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CFD INVESTIGATION ON NUSSELT NUMBER AND FRICTION FACTOR OF CIRCULAR AND SQUARE SECTIONED RIB ROUGHENED SOLAR AIR HEATER

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Abstract- ***Solar air heater is the cheapest and extensively used solar energy collection device for drying of agricultural products, space heating, seasoning of timber and curing of industrial products. The use of an artificial roughness on a surface is an effective technique to enhance the rate of heat transfer to fluid flow in the duct of a solar air heater. In this study to investigate the relative performance of different types of artificially roughened solar air heater. The objective of this article is toper form such a study. In this article two known different shapes and orientations of roughness elements are considered for comparative analysis. Correlations for heat transfer and friction factor, developed by various investigators for artificially roughened solar air heaters have been reported in this article. The effects of various rib parameter son heat transfer and fluid flow processes are also discussed.***

Keywords- ***Solar energy, Nusselt number, Temperature, Pressure, Efficiency.***

Introduction

Due to an increasing world population and increasing modernization, global energy need is projected to more than double during the first half of the twenty-first century and to more than triple by the end of the century. Presently, the world's population is nearly 7 billion, and projections are for a global population approaching 10 billion by midcentury. Future energy needs can only be met by introducing an increasing percentage of alternative fuels. Incremental improvements in existing energy networks will be inadequate to meet this increasing energy need.

There are many different types of energy. Kinetic energy is energy available in the motion of an object, particles—wind energy is one example of this. Potential energy is the energy available because of the position between objects—for example, water stored in a dam, the energy in a coiled spring, and energy stored in molecules (gasoline). There are many examples of energy: mechanical, thermal, electrical, magnetic, chemical, nuclear, tidal, biological, geothermal, and so on. Renewable energy denotes a clean energy, nontoxic energy source that cannot be exhausted.

Solar energy has been used since prehistoric times, but in a most primeval manner. Before 1970, some evolvement and research was carried out in a few countries to exploit solar energy more efficiently, but most of this work remained mainly academic. After the dramatic rise in oil prices in the 1970s, several countries began to formulate extensive evolvement and research programmers to exploit solar energy. The sun is more than 100 times larger than the earth, & is 1.4 million km. wide. it is so far away that it's light takes 8 minute to reach the Earth.

Solar Air Heater

A conventional solar air heater generally consists of an absorber plate with a parallel plate under forming a passage of high aspect ratio through which the air to be heated flows. As in the case of the liquid flat plate collector, a transparent cover system is provided up the absorber plate, while a sheet metal container filled with insulation is provided on the bottom and sides. Two other arrangement, which are not so common are also, the air to be heated flows. between the cover and the absorber plate itself instead of through a separate passage, while in, the air flows between the cover and absorber plate; as well as through the passage under the absorber plate.

However, the value of the heat transfer coefficient between the absorber plate and air is low and this result in lower efficiency. For this reason, the surfaces are sometimes roughened or longitudinal fins are provided in the airflow passage. A ruggedness element has been used to improve the heat shifting coefficient by creating turbulence in the flow. However, it would also result in increase in friction losses and hence greater power requirements for pumping air through the pipe. In order to keep the friction losses at a low level, the turbulence must be created only in the region very close to the pipe surface that is in laminar sub layer.

Past Studies on solar air heater:

The use of artificial ruggedness in the form of repeated ribs has been found to be an efficient method of enhancing the heat shifting to fluid flowing in the pipe. Detailed information about the heat shifting and flow characteristics in ribbed pipes is very vital in designing Solar air Heater Pipes, Heat Exchangers and cooling systems of gas turbine engines. The application of artificial ruggedness in the form of fine wires and ribs of different shapes has been recommended to enhance the heat shifting coefficient by several investigators. It has been found that the prime thermal resistance to the convective heat shifting is due to the presence of laminar sub layer on the heat-shifting ring surface. The ribs break the laminar sub layer and create local wall turbulence due to flow separation and reattachment between consecutive ribs, which reduce the thermal resistance and greatly enhance the heat shifting. However, the use of artificial ruggedness results in higher friction and hence higher pumping power requirements.

Yadav and Bhagoria [1] carried out a numerical investigation on a rectangular pipe of a solar air heater having triangular rib ruggedness on the absorber plate. A commercial finite volume package ANSYS FLUENT 12.1 was used as a solver. Solar air heater with triangular ribs ruggedness provided 1.4 to 2.7 times enhancement in Nusselt number as compared to smooth pipe. Good agreement was observed with experimental results.

