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COMPUTATIONAL FLUID DYNAMICS BASED ANALYSIS OF ARTIFICIALLY ROUGHENED SOLAR AIR HEATER DUCT USING S-SHAPE RIBS

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Abstract : In a solar air heater ductproviding artificial roughness on the heat transfer surface in the form of projections enhances the heat transfer coefficient by creating the turbulence and breaking the laminar sub-layer near the heat transferring surface. In the present work performance of a solar air heater duct provided with artificial roughness in the form of thin circular wire arranged in 'S' shape rib geometries has been analyzed using Computational Fluid Dynamics (CFD). The effect of roughness geometry on heat transfer and friction factor and performance enhancement was investigated for roughness parameters, $e/D_h=0.043$, $P/e=8$, $W/w=3$, $\alpha=60°$ and Reynolds number (Re) from 2,400 to 20,000. Different turbulent models have been used for the analysis of heat transfer and friction factor and their results are compared with Dittus-Boelter and Blasius empirical relationship for smooth surface. Renormalization k-epsilon model based results have been found in good agreement with the empirical results and hence this model is used to predict heat transfer and friction factor in the duct.

Keywords:CFD;Renormalized;Roughness;Nusselt number; Heat transfer.

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1. Introduction

Air heating by using solar energy is one of its simplest applications [1]. Solar air heaters (SAH) are the common devices used to convert the solar energy in to heat energy of air. The thermal efficiency of solar air heater is low because of low convective heat transfer coefficient between the absorber plate and air. It has been found that the main thermal resistance to the convective heat transfer is due to the formation of boundary layer on the heat transferring surface. Efforts for enhancing heat transfer have been made by various researchers towards artificially destroying this boundary layer. The application of artificial roughness in the form of repeated ribs on the heat transfer surface has been recommended by several researchers to enhance the heat transfer coefficient as this is the only wall which is receiving solar energy and other walls are well insulated and there is no need to increase the roughness on these walls [2]. But the use of ribs also leads to the increase in frictional losses [3] which results the rise in pumping power required to make the flow of air through solar air heater and hence affecting the efficiency adversely. Wire in the form of repeated ribs was used by Prasad and Mullick [4] for the first time to increase the thermal efficiency of solar air heater. After that a number of experimental studies were carried out by many researchers and artificial roughness was expressed in form of dimensionless parameters. Prasad and Saini [5] discussed the effect of relative roughness height (e/D_h) and relative roughness pitch (P/e) on Nusselt number and friction factor. The maximum enhancement in Nusselt number and friction factor were found to be 2.38 and 4.25 times respectively as compared to the smooth duct. Gupta et al. [6] experimentally studied the effect of relative roughness height and angle of attack on Nusselt number and friction factor in rectangular duct having inclined circular wire ribs on the absorber plate for the Reynolds number range of 3000-18000.Authors were also found that roughened duct has a better thermo-hydraulic performance for lower Reynolds number which decreases as the value of Reynolds number increases. Kumar et al. [6–8] also conducted the experiments to study the effect of angle of attack on heat transfer and fluid flow characteristics and found that the value of angle of attack of 60^o corresponds to maximum heat transfer. Karwa et al. [10] experimentally investigated the performance of solar air heater having chamfered repeated rib-roughness and found significant enhancement in thermal efficiency (10-40%) over solar air heaters with smooth duct. Singh et al. [11] conducted experiments to investigate the heat transfer characteristics of rectangular duct roughened with periodic ‘discrete V-down ribs’. Authors found optimum value of Nusselt number and friction factor corresponding to relative roughness pitch (p/e) value of 8.

