Asian Journal of Applied Science and Technology (AJAST)
(Open Access Quarterly International Journal) Volume 2, Issue 3, Pages 73-82, July-September 2018

CFD Analysis of Solar Air Heater Roughened With Crown Shape Roughness

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Article Received: 20 April 2018 *Article Accepted: 29 July 2018* *Article Published: 24 August 2018*

ABSTRACT

Solar air heater is a device which is used to trap incoming solar radiations from the sun but the efficiency of solar air heater is low because of low value of heat transfer coefficient of air so the roughness is provided at the bottom of the absorber plate so as to increase the value of heat transfer. So, here we have used the crown shape roughness to increase the heat transfer rate. The parameters used are: heat flux of 1000W/m2, Reynolds number (Re) ranging between 2000and 20,000 and the relative roughness pitch (p/e) used are 10, 15, 20, 25mm at various rib heights: 0.8,1.2,1.8 and 2.2mm respectively. The duct size and depth are 640mm and 20mm, hydraulic depth is 33.33mm and angle of attack used are 350, 450 and 550.The heat transfer and friction factor values obtained are compared with those of smooth duct under similar flow conditions. Investigation shows that better performance is achieved by reducing the friction factor and increasing the Nusselt number. The average variation in the Nusselt number and friction factor in the range of 3.386632 - 4.823277 and 1.776364 - 1.937077 times of the results of Smooth Duct respectively.

Keywords: Sola air heater, Artificial roughness, Reynolds number.

1. INTRODUCTION

Solar energy is one of the type of renewable energy that is received from the sun. This solar energy has got today utmost importance as it is harnessed from the sun directly by certain devices such as photovoltaic systems, concentrated solar power and solar water heating, space heating of a building etc. The sun's radiation is the input part and this energy is processed in devices to get useful output such as water heating or room heating. There are several devices like solar water heater[1-2] and solar air heater[3-4] are used to harness the solar energy. Many researchers have conducted numerical study of solar air heater[5-9]. CFD is a vital tool to analyze thermal systems [10-11].

Kumar et.al [12] carried out 3D CFD investigation of solar air heater using broken curved ribs and concluded that these ribs augmented thermo-hydraulic performance. Gupta and Varshney [13] carried out CFD study of solar air heater, they concluded that by incorporation of sectioned tapered rib thermal performance of Solar air heater enhances. Gupta et.al [14] concluded that transverse ribs enhance the heat transfer rate of air flowing in solar air heater duct.

2. METHODOLOGY

This paper is an attempt to bridge this gap by presenting a detailed CFD investigation of artificially roughened solar air heater having roughness on the absorber plate. The main advantage of CFD simulation is that any complex geometry and any range of flow/roughness parameters can be implemented to predict the performance of an artificially roughened solar air heater, which cannot be done through experimental investigations.

The main objectives of the present CFD analysis are:

1. To investigate the effect of flow and roughness parameters on average heat transfer and flow friction characteristics of an artificially roughened solar air heater.

2. To find out optimal configuration of different type geometry through the artificially roughened solar air heater. The commercial finite-volume based CFD code ANSYS, has been used to simulate fluid dynamics and heat transfer.

2.1 Meshing

In the section design method is used for creating the model of solar rectangular duct. Firstly rectangular duct design in smooth model is created because we have to check and compare the heat transfer results with theoretical heat transfer equation and validation paper. In second section rectangular duct is designed with roughness as Crown shaped rib. The crown shape roughness ribs are designed with modification in the parameters of the angle of attack, crown ribs height, and space between crown ribs. These crown roughness ribs are investigated to create the heat transfer rate and the transition of warm air to turbulent flow from laminar because the turbulent flow of warm air is more effective for high thermal performance. The rectangular channel is design in x-y zone and in x-axis the duct's length is L = 640 mm and in y-axis the solar duct's height is H = 20 mm. Uniform heat flux I = 1000 w/m^2 is given to the model mathematical calculation. There are some variation in the crown shaped roughness rib like height of the crown ribs, e = 0.8 mm, 1.2 mm, 1.8 mm, and 2.2 mm. the variation in height is used for increasing the reattachment zone of the warm air with surface of the model and another variation angles of attack θ = 35°, 45°, and 55°for more circulation of air, reduce the pressure drop and friction factors. It is also used for reducing the wear problem.

