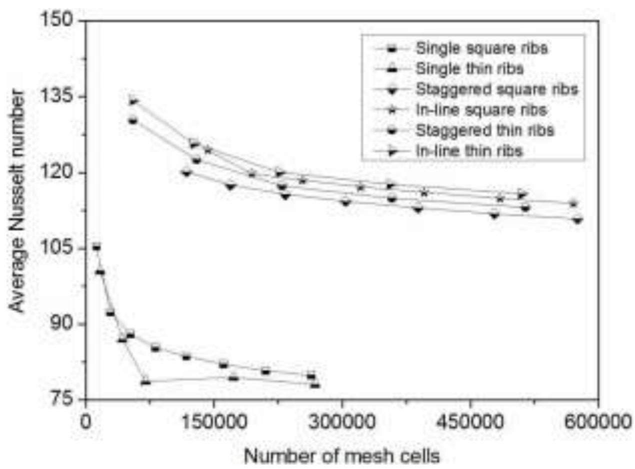


Fig. 4.3 Grid independence test results for different rib arrangements

3.3 Grid Independence test results

Rib configuration	Range of mesh cells	Best number of mesh cells
Single square	12516-268396	210636
Single thin	16500-268366	172620
Staggered square	117644-575320	477864
In-line square	142316-570576	484284
Staggered thin	55048-514568	357962
In-line thin	54934-509856	355882

3.4 Simulation for different roughened ducts at different Reynolds number

These are the results obtained for grid test for different arrangements of ribs/baffles at Reynolds number

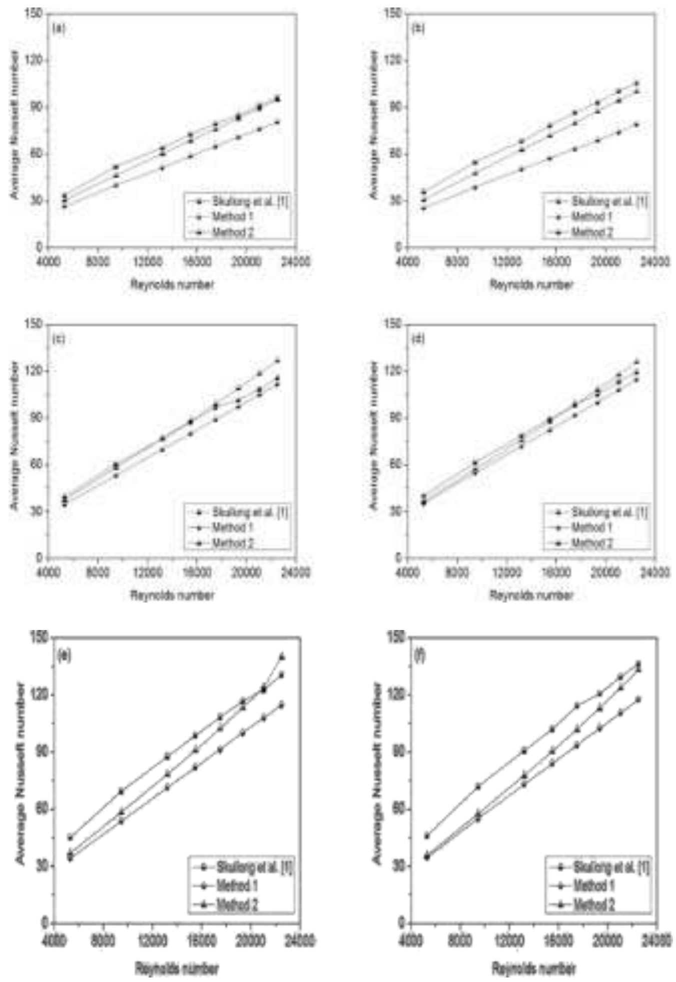


Fig. 4.4 Results of numerical analysis at different Reynolds number for (a) single square ribs, (b) single thin ribs, (c) staggered square ribs, (d) in-line square ribs, (e) staggered thin ribs and (f) in-line thin ribs.