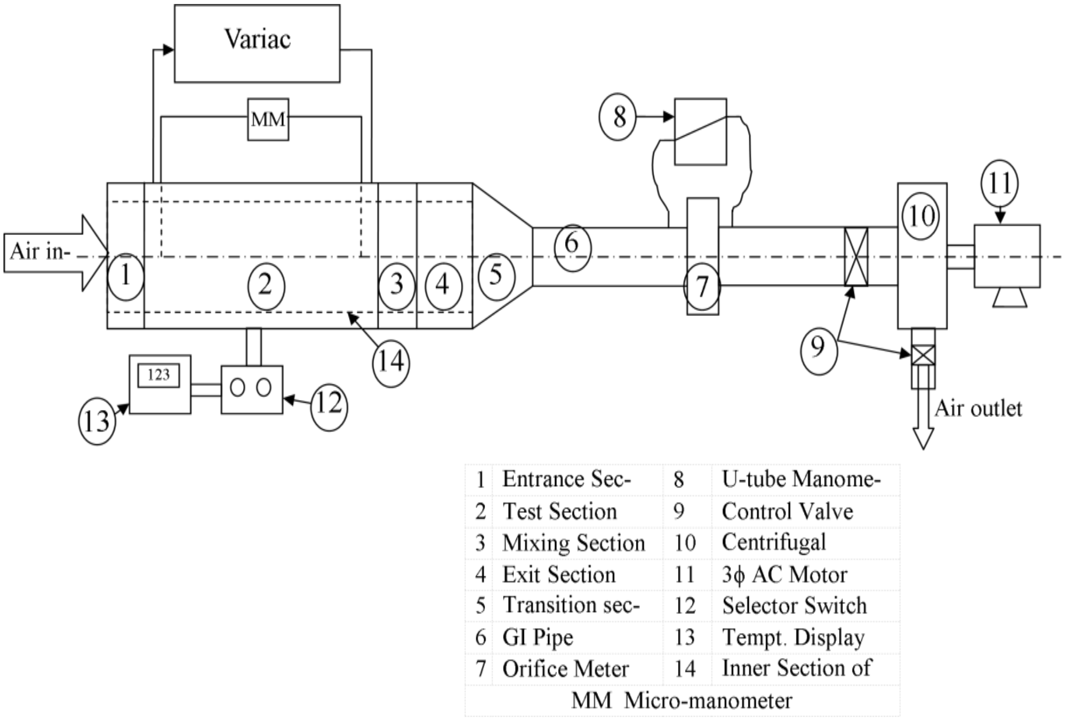
Saini and Saini [12] experimentally studied the effect of arc shaped ribs on the heat transfer coefficient and friction factor of rectangular ducts. The parameters studied were Reynolds number (Re), relative roughness height (e/D_h) and relative arc angle ($\alpha/90$). Enhancement of Nusselt number and friction factor was reported to be 3.6 and 1.75 times respectively compared to smooth duct corresponding to relative arc angle ($\alpha/90$) value of 0.3333 and relative roughness height (e/D_h) value of 0.0422. The correlations for Nusselt number and friction factor were also developed for the studied parameters. Singh et al. [13] carried out experimental investigation to study the effect of geometrical and operating parameters on heat transfer and fluid flow characteristics of a rectangular solar air heater duct. Based on the experimental results correlations for Nusselt number and friction factor were also developed. It was found from the study that a maximum enhancement in Nusselt number and friction factor was obtained as 5.07 and 3.71 respectively for multiple arc-shaped roughness geometry as compared to smooth duct. The maximum enhancement for Nusselt number was found for Reynolds number (Re) value of 22,300, relative roughness width (W/w) value of 5, relative roughness height (e/D) value of 0.045, relative roughness pitch (p/e) value of 8 and relative arc angle ($\alpha/90$) value of 0.667. Also the maximum friction factor takes place at Reynolds number (Re) value of 22,300, relative roughness width (W/w) value of 7, relative roughness height (e/D_h) value of 0.045, relative roughness pitch (p/e) value of 8 and relative arc angle (a/90) value of 0.667. Developed correlations for Nusselt number and friction factor as function of various operating parameters and roughness parameters were found to predict the values of Nu and f with reasonable accuracy.

Singh et al. [14]investigated experimentally the effect of multiple arc shaped ribs on heat transfer and fluid flow characteristics in a rectangular solar air heater duct. Authors carried out experiments to study the effect of geometrical parameters of multiple arc shape ribs. The effect of relative roughness pitch (p/e), relative roughness width (W/w), relative roughness height (e/D_h) and arc angle (α) on heat transfer and friction factor was studied for a Reynolds number range of 2200-22000. Based on the experimental results authors concludes that the relative roughness width (W/w) value of 5 has the best performance. Lanjewar et al. [15]experimentally investigated the effect of orientation of double arc shape ribs on heat transfer and fluid flow characteristics of rectangular cross section duct and found that the double arc down orientation performs better than the double arc up and single arc ribs.