Amraoui and Aliane [2] performed a CFD analysis to simulate the solar collector for better understanding of its heat shifting capability. Using a 3D model of the collector involving air inlet, the collector is modelled by ANSYS Workbench and the grid was created in ANSYS ICEM. The results were obtained by using ANSYS FLUENT. The outlet temperature of air was compared with experimental results and there was a good agreement between them.

Wang et Al. [3] performed a experimental work for water flow forced convection channel with repeated ribs surface in the range of Reynolds number from 20,000 to 60,000 at e/D=0.05. Heat shifting and flow behaviours past the single-phase channel are apprize. The maximum values of the heat shifting rate are detected, such as at p/e=5 for the compound rib with e/d=0.06 and p/e=6 for the triangular rib and asymmetric arc rib.

Prasad et al. [4] apprize the optimal thermo hydraulic performance of three sides artificially roughened solar air heater of high aspect ratio. For a particular set of values of ruggedness and flow parameters the optimal thermo hydraulic performance condition always corresponds to an optimal value of ruggedness Reynolds number.

Singh et al. [5] carried out a 3-dimensional CFD (computational fluid dynamics) investigation to study the heat shifting and friction characteristics of solar air heater pipe roughened with periodic transverse rib. The k-ε turbulence model was selected for analysis. The non-uniform cross-section saw tooth rib was found to result in higher Nusselt number than uniform cross-section ribs for Reynolds number up 7000 due to reduced low heat shifting area downstream of the rib caused by disruption in re-circulations. The maximum enhancement in Nusselt number for duct roughened with saw-tooth rib and trapezoidal rib was 1.78 and 1.50 respectively.

Singh et al. [6] presents thermo-hydraulic performance comparison of rib ruggedness under investigation, 'V- down ribs with gap' and similar reported rib ruggedness geometries used in solar air heater pipe. Five rib roughened plates having relative ruggedness pitch of 4, 6, 8, 10 and 12 have been tested. The Nusselt number and friction reality or were found to be highest for relative ruggedness pitch of 8. Maximum enhancement in Nusselt number and friction reality or has been found to be 2.70 and 2.86, respectively. Thermo-hydraulic performance parameter ranged from 1.27 to 1.93. Thermo-hydraulic comparison with similar rib geometries show that the present ruggedness geometry performs better for Reynolds number range of 3000–12,000.

Clement A. Komolafe et al. [7] experimentally investigated the thermal analysis of solar air heater having rectangular roughness on the absorber plate. The result showed that the calculated thermal efficiency value ranged between 14.0 to 56.5%. the simulated minimum and maximum temperature of the solar air heater were 21 and 127 °C respectively, which were in reasonable agreement with experimental result of 20 and 112 °C.

Prashant Singh et al [8] observed the experimental and numerical study of heat and fluid flow in a straight square duct featuring rib tabulators in a criss-cross pattern formed by 45 angled rib tabulators. Heat transfer and pressure drop experiments were carried out for Reynolds number ranging from 30,000 to 60,000. The results indicated that the thermal hydraulic performance of both the inline and staggered configurations were similar to each other and the values changed from 1.2 to 1.5

Ajeet Pratap Singh et al.[9] carried out an experimental investigation of various curved solar air heater designs that shows significant enhancement of heat transfer. The Computational Fluid Dynamic (CFD) model was first validated by the results reported by Mahboub et al. It was observed that secondary vortex formation near the absorber wall increases the Nusselt number significantly. The numerical simulations have been carried out for different geometries of curved absorber plate to study the dynamic thermal performance of smooth and effect of different relative height and pitch ratios of semicircular groove and V-groove corrugation of the absorber plate of curved solar air heater.

Inderjeet Singh et al. [10] experimentally investigated the thermal and hydraulic performance of solar air heater duct roughened with non-uniform cross-sectioned square wave profiled transverse rib is carried out in ANSYS Fluent 15.0. The result showed that the adopted CFD methodology has been validated with the experimental results from the previous literature. The effects of rib cross-section, Reynolds number and relative roughness pitch on the heat transfer and fluid flow process are discussed and visualized using streamlines.