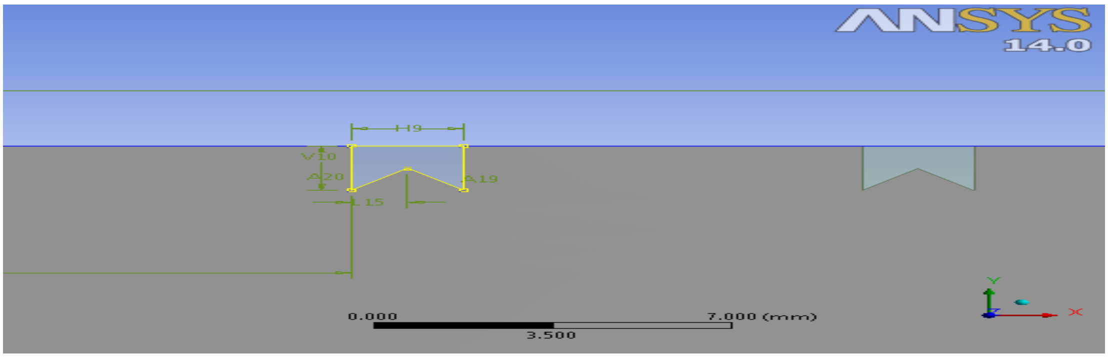

Fig 1- Design of crown shape rib roughness

2.2 Parameters Range and values

S. NO.	PARAMETERS	RANGE OF VALUES
1	Duct Total Length, L	640mm
2	Duct Entrance Length, L1 Duct Test Length, L2 Exit Length, L3	180 mm 350 mm 110 mm
3	Duct Width, W	100mm
4	Duct Height, H	20mm

5	Hydraulic Diameter, D_h	33.33mm
6	Pitch (Relative Roughness), p/e	4.54 – 31.25
7	Height (Relative Roughness), e/D_h	0.024, 0.036, 0.054 and 0.066
8	dimple and boot shaped Height, e	0.8mm, 1.2 mm, 1.8mm, and 2.2mm
9	Uniform Heat Flux, I	$1000 w/m^2$
10	Reynolds Number, Re	2000 to 20000 with interval of 2000
11	Prandtl Number, Pr	0.707
12	Crown shaped rib angle of attack, θ	35°, 45° and 55°
13	Pitch space between the crown roughness, P	10 mm, 15 mm, 20 mm, 25 mm

2.3 Verification

Grid Independence Test-Grid independence test method is used after the mesh generation section. Mesh generation is required for different types of results and heat transfer enhancement but for accurate meshing as well as results there is a need for grid independence test. For finding grid independence test, we did meshing of the rectangular duct until the mesh where change in the number of cells and nodes did not rely upon the results, that means this test is a meshing on which mesh did not depend on each-other. This grid is called grid independence test and at this point mesh is accurate and found accurate results. It is also known as refinement method of meshing. In this method grid independence test mesh originate as number of cells = 127884 and number of nodes = 129909.As depicted in table after 12990 numbers of nodes, the change in the value of heat transfer is negligible or did not depend upon the meshing test. Therefore, the further analysis with the use of meshes with 129909 nodes and number of elements are used for grid independence test 127884.