The literature shows that the use of artificial roughness in different forms and shapes is an effective method of improving the performance of rectangular ducts. Many experimental investigations have been carried out for roughness elements of various shapes, sizes and orientations with respect to flow direction in order to obtain an optimal arrangement of roughness element geometry. It was found that ribs arranged in the arc shape enhance the heat transfer coefficient by angling and separation of flow. Generation of vortices on the upstream and downstream of rib and reattachment of flow in the inter-rib spaces results in the turbulence of flow and enhancing the fluid flow. Increasing the number of arc across the duct width further enhances the heat transfer on account of increase in the number of vortices and secondary flow which results in high heat transfer.In the present work, CFD based study on the performance of rectangular duct, having the absorber plateartificiallyroughenedby using the arc form in two different directions (one in forward and another in backward) forming ‘S’ shape has been carried out.

2. Details of Experimental Set-up

A schematic diagram of experimental setup is shown in Figure 1. It consists of mainly three parts an entry section, test section and exit section. A centrifugal blower with a control valve was used to make the flow through duct. A flow measuring orifice-meter at the exit of duct is used to measure the flow rate of air in the duct. The wooden rectangular duct having a size of 2300 mm×300 mm×25 mm and is provided with an entrance section, a test section and an exit section of lengths 800 mm, 1000 mm and 500 mm, respectively, was used in order to minimize the end effects on the test section as per the recommendations of ASHRAE Standard 93-97 [16].



1	Entrance Sec-	8	U-tube Manome-
2	Test Section	9	Control Valve
3	Mixing Section	10	Centrifugal
4	Exit Section	11	3ϕ AC Motor
5	Transition sec-	12	Selector Switch
6	GI Pipe	13	Tempt. Display
7	Orifice Meter	14	Inner Section of
MM	Micro-manometer		

Figure 1 Schematic diagram of the experimental set-up

3. Roughness Parameters

In the present investigation the relative roughness height (e/D_h),relative roughness pitch (p/e), relative roughness width (W/w) and arc angle (α)were chosen as roughness parameters and their values were selected as ($e/D_h= 0.043$, $p/e=8$, $W/w=3$, $\alpha=60°$) based on the optimum value of these parameter reported in the literature. Operating parameterReynolds number (Re) values varied in the range from 2400 to 20000. Table 1 shows the values of roughness and operating parameters for this study.

Table 1. Range of geometrical and operating parameters

S. N.	Parameters	Range
1.	Reynolds number (Re)	2400 to 20000 (7 values)
2.	Duct aspect ratio (W/H)	12 (fixed)

3.	Relative roughness height (e/D_h)	0.043
4.	Relative roughness pitch (p/e)	8
5.	Relative roughness width (W/w)	3
6.	Arc angle (α)	60°
7.	Heat Flux (q)	1000 W/m^2 (fixed)

4. Computational fluid dynamics (CFD)

Computational fluid dynamics is the analysis of system, involving the fluid flow heat transfer and associated phenomena such as chemical reaction by means computer based simulation.In this investigation a three dimensional numerical simulation of the conjugate heat transfer and fluid flow was conducted using the Ansys 14.5. The modeling was carried out in order to predict and explain the experimental observations.

4.1 Solution Domain

A rectangular duct having height (H) of 25 mm and width (W) of 300 mm with an aspect ratio of 12 was prepared and a solution domain for the present study had been generated as shown in Figure 2. The three walls of the duct were kept as adiabatic which offers no heat transfer to surroundings. A uniform heat flux (q) of 1000 W/m2 was added at the roughened (Top) wall. The simulation analysis of the model had been carried out by solving the model using ANSYS 14.5 Fluent for continuity, momentum and energy by using the finite volume method in the steady state regime.

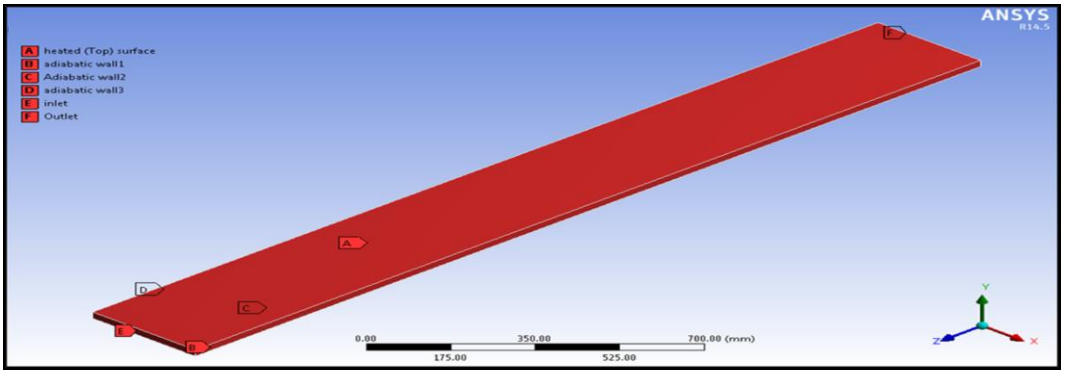


Figure 2 Solution Domain used in ANSYS for analysis.