R.S. Gill et al. [11] carried out an experimental investigation of solar air heater duct having aspect ratio 12 roughened with broken arc rib has been viewed. The broken arc is formed by creating symmetrical gap in continuous arc with gap width equal to roughness height. Author reported that for comparison continuous arc rib for same roughness parameters was also investigated. The effect of gap in continuous arc rib on flow pattern and absorber temperature was investigated using computational fluid dynamics (CFD) software ANSYS Academic Research CFD 15.0.

Vipin B. Gawande et al. [12] investigated that the developed solar air heater is a thermal system which uses artificial roughness in the form of repeated ribs on the absorber plate to enhance the heat transfer rate. Forced convection heat transfer of air in a solar air heater with reverse L-shaped ribs has been carried out experimentally and numerically. The results indicate that the maximum enhancement in Nusselt number has been found to be 2.827 times over the smooth duct corresponding to relative roughness pitch (P/e) of 7.14, relative roughness height (e/D) of 0.042 at Reynolds number (Re) of 15,000 in the range of parameters investigated.

Han et al. [13] experimentally investigated the effects of rib shape, angle of attack and pitch-to-rib height ratio on friction reality or and heat shifting coefficient. Author reported that ribs with 45° inclinations produced better heat shifting performance than ribs with 90° orientations, when compared at the same friction power**.**

Han [14] investigated the developed heat shifting in rectangular channels with rib turbulators for rib angle varying from 90° to 30°. The combined effects of rib angle and channel aspect ratio on local heat shifting coefficient were studied. The results indicate that the best heat shifting in square channel was obtained with angled ribs at 30- 45° and was about 30% higher than the 90° transverse ribs for constant pumping power. However, for rectangular channel with aspect ratio of 2 and 4, the heat shifting enhancement using 30°-45° ribs was only 5% more than the 90° transverse rib. In general, it was noted that in square channel the heat shifting enhanced with decrease in rib angle whereas in rectangular channel the be dependence of heat shifting on rib angle was negligible.

Verma and Prasad [15] developed the relations to calculate the average friction reality or and Stanton number for artificial ruggedness of absorber plate by small diameter protrusion wire. They used these relations to compare the effect of height and pitch of ruggedness element on heat shifting and friction factor with already available experimental data. The friction reality or for one side rough pipe is apprize by assuming that the total shear force in the one side rough pipe is approximately equal to the combined shear force from three smooth walls in a four-sided smooth pipe and the sheer force from one rough wall in a four-sided rough pipe. They used the friction similarity law and heat–momentum shifting analogy

Han et al. [16] studied a square channel with two ribbed walls for five different rib profiles. Their study illustrated that rib turbulators with greater number of sharp corners yield increasingly higher heat shifting coefficient as well as pressure drop.

Chandra et al. [17] carried out an experimental study of surface heat shifting and friction characteristics of a fully developed turbulent air flow in a square channel with transverse ribs on one, two, three, and four walls. Tests were performed for Reynolds numbers ranging from 10,000 to 80,000. The pitch to rib height ratio, P/e, was kept at 8 and rib height to channel hydraulic diameter ratio, e/D was kept at 0.0625. The channel length to hydraulic diameter ratio, L/D, was 20. The heat shifting coefficient and friction factor results were enhanced with the increase in the number of ribbed walls. The friction ruggedness function, R(e+), was almost constant over the entire range of tests performed and was within comparable limits of the previously published data. The heat shifting ruggedness function, G(e+), enhanced with ruggedness Reynolds number and compared well with previous work in this area. Both correlations could be used to foreshow the friction factor and heat shifting coefficient in a rectangular channel with varying number of ribbed walls. The results of could be used in various applications of turbulent internal channel flows involving different number of rib roughened walls.

Gupta et al. [18] carried out an experimental investigation on solar air heater with angled ribs with circular cross-section. They have investigated the effect of relative ruggedness height (e/D), inclination of rib with respect to flow direction and Reynolds number on fluid flow characteristics in transitionally rough flow region and evaluated the thermo hydraulic performance of solar air heaters.

Zhang et al. [19] observed that deploying of groove in between the ribs enhances the turbulences as well as reattaches the free shear layer nearer to the rib. They have reported that the addition of grooves in between adjacent square ribs enhances the heat shifting capability of the surface considerably with nearly same pressure drop penalty. It appears that it will be fruitful to investigate an artificially roughened surface with optimally chamfered rib combined with grooves present between two ribs in order to achieve further decrease in relative ruggedness pitch and enhancement of heat shifting rate from such a surface. In view of the up an experimental

Investigation has been planned to investigate the heat and fluid flow characteristics of artificially roughened surface with chamfered rib-grooved ruggedness.