Grid independence test for rectangular duct with crown-shape roughness

S. No.	Number of nodes	Number of cells	Nusselt number
1	66078	58882	76.0890
2	100655	96959	25.2137
3	129909	127884	38.4570
4	133900	123859	38.3271

2.4 Validation

The current numerical analysis of the designed solar rectangular duct is validated with reference to the results of the research paper "Thermo-hydraulic performance analysis of the equilateral triangle ribs in rectangular channel" which is presented by **Yadav and J.L.Bhagoria [15]**. So, the number of parameters is taken from the research paper. The numerical data is utilized to arrive at the heat transfer from two-dimensional model. The geometric modeling of the rectangular duct having dimensions- 640mm×100mm×20mm, have been used and observed and the results of Nusselt numbers and friction factors have been obtained in the range of Reynolds numbers (2000 - 20000). Results obtained from numerical investigation are plotted as a function of Nusselt number and Reynolds number as shown in Figure. Numerical results are plotted against the experimental results and found deviation of 5 % which is considerable for numerical results obtained by using CFD (fluent) analysis. Maximum Nusselt number of Smooth duct is 51.7718 and the validation Nusselt number of Research paper is 46.11938.

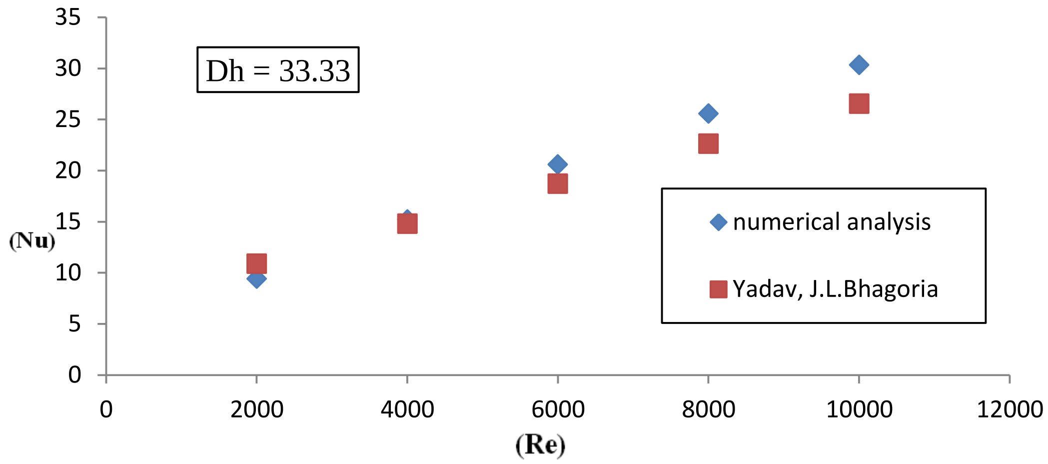

Fig-2-Validation of numerical analysis with CFD results Bhagoria

3. RESULTS AND DISCUSSION

The numerical analysis of rectangular solar duct with crown shaped roughness ribs are performed by the CFD. The results of the model depend upon the variation of the roughness like crown rib height variation, e = 0.8 mm, 1.2 mm, 1.8 mm and 2.2 mm, change in the angle of attack of the crown shape roughness, θ = 35°, 45°, and 55°, variation in the pitch space between the crown ribs, p = 10 mm, 15mm, 20 mm, and 25 mm, and variation in the pitch height to hydraulic diameter ratio, e/ D_h = 0.024, 0.036, 0.054 and 0.066. So these variations are more effective for the heat transfer rate and all characteristics of the solar air heater. The air enters in the rectangular solar duct and transmitted from laminar flow to turbulent flow around the roughness and gets warm by using the heat transfer rate around the solar air heater. The characteristics of the heat transfer rate changes in the following terms like temperature contour, turbulent kinetic energy, Nusselt numbers, friction factors and thermal performance of the solar air heater.