4.2 Boundary Conditions

The solution domain is of rectangular section having the Inlet, Outlet and the wall boundaries. The properties of the working fluid (Air) and the absorber plate (Aluminium) have assumed to be remains constant. No-slip conditions for the fluid velocity in the solid surfaces were assumed with turbulent kinetic energy set at zero on all the solid walls. The two side walls and bottom wall are set as the adiabatic walls and a uniform heat flux (q) of 1000 W/m2 was added at the top wall. The temperature of the air inside the duct is assumed at 300K at the initial stage. Reynolds number (Re) is varied from 2400-20000 and the mean inlet flow velocity is calculated using the Reynolds number (Re). A pressure outlet condition is applied at exit of duct.

4.3 Selection and validation of the model

The selection of model is carried out by comparing the predictions by different turbulent models with experimental results available in the literature. The different models namelyRenormalization (RNG) group k-epsilon model, Standard k-epsilon modeland Realizable k-epsilon model have been tested for smooth duct to find out the validity of the models.

$$Nu = 0.024 Re^{0.8} Pr^{0.4} \tag{1}$$

Figure 3 shows the variation of Nusselt number with Reynolds number for different models and the results are compared with results computed from the Dittus-Boelter empirical relationship for a smooth duct. It has been observed that the results obtained by Renormalization (RNG) group k-epsilon model are in good agreement with Dittus-Boelter empirical results. Hence, for the present numerical study Renormalization (RNG) group k-epsilon model has been selected to simulate the fluid flow and heat transfer.

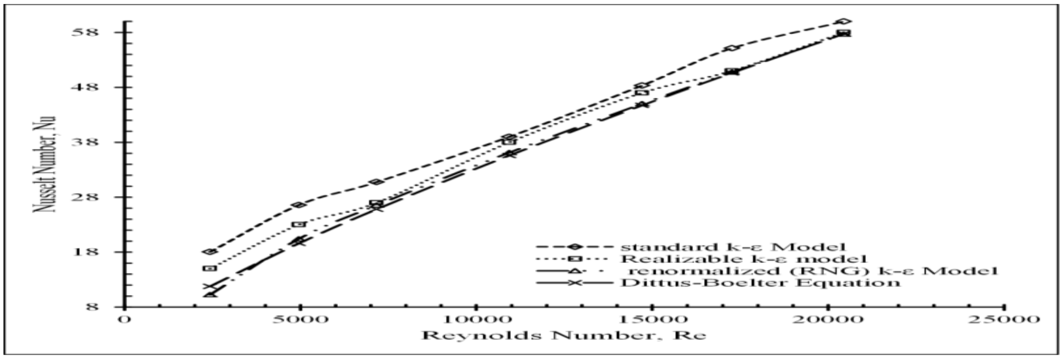


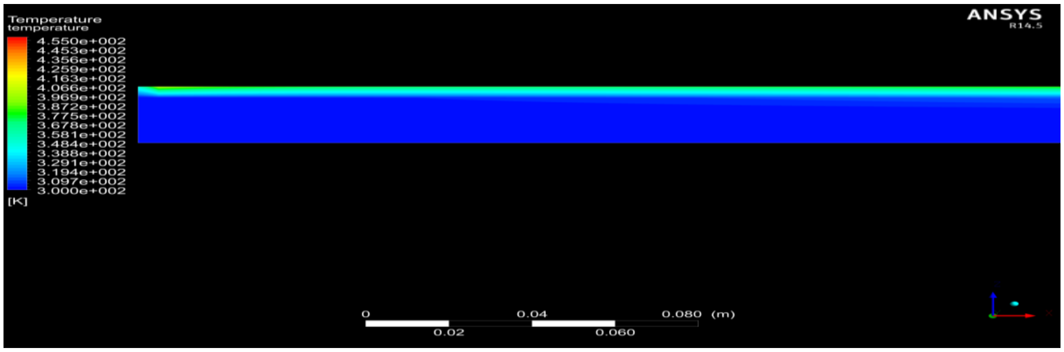
Figure 3 Comparison of predicted values of different models with values of Dittus-Boelter equation