Park et al. [20] presented the results of heat shifting and friction factor data measured in five short rectangular channels with turbulence promoters.

Author investigated the combined effects of the channel aspect ratio, rib angle of attack, and flow Reynolds number on heat shifting and pressure drop in rectangular channels with two opposite ribbed walls. The channel aspect ratio (width to height, W/H, ribs on side W) varied from ¼ to ½ , to 1, 2 and 4, while the corresponding rib angles of attack were 90°, 60°, 45°, and 30°, respectively. The Reynolds number range was 10,000–60,000. The results suggested that the narrow aspect ratio channels (W/H < 1) gave much better heat shifting performance than the wide aspect ratio channels (W/H > 1). For the square channel (W/H = 1), the 60°/45°angled ribs provided the best heat shifting performance. For the narrow aspect ratio channel (W/H=1/4 or 1/2), the 45°/60°angled ribs were recommended while the 30°/45°angled ribs were better for wide aspect ratio channels (W/H = 4 or 2).

Computational fluid dynamics

Computational fluid dynamics (CFD) is the analysis of systems involving fluid flow, heat shifting and associated incident such as chemical reactions by means of computer based simulation. The technique is very powerful & spans a wide range of industrial and non-industrial application areas.

In words we have:

$$\begin{bmatrix}\text{Rate of change}\\ \text{of } \emptyset \text{ in the control}\\ \text{volume with respect}\\ \text{to time}\end{bmatrix} = \begin{bmatrix}\text{Net Rate of increase}\\ \text{of } \emptyset \text{ due to convection}\\ \text{in to the control}\\ \text{volume}\end{bmatrix} + \begin{bmatrix}\text{Net Rate of increase}\\ \text{of } \emptyset \text{ due to diffusion}\\ \text{in to the control}\\ \text{volume}\end{bmatrix} + \begin{bmatrix}\text{Net Rate of creation}\\ \text{of } \emptyset \text{ inside the}\\ \text{control volume}\end{bmatrix}$$

Mass balance equation is given by

Rate of increase of mass in fluid element = Net rate of flow of mass element in to fluid element

$$\frac{\partial \rho}{\partial t} + div\ (\rho u) = 0$$

This is unsteady, 3D mass patronage or continuity equation in compressible fluid.

For incompressible fluid it is given by,
div (u) = 0
or $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$

1. Momentum patronage

Rate of increase of momentum = Sum of forces

$$\frac{\partial (\rho \overline{v})}{\partial t} + \nabla . (\rho \overrightarrow{v} \vec{v}) = \rho g - \nabla P + \nabla . (\vec{\tau})$$

2. Energy patronage

Rate of increase of energy = Net heat added + Net rate of work done

$$\frac{\partial (\rho E)}{\partial t} + \nabla . \left(\overrightarrow{v} (\rho E + p) \right) = \nabla . \left(k_{eff} \ \ \nabla T + (\vec{\tau}\ . \overrightarrow{v}) \right)$$

Where,

$$\overline{\tau} = \mu((\nabla \vec{v} + \nabla \overrightarrow{v}) - \frac{2}{3} \nabla . \overrightarrow{\mathrm{v}} \mathrm{l})$$