3.1. Temperature Contour

The figure 3 showed the variation in the temperature of the rectangular duct with crown rib roughness. The inlet temperature T = 300 k but roughness height e = 2.2 mm is increased the temperature also increased so the temperature at outlet T_o = 339 k at the angle of the crown ribs θ = 55° and relative pitch ratio p/e = 4.54

 Online ISSN: 2456-883X

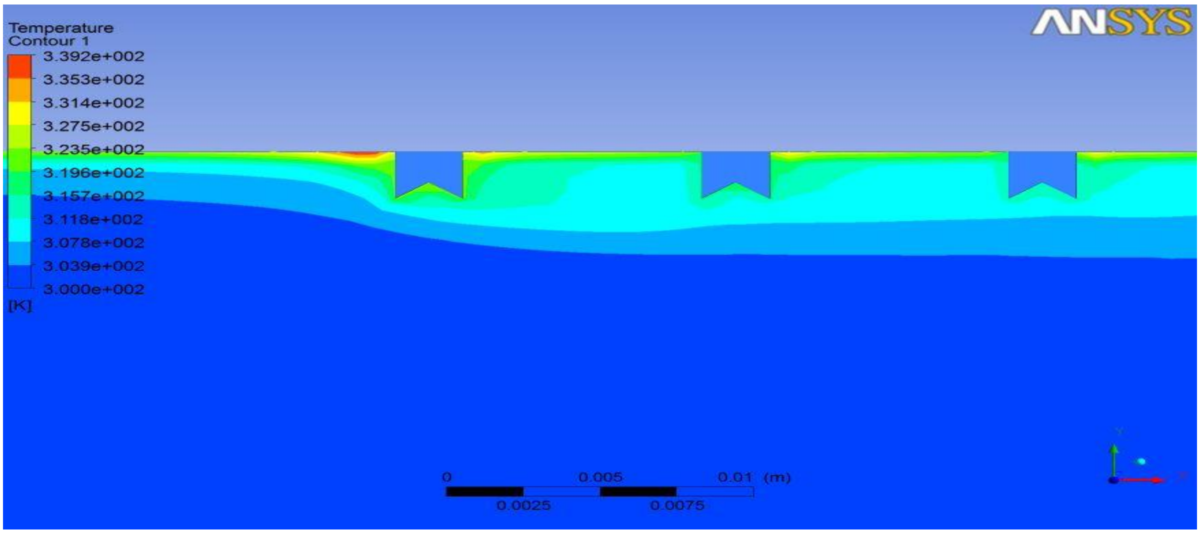

Fig 3-the variation in the temperature around the solar rectangular with crown ribs at the angle of attack θ = 55° and height of the ribs e = 2.2 mm.

3.2. Turbulent Kinetic Energy

Turbulent kinetic energy is a process to increase the enhancement of heat transfer. Turbulent kinetic energy is dependent upon the circulation velocity of the warm air which is used in the solar rectangular duct. Turbulent kinetic energy is increased with increased in the Reynolds number. The reattachment zone of the air and transition mass flow rate circulates around the surface of the duct. It becomes potent when roughness parameters (height of the crown ribs e = 2.2 mm and variation in the angle of attack θ = 55°, 45°, and 35°) are used in the duct for increasing the heat transfer coefficient and friction factor as well as turbulent kinetic energy also increased. This turbulent kinetic energy is examined to improve the solar thermal power. The turbulent kinetic energy is increased at the decreased in the angle of the crown because air is trapped in the center of the crown roughness rib and it circulated in the roughness region which is effective to transfer the energy in the duct.