5. Results andDiscussion

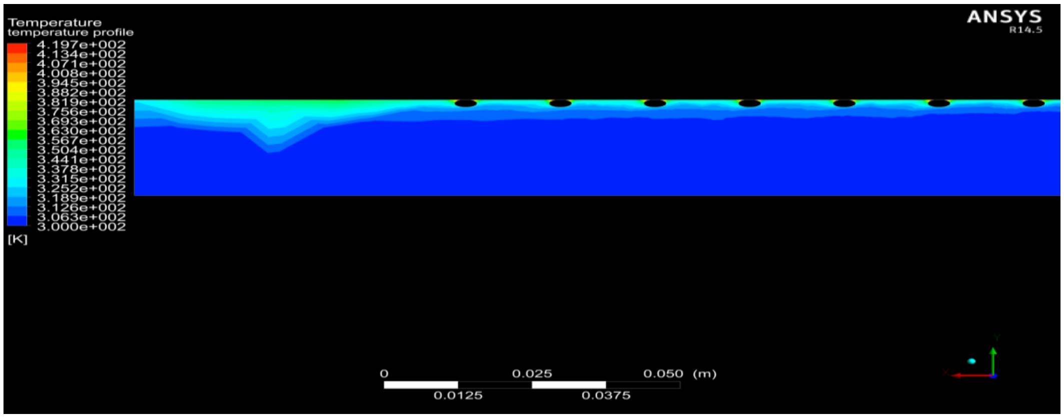
The major objectives of the present investigation is to see the effects of 'S' shape rib roughened solar air heater duct with the help of Computational fluid dynamics (CFD) software on heat transfer and friction factor.

5.1 Temperature Profile (Heat Transfer)

In most of the practical application fluid flow is generally turbulent in nature and the velocity of the fluid particles near to the boundary surface is almost zero in this region the kinetic energy of the particles is very low. This region with lowest kinetic energy is called laminar sub-layer. As the thermal conductivity of air is very low and therefore laminar sub-layer act as the barrier for heat transfer from heated surface to fluid medium. So by using the ribs in 'S' shape on underside of heated surface disturbs the flow and breaks the laminar sub-layer leading to the rise in heat transfer. Figure 4 (a and b) shows the temperature profile for smooth and roughened duct. It is clearly seen from the Figure 4 that by using the roughness on underside of the heated surface temperature distribution is more i.e. extended over a larger area as compared to the smooth surface which is due to the breaking of boundary sub-layer by obstruction caused by rib elements.



(a)



(b)

Figure 4 temperature distributions for (a) smooth surface (b) Roughened Surface

5.2 Velocity Profile

Figure 5 shows the velocity profile over the roughened heated surface. It is seen from the figure that temperature of air along the rib surface is more which is due to the fact that obstruction in flow passage results in the formation of secondary flow which in turn leads to the acceleration of fluid flow. This acceleration of fluid flow increases the kinetic energy of fluid near to the surface and leads to the enhancement in heat transfer. Also the formation of secondary flow increases the obstruction in fluid flow and leads to the significant rise in the flow friction which is not desired. The pressure along the length of duct due to presence of ribs is shown in Figure 6. It is clearly seen from the Figure 6 that there is decrease in the fluid pressure along the duct length hence it increases the power required for the pumping of fluid which is not desired.

