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A CFD Based Thermal Analysis of Solar Air Heater Duct Artificially Roughened With 'S' Shape Ribs on Absorber Plate

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ABSTRACT: In the present work performance of solar air heater duct provided with artificial roughness in the form of 'S' shaped ribs geometry has been analyzed using CFD. The main objective is to increase the heat transfer rate by providing artificial roughness over the absorber plate. The effect of 'S' shaped ribs geometry on Nusselt number, friction factor and performance enhancement are investigated for relevant Reynolds number ranging from 6000-18000. Different turbulent models have been used for solving the problem and the results are then compared with Dittus-Boelter equation. Renormalization-group (RNG) k-ε model-based results have been found in good agreement with Dittus – Boelter equation and accordingly this model is used to predict heat transfer and friction factor in the duct. It has been observed that with a uniform heat flux of 1000 W/m^2 the maximum thermo-hydraulic performance ratio is found to be 1.48 at a particular Reynolds number.

KEYWORDS: CFD Analysis, Solar Air Heater Duct,Artificial Roughness, Absorber Plate, Reynolds number, thermo-hydraulic performance.

I. INTRODUCTION& LITERATURE SURVEY

In the environment, huge amount of solar energy is present which can be used as an energy resource. So, for the society, the utilization of solar air heater has become one of the most important topics for the research field. In the thermal system, solar air heater is extensively utilized for the purpose of heating like space heating, winter home heating, drying of crops, seasoning of timber etc. Since it works as heat exchanger where heat is transfer from absorber plate to air and the convective heat transfer coefficient between the air and absorber plate is quite low due to that thermal performance of solar air heater is low. So, it is need to improve heat transfer in the duct. There is lots of techniques are available to increase heat transfer. But among them, one of the easiest ways to increase performance of solar air heater by providing artificial roughness on absorber plate. In the absorber plate by providing protrusions, fixing ribs and different type of shape can make it rough. Whereas ribs on absorber plate as an artificial roughness can disturb the laminar sub layer and produce turbulence in the flow of air which can help to enhance the performance of solar air heater. This arrangement also increases the pumping power requirement of air because of increase in friction in the duct. Lots of experiment has conducted to analyses the consequences of providing artificial roughness in absorber plate for the heat transfer and the flow characteristic.

Bhushan and Singh [1] have analyses that solar air heater has very low thermal efficiency because of low thermal conductivity but its construction and utilization is very easy. Kumar et al [2] investigated that laminar sub layer form in the region of heat transferring surface, cause very low thermal conductivity and need to provide artificial roughness so that it can break laminar sub layer in the region of heat transferring surface so that heat transfer coefficient get improved. Varun et al [3] investigated that to improve heat transfer, many researchers have provided ribs, fins, wire mesh, baffles and different type of shape on the absorber plate as an artificial roughness but along with improve in heat transfer coefficient, friction factor also increased due to that pumping power of air get increased. Prasad and Saini [4] present a paper having protrusion as the shape of small diameter wires on the absorber plate and investigate that for similar roughness geometry get similar effect on thermal performance as well as heat transfer and friction factor. Saini and Verma [5] present experimental analysis on Nusselt number and friction factor characteristic of solar air heater duct having artificial roughness as dimple shaped geometry on absorber plate. They concluded that at a relative roughness height of 0.039 and relative roughness pitch of 10 gets maximum value of Nusselt number. They also evaluate friction factor of minimum value at relative roughness height of 0.0289 and relative