$$\mathrm{E} = \mathrm{h} - \frac{P}{\rho} + \frac{v^2}{2}$$

ANALYSIS OF CFD

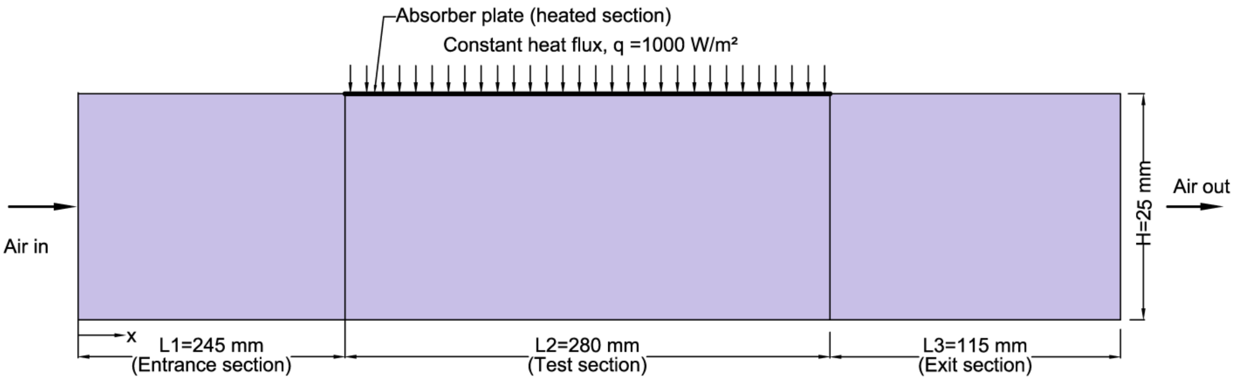


Figure: 1 with reference by CFD

In CFD calculations, there are three prime steps.

1. Pre-Processing
2. Solver Execution
3. Post-Processing

Pre-Processing is the step where the modeling goals are apprize and computational grid is created. In the second step numerical models & boundary conditions are set to start up the solver. Solver runs until the convergence is reached. When solver is terminated, the results are examined which is the post-processing part.

RESULTS AND DISCUSSION

Table 1 shows the values of heat shifting coefficient generated from CFD for different values of relative ruggedness height and Reynolds number at a fixed value of ruggedness pitch.

Table: 1 Values of heat shifting coefficient generated from CFD.

E	**e/D**	**P**	**Re**	**V**	**Nu_s**	**Circular Rib**		**Square Rib**	
						h_r	**NU_r**	**h_r**	**NU_r**
1	0.03	10	3800	1.67	14.58	18.9188	26.0339	20.8105	28.637
			5000	2.19	18.153	23.8893	32.8736	26.2782	36.161
			8000	3.51	26.44	35.6209	49.0173	39.1829	53.919
			12000	5.26	36.57	50.2785	69.1874	55.3062	76.106
			15000	6.58	43.72	60.7793	83.6374	66.8571	92.001
			18000	7.9	50.58	70.9675	97.6572	78.0643	107.423
1.5	0.045	10	3800	1.67	14.58	23.7317	32.6568	26.1045	35.922
			5000	2.19	18.153	29.9666	41.2365	32.9631	45.36
			8000	3.51	26.44	43.9559	60.487	48.3517	66.536
			12000	5.26	36.57	60.9556	83.88	67.0512	92.268
			15000	6.58	43.72	73.3967	101	80.7364	111.1
			18000	7.9	50.58	85.0239	117	93.5263	128.7
2	0.06	10	3800	1.67	14.58	28.478	39.1882	31.3259	43.107
			5000	2.19	18.153	35.9599	49.4838	39.5557	54.432
			8000	3.51	26.44	52.7471	72.5844	58.0219	79.843

			12000	5.26	36.57	73.1467	100.656	80.4617	110.722
			15000	6.58	43.72	88.076	121.2	96.8836	133.32
			18000	7.9	50.58	102.029	140.4	112.232	154.44

Fig.2 shows the effect of Reynolds number on average Nusselt number for different values of relative ruggedness height (*e/D*) and fixed value of ruggedness pitch (*P*). The average Nusselt number is observed to increase with increase of Reynolds number due to the increase in turbulence intensity caused by increase in turbulence kinetic energy and turbulence dissipation rate.