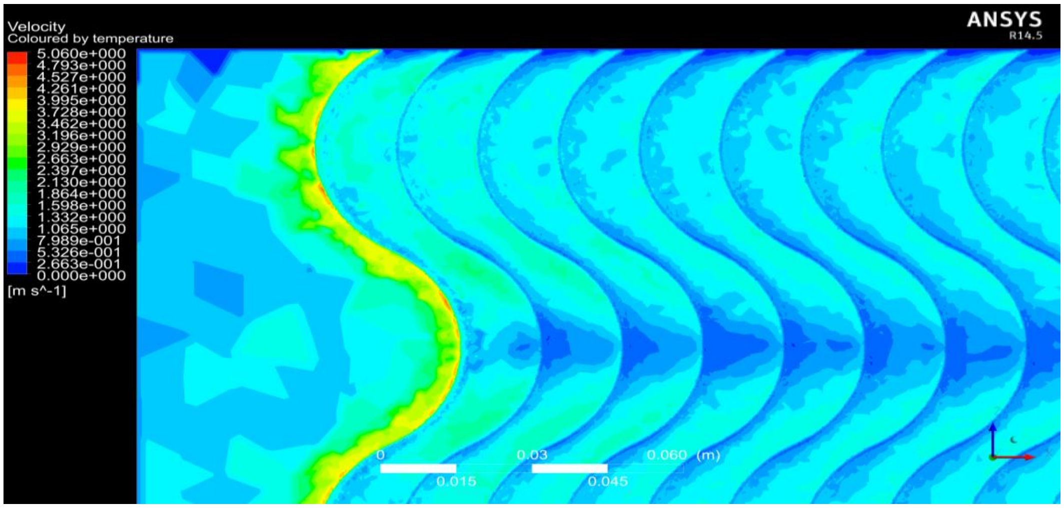


Figure 5 Velocity profile colored by temperature

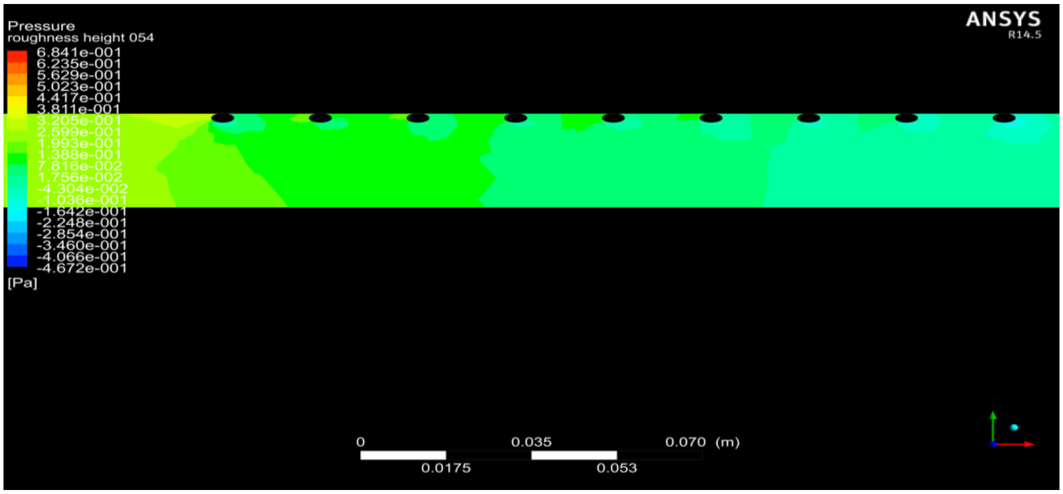


Figure 6 Pressure distributions along the duct length

5.3 Enhancement in Nusselt number and friction factor

The experimental and CFD results of the Nusselt number ratios (Nu/Nu_S) as a function of Reynolds number for 'S' shaped rib roughness geometry are shown in the Figure 7. It is observedfrom the Figure 7that the CFD values and experimental values of Nusselt number are very close to each other. It has been observed that Nusselt number ratio (Nu/Nus) increases monotonically with increase in Reynolds number and the maximum value of Nusselt number ratio corresponding to Reynolds number value of 15000.