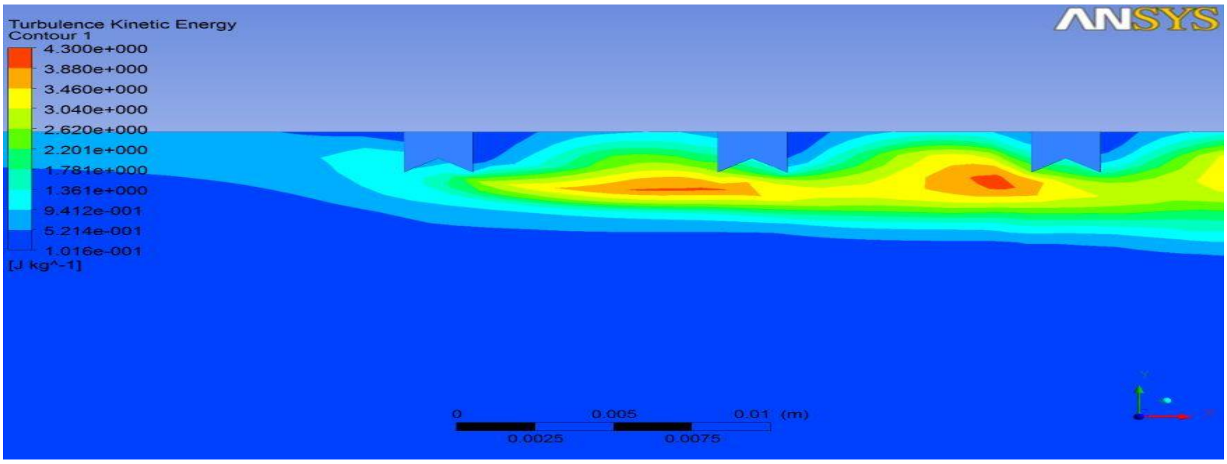

Fig4- the variation in the turbulent kinetic energy around the solar rectangular with crown ribs at the angle of attack θ = 55° and height of the ribs e = 2.2 mm

3.3 Effects of the Crown Rib Roughness in Solar Rectangular Duct and Reynolds Number on The Heat Transfer Characteristic

In this section the numerical analysis is investigated and explained as shown figure below. The figure plotted between the Nusselt number and Reynolds number that mean heat transfer changes with the variation of Reynolds number. The flow of thermal energy from one region without inserted roughness to the region with inserted roughness is known as heat transfer. The heat transfer is circulated and effective around the surface of the solar air heater. We can see maximum time all the results depend upon the variation in the Reynolds number Re = 2000, 4000, 6000, 8000, 10000, 12000, 14000, 18000, and 20000 of the working fluid and all the heat transfer characteristics consolidated the rectangular duct. In second step results also manipulated by the variation the height of the crown rib roughness e = 0.8 mm, 1.2 mm, 1.8 mm and 2.2. These variations of the crown rib impinged on the heat transfer rate and friction factors. We can see that when the height of the crown increased than the results are also increasing and the maximum results achieved at e = 2.2. Another variation in the angle of the crown rib roughness θ = 35°, θ = 45°, and θ = 55 ° and heat transfer rate also increased with increased in the space p = 10, 15, 20, and 25 between the crown rib roughness.

Figure 4 shows the comparison between the Nusselt numbers and Reynolds numbers (Re = 2000 – 20000) for different values of the relative roughness pitch, p/e = 4.54, 6.75, 9.09, and 11.36 and at the fixed values height of the crown rib roughness e = 2.2 mm, hydraulic pitch roughness e/D_h = 0.66 and angle of attack θ = 55°. The maximum Nusselt number is Nu = 249.8125 because at Re = 20000, p/e = 4.54 maximum heat transfer rate produced around the surface of the rectangular duct. The minimum Nusselt number is 208.3622 at p/e = 11.36 at this relative roughness pitch p/e low turbulence flow achieved and at p/e = 6.75 and p/e = 9.09 are the Nusselt number Nu = 231.4406and Nu = 219.3252 respectively.