3.5 Comparison of Nusselt number variation with Reynolds number for all the geometries

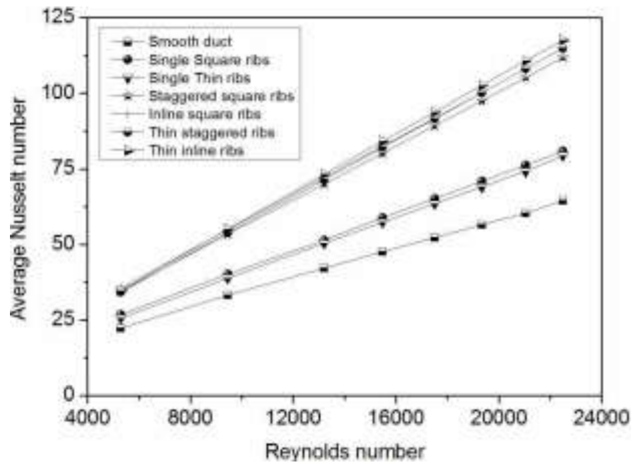


Fig. 4.5 Variation of Nu with Re for all the cases

3.6 Nusselt number enhancement (Nu/Nu_0) versus Reynolds number for separate geometries

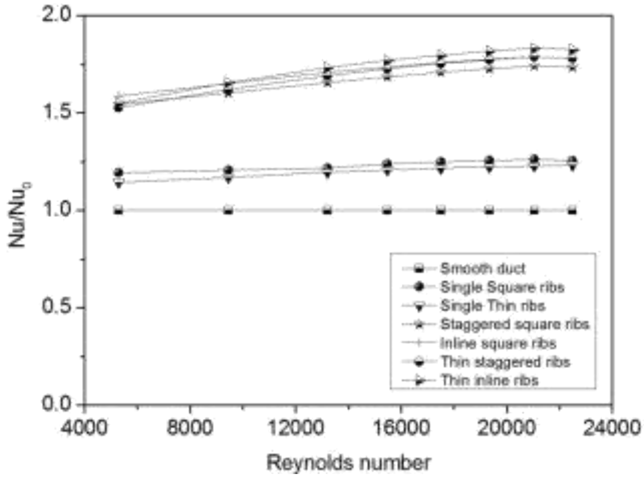


Fig. 4.6 Variation of Nu/Nu_0 with Re for all the cases

3.7 Local Nusselt number variation with length

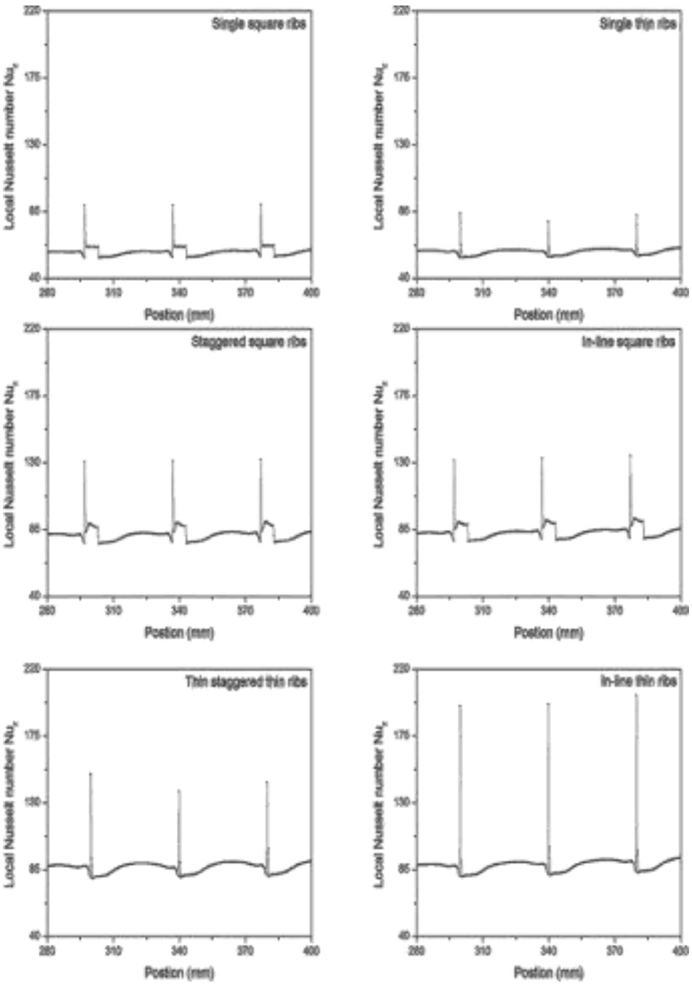
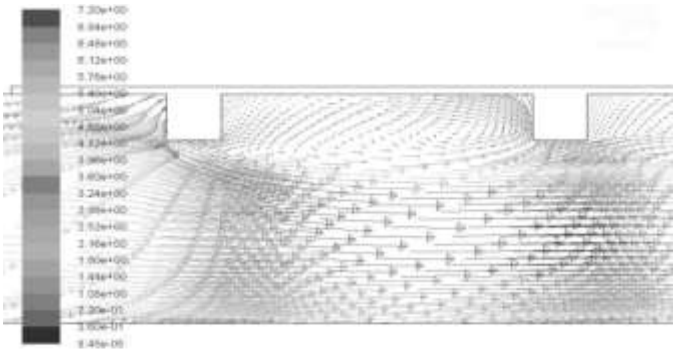
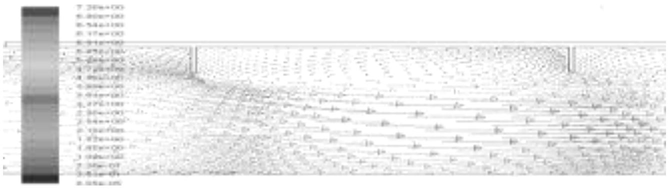