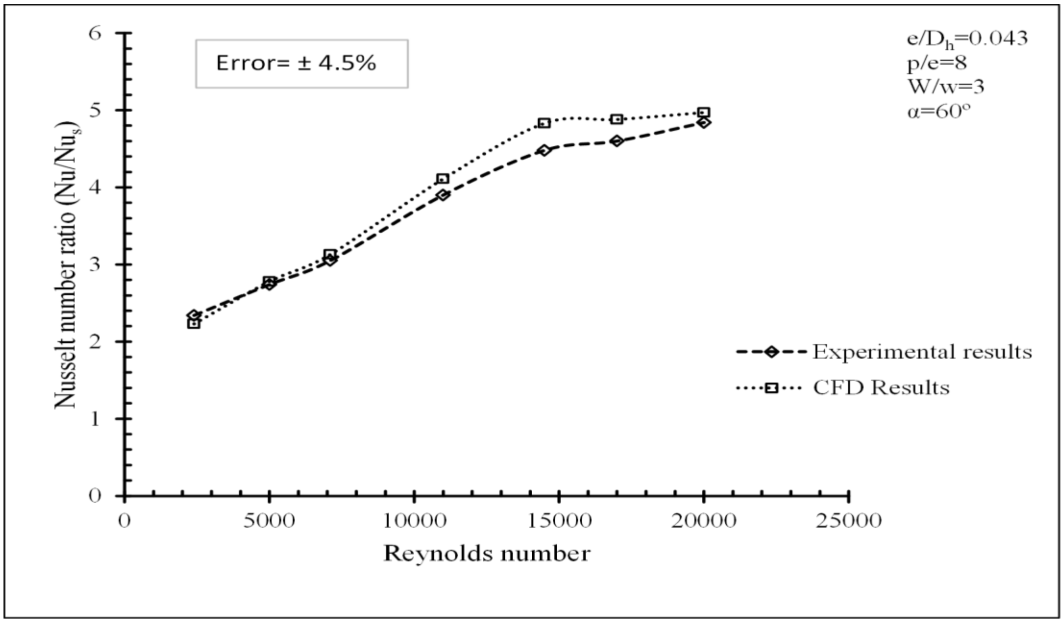


Figure 7 Nusselt number ratios (Nu/Nus)

The experimental and CFD results of the friction factor ratio (f/f_s) as a function of Reynolds number for ‘S’ shaped rib geometry are shown in the Figure 8. It is observed that the CFD values and experimental values of friction factor (pressure drop) are very close to each other and friction factor ratio increases with the rise in Reynolds number.

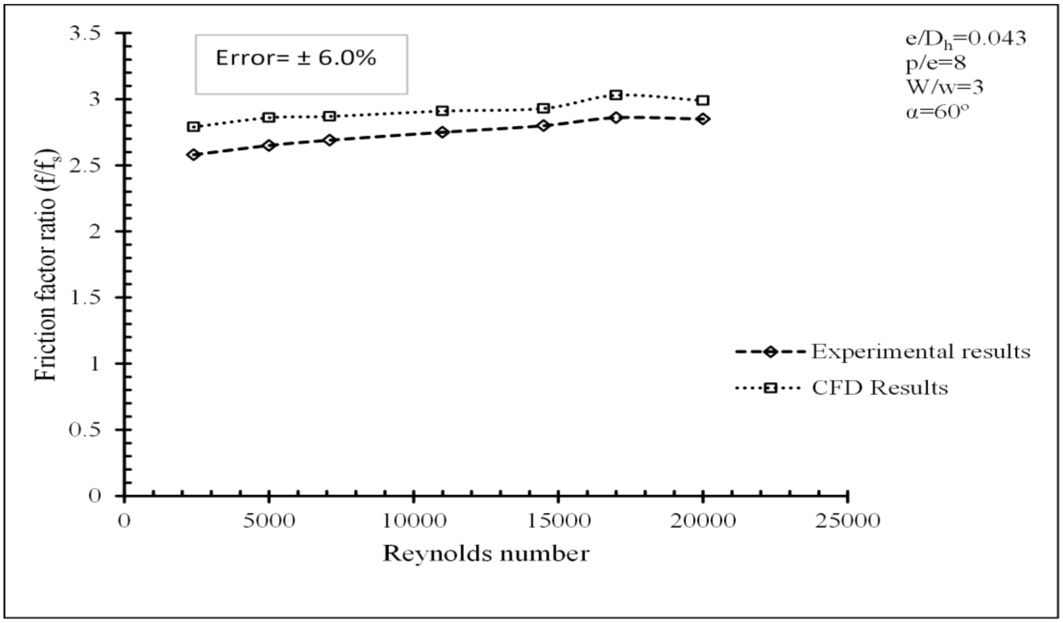


Figure 8 friction factor ratios (f/fs)

4. Conclusions

On the basis of Computational fluid dynamics (CFD) analysis of heat transfer and friction factor characteristics of the solar air heater duct with ‘S’ shaped rib roughness geometry on the absorber plate. The enhancements in heat transfer and friction factor arefound to be increased by 2.86 and 3.03 times respectively as compared to that of the smooth surface. CFD results obtained by using different CFD modelswere also compared with Dittus-Boelter empirical relationship for the smooth duct and it is concluded that among all the models used, Renormalization k-epsilon model results have been found to have good agreement with the empirical results.

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