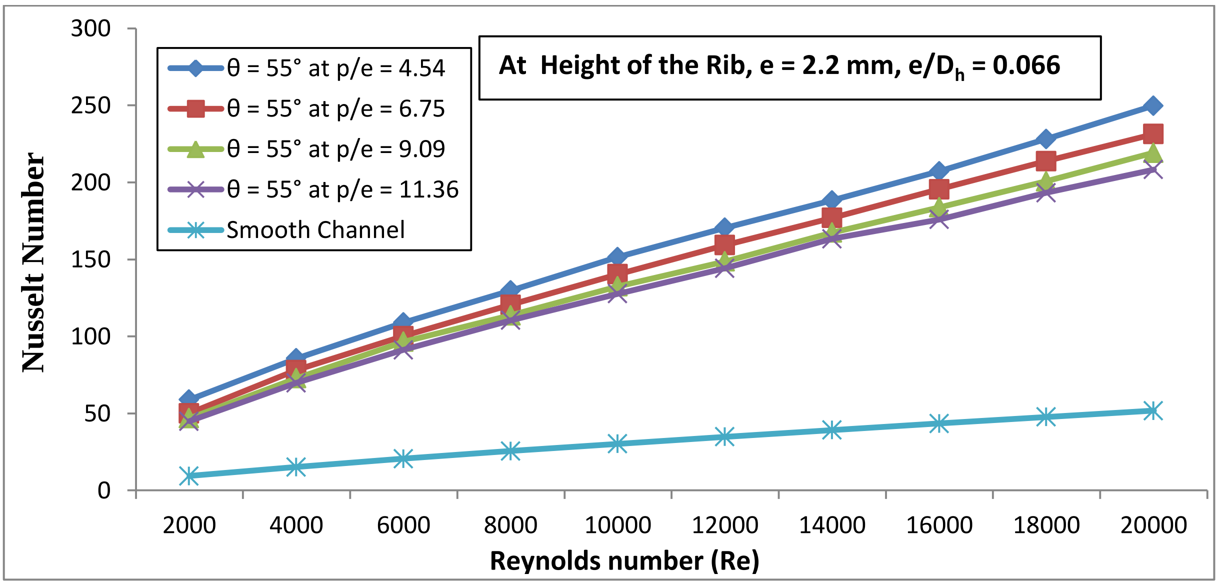

Fig. 4 Variation in the heat transfer rate as Nusselt numbers with Reynolds number (Re = 2000 – 20000) for different values of relative roughness pitch (p/e= 4.54– 11.36) at the angle of the crown θ = 55° and height of the crown ribs e = 2.2mm.

3.4 Friction Factor Of The Solar Air Heater

In this section friction factors are presented in the solar air heater with the variation in the Reynolds numbers Re 2000, 4000, 6000, 8000, 10000, 12000, 14000, 16000, 18000, and 20000. Variation in the height of the crown rib roughness e = 0.8 mm, 1.2 mm, 1.8 mm, and 2.2 mm which is used in the Smooth duct after that friction factors increased. In the above figure we examined that maximum heat transfer rate at e = 2.2 mm but in case of friction we analyses that friction factors also increased and at e = 0.8 minimum friction achieved which is explained in the following figures below. The figure 5 shows the minimum friction factor Fr =0.007599684 of the overall solar air heater at all variation in the Reynolds number, relative pitch roughness, height of the rib e = 0.8 mm, angle of the crown rib θ = 35°, and e/D_h = 0.024 and maximum friction factor fr = 0.015441503 at p/e = 12.5.