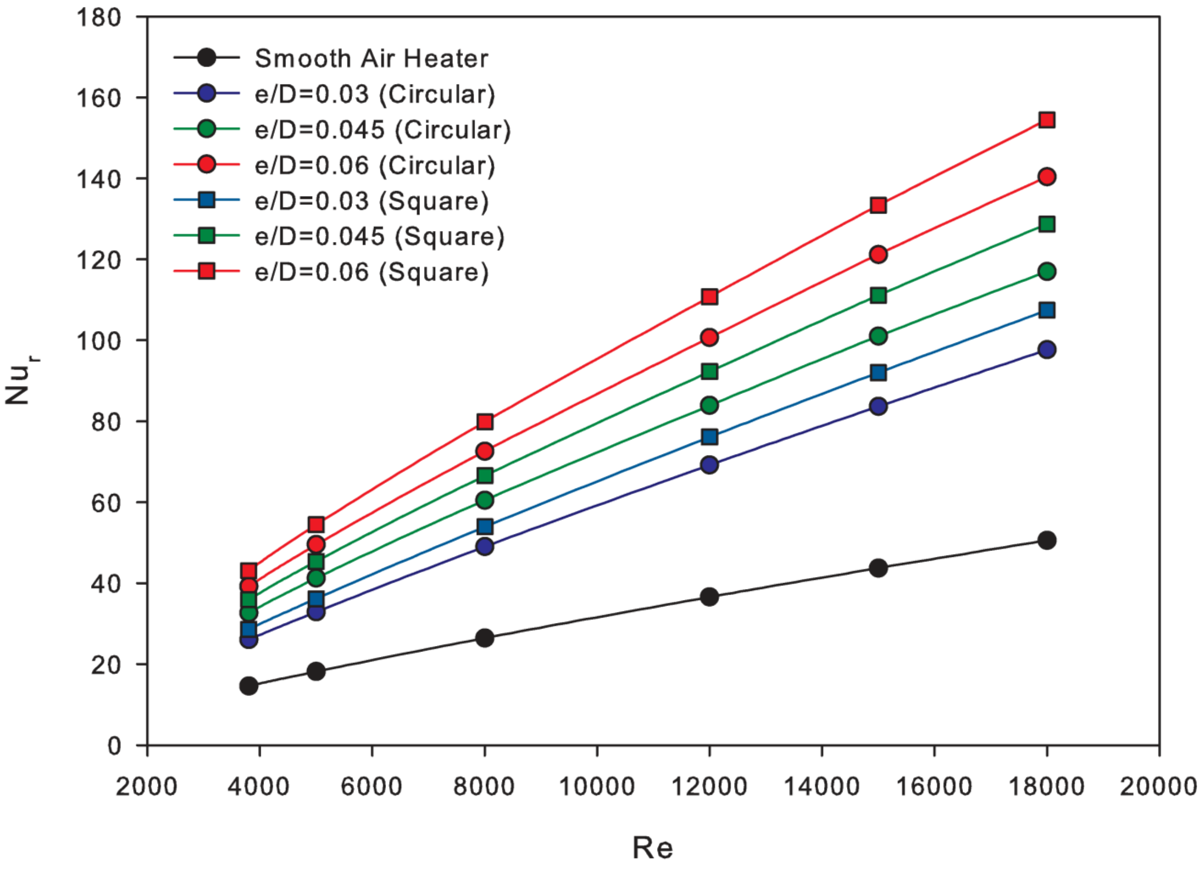
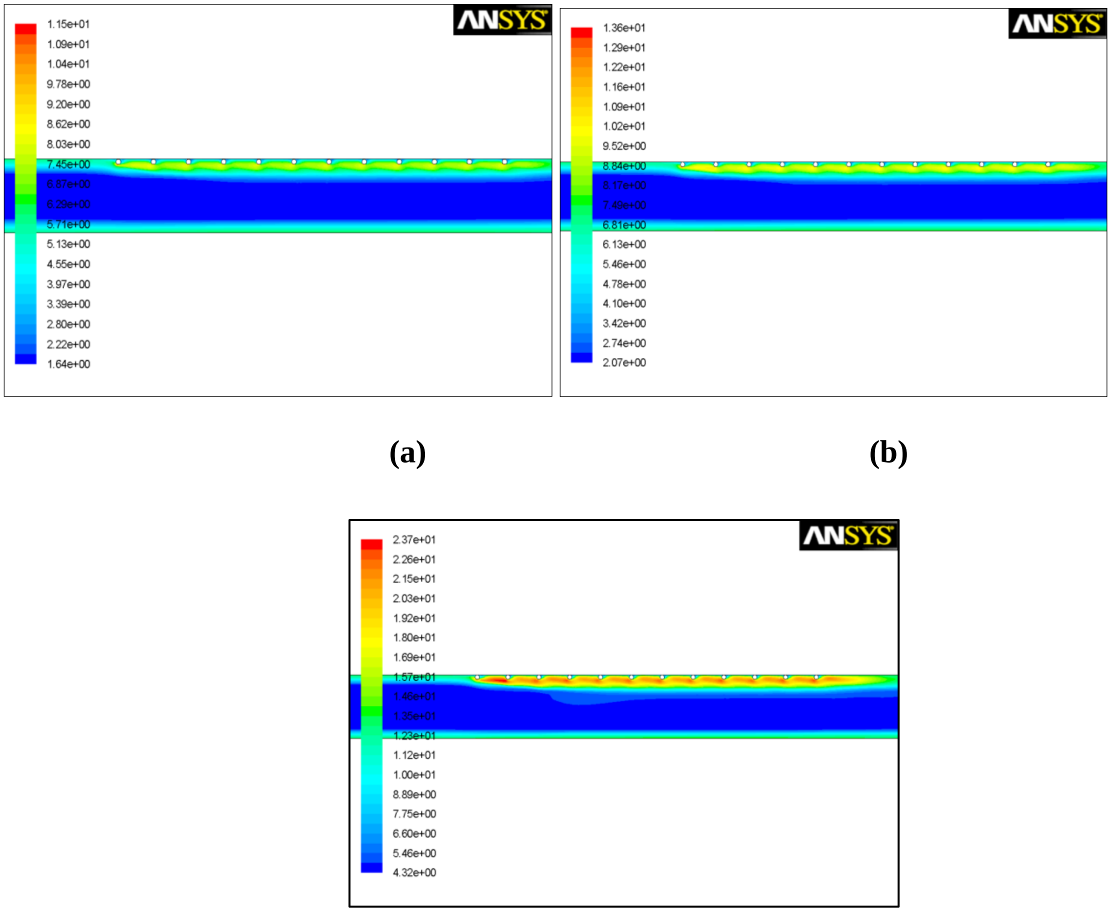