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roughness pitch of 10. Singh et al. [6] this paper present experimentally on the heat transfer characteristic having rectangular duct with V-down ribs periodically on the absorber plate. They evaluate highest value of Nusselt number and friction factor at relative roughness pitch of 8. Tanda [7] have experimentally found the correlation of Nusselt number and friction factor having rectangular duct with roughened absorber plate. He investigates with angled continuous ribs, discrete v-shaped ribs, transverse continuous and broken ribs and finally concluded that transverse broken ribs are the most promising developing technique for enhancement of heat transfer. Kumar et al [8] this paper experimentally analyses the characteristic of heat transfer and friction factor of solar air heater having discrete w-shaped geometry as artificial roughness on one wall. Authors compared the result with smooth duct having angle of attack 600 and relative roughness height of 0.0388 and found 2.16 and 2.75 times more value of Nusselt number and friction factor providing with artificial roughness. Gupta and Kaushik [9] experimentally investigated that a solar air heater having rectangular duct with expanded metal mesh as artificial roughness, found out variation of Nusselt number and friction factor. Kumar and Saini [10] this paper investigate the characteristic of heat transfer and fluid flow of solar air heater having rectangular duct with arc shape geometry as artificial roughness on absorber plate. This analysis has been conducted in 3- D model on CFD. Author have kept wall smooth other than absorber plate. They have tried different turbulence model like realizable k-ε , renormalization group (RNG) k-ε , standard k-ε , and shear stress transport k-ε on smooth duct as well as roughened absorber plate of solar air heater and concluded that RNG k-ε have given the proper result and get maximum value of Nusselt number. Sharma and Thakur [12] a CFD based analysis of V shaped ribs geometry provided on the underside of the absorber plate with relative angle of 600 in the direction of flow have worked to investigate the Nusselt number and friction factor. Simulations have conducted with SIMPLE algorithm for air flow by finite volume method. The value of Nusselt number and friction factor have compared with smooth duct and validate it with fully developed turbulence flow forced convection. Khushmeet et al [13] carried out experimentally correlation of heat transfer and friction factor having arc shaped wires ribs in the form of 's' shaped geometry on the absorber plate for a relative roughness pitch of 4-16, relative roughness width of 1-4 and relative roughness height of 0.022-0.054 for a particular range of Reynolds number. Author have evaluated the maximum deviation of Nusselt number and Friction factor are ± 10.8 % and ± 10 % respectively.

After going through literature survey, it is concluded that heat transfer and friction factor have sufficiently enhanced by providing various shape and geometry as artificial roughness on the absorber plate. Among various shape and geometry, I found very less research on arc shaped ribs but arc shaped geometry become one of the effective techniques to increase the heat transfer which lead to increase in Nusselt number as well as friction factor. The following aims of present CFD analysis are; I. Investigate the roughness effect on absorber plate of solar air heater by heat transfer coefficient and friction factor II. Comparison of analytical result of thermal performance of roughened solar air heater to the smooth solar air heater.

II. CFD INVESTIGATION

Mathematical modeling ANSYS FLUENT 19.2 has been used for CFD analysis to simulate roughness effect of solar air heater. In this analysis, we have taken flow as steady and incompressible. There is no slip boundary condition with wall to air. With increase in temperature of roughness material and duct wall, the thermal conductivity does not change. We have taken homogenous and isotropic roughness material and duct wall.

2.1 Computational domain and meshing:

Fig.1 shows an absorber plate is modeled in ANSYS FLUENT 19.2, having 'S' shape rib roughness over the plate. Ribs conforming meshing having polyhedral materials with medium grain size method of computational domain along with enlarged view is shown in Fig.2.

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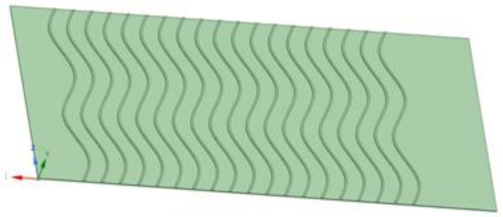

Fig.2.1 Schematic view of absorber plate

Fig.2.2 Absorber plate with Meshing

There are two zones in the computational domain. One is fluid zone where air is passing over the absorber plate whose dimensions are 1000× 300 × 40 in mm. Second zone is absorber plate having thickness of 0.5 mm, relative roughness height of 0.021, relative roughness pitch of 7.15, relative roughness width of 2 and remaining dimensions are similar to fluid zone. A uniform heat flux of 1000 w/m2 was considered for the simulation. 'S' shape ribs is considered on the top side of the absorber plate while the other surfaces are remained as smooth.

Table (1)
Thermo physical properties of air and aluminum absorber plate

Properties	Air	Aluminum
Density (ρ)	1.225 kg/m^3	2719 kg/m^3
Specific heat (Cp)	1006.43 j/kg-k	871 j/kg-k
Viscosity(μ)	1.789e-05 kg/m-s	-
Thermal conductivity (K)	0.0242 w/m-k	202.4 w/m-k

2.2 Turbulence model:

It is important to optimize the physical modeling error as well as minimize simulation time for that an appropriate turbulence model required. But it is very difficult to select perfect turbulence model because it depends on the various factor like flow behavior, boundary condition etc. A suitable model in CFD analysis can reduce the error by imperatively selection. Those turbulence model whose result comparatively closer to the existing result have taken as perfect turbulence model. After examine several turbulence models like realizable k-ε , renormalization group (RNG) k-ε , standard k-e, and shear stress transport k-ε only RNG standard k-ε turbulence model provide accurate result with experiment result of smooth duct solar air heater and in case of artificial roughened solar air heater, same turbulence mode is used. Hence for the current analysis RNG k–ε turbulence model with enhanced wall function is used to solve the transport equations.