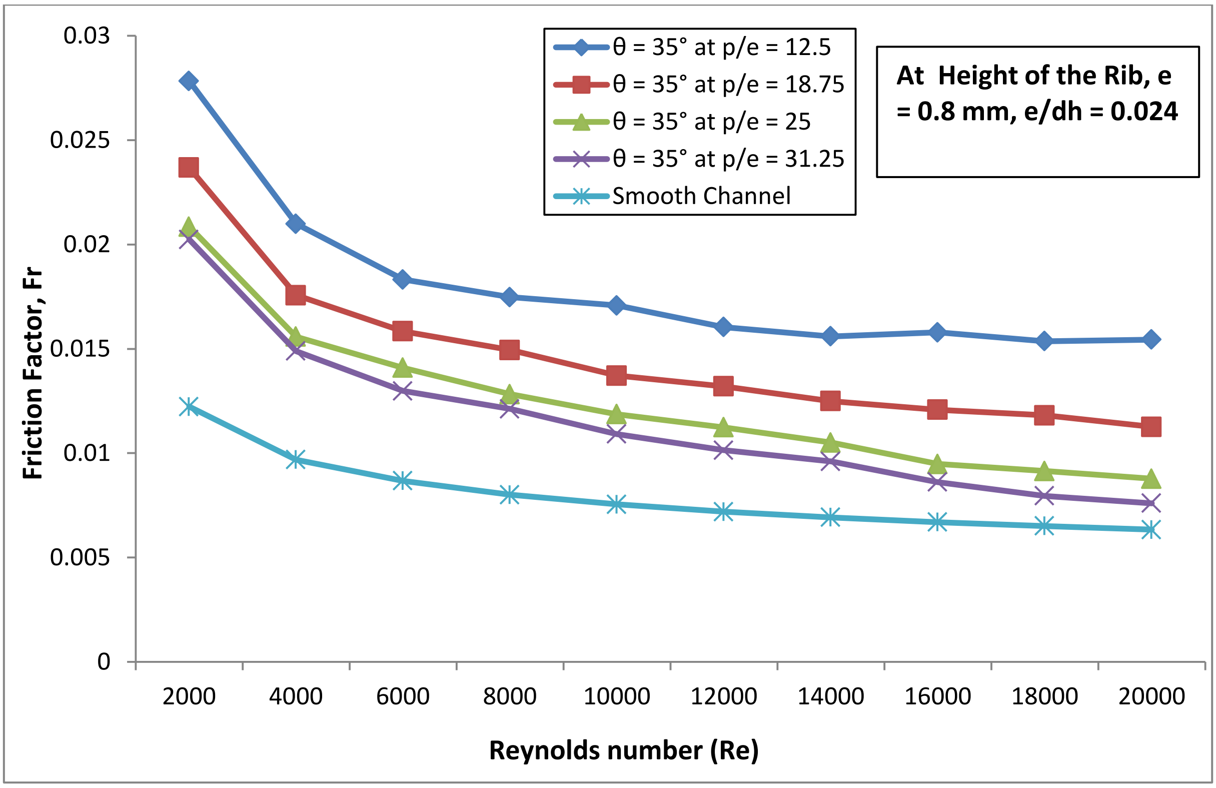

Fig. 5 variation in the friction factor with Reynolds Number Re = 2000 – 20000 at p/e = 12.5 – 31.25 and various fixed values e = 0.8 mm, e/D_h = 0.024 and crown rib angle θ = 35°.

3.5 Thermo – Hydraulic Performance

Thermal – hydraulic performance of the solar rectangular air heater is calculated and examined by the overall numerical analysis with crown shape rib roughness and without roughness. Thermal hydraulic performance explains the average heat transfer characteristic and friction factor coefficient under the all condition which is shown in above following figures. This performance is effective to generate the natural energy into thermal power for the solar air heater without any damage and loss of energy. The design of the solar air heater and its numerical analysis is usable for natural working fluid and Thermal performance of a solar air heater is explained by Web band Eckert Thermo-hydraulic performance in which presented heat transfer enhancement is more effective in case of roughness and in case of smooth duct. The thermal performance THPP = 3.443909204 of the rectangular solar duct is examined from the above results which are discussed.

$$\eta = \frac{(Nu_r/Nu_s)}{(f_r/f_s)^{\frac{1}{3}}}$$

The figure 6 shows variation the thermal hydraulic performance according to the change in the Reynolds number Re = 2000 – 20000. The maximum THPP = 3.443909204 at maximum height of the crown shaped rib roughness e = 2.2 mm, angle of the crown θ = 55° and p/e = 4.54.