Fig. 4.7 Local Nusselt number variation with the length of test section for different arrangements of rib

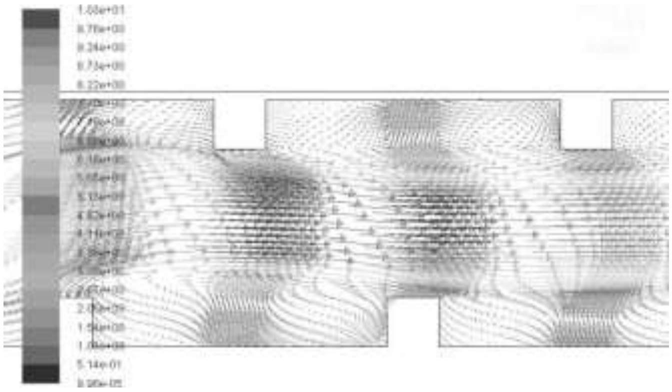
3.8 Velocity characteristics



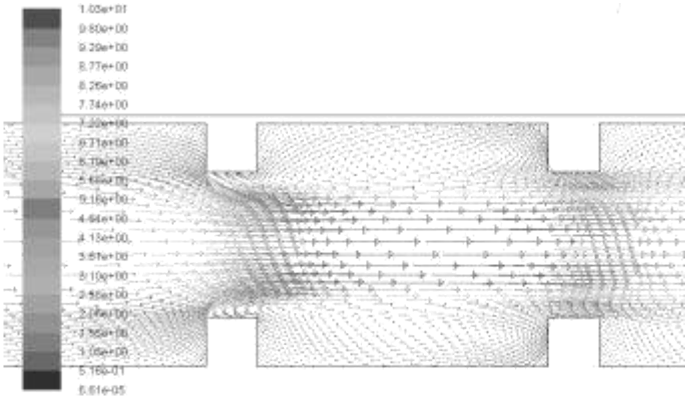
(a) single square ribs



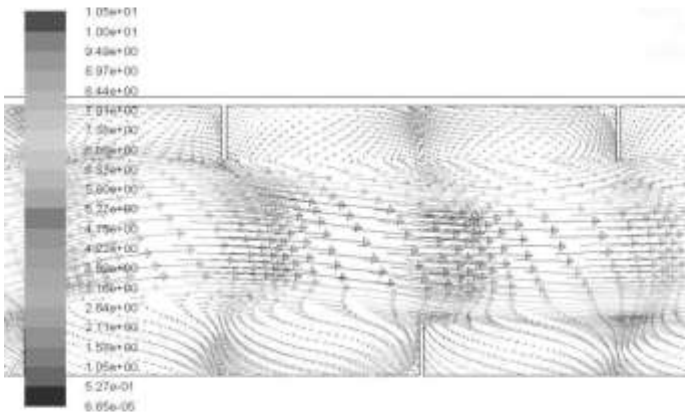
(b) single thin ribs



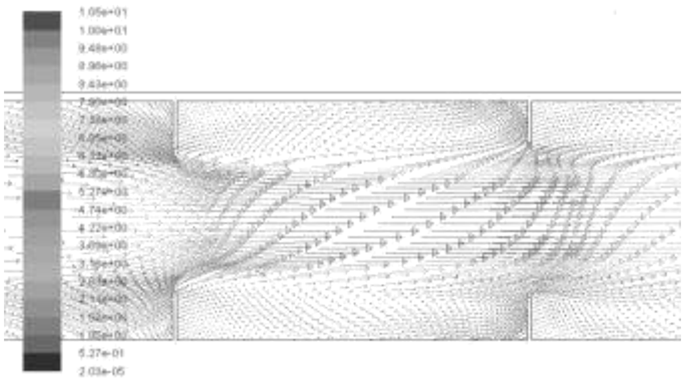
(c) staggered square ribs



(d) in-line square ribs



(e) staggered thin ribs



(f) in-line thin ribs

3. CONCLUSIONS & future scope

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.
- The results revealed that the thin ribs yielded better performance than the squared ones. Similar results were also observed by Skullong et al in their experimental work.
- 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.

Reference

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- Aharwal K. R., Pawar C. B. and Chaube, A., 2014, Heat transfer and fluid flow analysis of artificially roughened ducts having rib and groove roughness, Heat and Mass Transfer, 50(6): pp. 835-847.