Figure.2 Nusselt number Vs. Reynolds number

Effect of the relative ruggedness height (*e/d*) on heat shifting is also shown typically in Fig.2. It can be seen that the enhancement in heat shifting of the roughened pipe with respect to the smooth pipe also increases with an increase in Reynolds number. It can also be seen that Nusselt number values increases with the increase in relative ruggedness height (*e/d*) for fixed value of ruggedness pitch (*P*). This is due to the reality that heat shifting coefficient is low at the leading edge of the rib and high at the trailing edge.

Higher relative ruggedness height produced more reattachment of free shear layer which creates the strong secondary flow.



(a) **(b)**

(c)

Figure.3 Contour plot of turbulent intensity for circular rib (a) Re=3800 (b) Re=5000 (c) Re=12000

Similarly Fig. 3 (a, b and c) shows the contour plot of turbulence intensity for square rib. The heat shifting phenomenon can be observed and described by the contour plot of turbulence intensity for square rib. The intensities of turbulence are reduced at the flow field near the rib and wall and a high turbulence intensity region is found between the adjacent ribs close to the prime flow which yields the strong influence of turbulence intensity on heat shifting enhancement.

Validation of model

In order to validate the present numerical model, the results are compared with available experimental results. Literature search in the area of artificially roughened solar air heater also reveal that the optimum value of relative ruggedness height generally lies between 0.03-0.047. Table shows the comparison of optimum value of relative ruggedness height between present CFD simulation and available experimental/widely accepted numerical results. On comparison, it has been observed that the optimum value of relative ruggedness height for present CFD model is found to be 0.045 for circular and square sectioned rib. The optimum value of relative ruggedness height from present CFD investigation is found to fall in-between the accepted range i.e. 0.033 and 0.043. It can be seen that there is a good agreement between CFD and experimental/numerical results.

CONCLUSION

A 2-dimensional CFD analysis has been carried out to study heat shifting and fluid flow behavior in a rectangular pipe of a solar air heater with one roughened wall having circular and square rib ruggedness. The effect of Reynolds number and relative roughness pitch on the heat shifting coefficient and friction factor have been studied. In order to validate the present numerical model, results have been compared with available experimental results under equal flow conditions. CFD Investigation has been carried out in moderate Reynolds number flow (Re = 3800–18,000).

1. The Renormalization-group (RNG) k-ε turbulence model foreshowed very close results to the experimental results, which yields confidence in the foreshow ions done by CFD analysis in the present study. RNG k-ε turbulence model has been validated for smooth pipe and grid in be dependence test has also been conducted to check the variation with increasing number of cells.

2. The roughened pipe having circular rib with relative ruggedness height of 0.06 supply the highest Nusselt number (Nu_r= 140.4) at a Reynolds number of 18000. The roughened pipe having square rib with relative ruggedness height of 0.06 supply the highest Nusselt number (Nu_r = 154.44) at a Reynolds number of 18000.

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