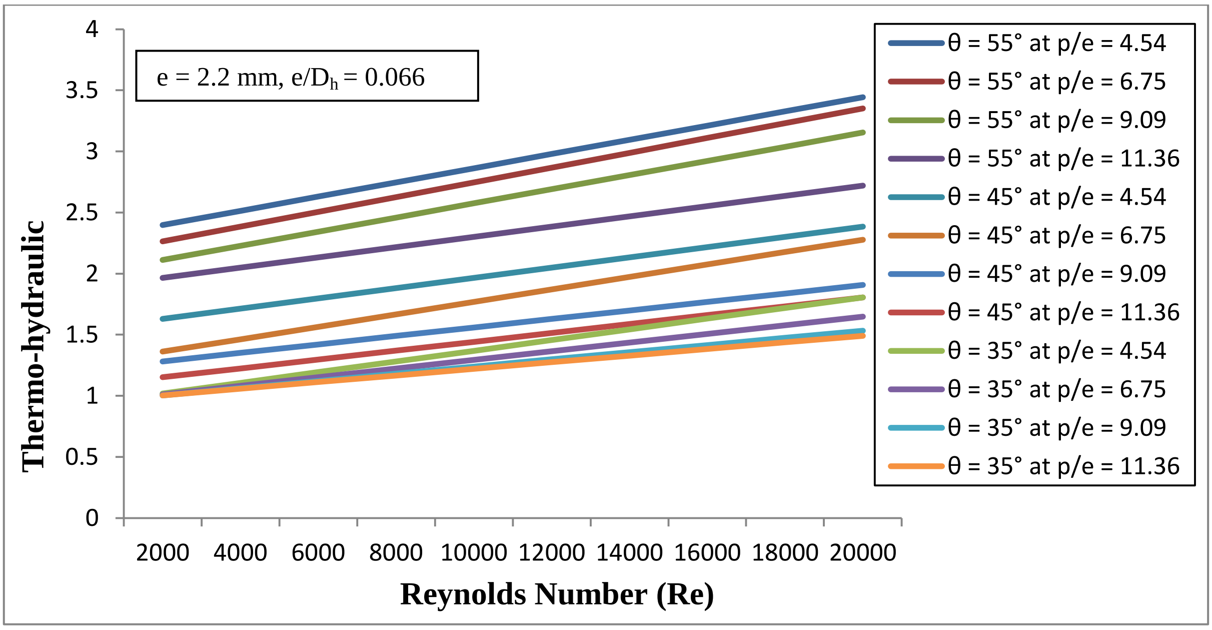

Fig. 6 shows the variation in the thermal hydraulic performance at different relative pitch roughness p/e = 4.54 – 11.36, angle of the crown θ = 35°, θ = 45° and θ = 55° and e = 2.2 mm.

4. CONCLUSION

The numerical investigations of the rectangular solar duct with crown rib roughness were conducted by the CFD. in this research work numbers of variation are taken to change the effect of heat transfer rate like variation in the relative pitch roughness p/e = 4.54 – 31.25 and there relative roughness ribs are based on the space between the crown ribs p = 10, 15, 20, and 25, height of the crown ribs e = 0.8 mm, 1.2 mm, 1.8 mm and 2.2 mm. some other factors taken as variation in Reynolds number Re = 2000, 4000, 6000, 8000, 10000, 12000, 14000,16000, 18000 and 20000 and Crown angle θ = 35°, θ = 45° and θ = 55° and these variations has been used to calculate the comparison between Nusselt number, friction factor and thermal hydraulic performance. The following conclusion is drawn from the present study of the rectangular solar air heater.

(1) Renormalizing group (RNG) turbulent model estimated for the accurate results which are done by the CFD.

(2) All range of the Nusselt number, friction factor and thermal hydraulic performance increase with increase in the height of the Crown ribs roughness.

(3) Nusselt number and friction factors are highest at decreasing in the relative pitch roughness, P/e and increasing in the angle of the crown rib roughness.

(4) The average variation in the Nusselt number and friction factor in the range of 3.386632 - 4.823277 and 1.776364 - 1.937077 times of the results of Smooth Duct respectively.

(5) The maximum heat transfer enhancement is obtained Nu = 249.8125 at height of the crown rib roughness e = 2.2 mm, angle of the crown θ = 55°, p/e = 4.54 and Reynold number Re = 20000.

(6) The lowest friction factor is obtained Fr = 0.00759968 at height of the crown rib roughness e = 0.8 mm, Crown angle θ = 35°, p/e = 31.25 and Reynold number Re = 20000.

(7) The highest thermal performance was obtained THPP = 3.443909204 at Reynold number Re = 20000, p/e = 4.54, e = 2.2 mm and Crown angle θ = 55°.

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