For smooth duct

➢ Friction factor is given as [Blasius equation]

$f_s = 0.0791\ R_e^{-0.25}$ ---------(1)

➢ Nusselt number is [Dittus-Boelter equation]

$Nu_s = 0.023\ R_e^{0.8}\ p_r^{0.4}$ ---------(2)

2.3 Governing equations:

The following equations of momentum conservation, energy conservation and transport equation govern air flow and heat transfer for the model. The incompressible fluid flow and forced convection turbulence flow is to be assumed steady state with negligible heat transfer. The governing equation of three-dimensional for system is as follows.

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Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \text{ ------- } (3)$$

Navier-Stokes equations (3D in Cartesian coordinates):

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \text{-----} (4)$$

$$\rho\frac{\partial v}{\partial t}+\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial y}+\rho w\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial y}+\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right] \text{-------} (5)$$

$$\rho\frac{\partial w}{\partial t}+\rho u\frac{\partial w}{\partial x}+\rho v\frac{\partial w}{\partial y}+\rho w\frac{\partial w}{\partial z}=-\frac{\partial p}{\partial z}+\mu\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right] \text{--------} (6)$$

Equation (4), (5) and (6) are Navier-Stokes equation in three-dimension Cartesian coordinates where First term of these transport equations expressed local acceleration and other convection, Piezometric pressure gradient and Viscous terms in "x", "y" and "z" direction, respectively.

Transport equations for the k-ε model will be as under:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u)}{\partial x}=-\frac{\partial}{\partial x}\left[\left(a_k\mu_{eff}\right)\frac{\partial k}{\partial x}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \text{ ---} (7)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u)}{\partial x}=-\frac{\partial}{\partial x}\left[\left(a_\varepsilon\mu_{eff}\right)\frac{\partial \varepsilon}{\partial x}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_k \text{ ---} (8)$$

In equations (7) and (8) G_k and G_b represent turbulence kinetic energy generation due to the mean velocity gradients and buoyancy respectively. $C_1\varepsilon$, $C_2\varepsilon$ and $C_3\varepsilon$ are model constants respectively.

The other applicable non-dimensional parameters of use in CFD investigation are

- Reynolds number ($Re=\rho vD/\mu$),
- Nusselt number (Nu=hD/k)
- friction factor ($fr=\Delta PD/2\rho lv2$).
- Thermo-Hydraulic Performance Parameter

(THPP) = $\frac{\left(\frac{Nu_c}{Nu_s}\right)}{\left(\frac{f_c}{f_s}\right)^{1/3}}$

$\left(\frac{Nu_c}{Nu_s}\right)$=Nusselt Number Enhancement Ratio

$\left(\frac{f_c}{f_s}\right)^{\frac{1}{3}}$= Friction factor Enhancement Ratio

It has been noticed that the artificial roughness of 'S' shaped ribs on the absorber plate results in significant enhancement in heat transfer with a penalty of increase in the *fr*hence more pumping loss.

2.4 Boundary conditions:

A three-dimensional CFD model having two zones with an interface in between is used in ANSYS FLUENT 19.2 in the present analysis. No slip condition is applied between solid zone and interface. Steady flow conditions are taken for all CFD analysis as followed in experimental studies using pressure and velocity based implicit solver. The boundary condition for the absorber plate, side and base wall of the duct, inlet as well as outlet.Velocity of air at inlet of duct is calculated with the help of Renumberand applied it at velocity inlet face. Pressure outlet is kept at null gauge pressure. At the absorber plate uniform heat flux 1000 W/m^2 is applied and other walls are considered to be insulated. COUPLE solver Scheme is used for discretization of pressure and velocity coupling. For terminating solution in ANSYS FLUENT maximum residual values for energy equation as well as heat transfer is set to 10^{-6} and 10^{-3} for all other equations.

2.5 Domain validation:

The methodology adopted to solve the domain is validated with the help of Dittus–Boelter equation. This validation for smooth duct is modeled and simulation is done for the same boundary conditions and the obtained Nusselt numbers are then compared with the values obtained from Dittus-Boelter equation. The comparison graph is shown in Figure (2.3). It is observed that the average error between the results obtained is 3.2 %. Only a small deviation is present in the Nusselt number values from the present analysis to that of Dittus-Boelter equation. With this we can validate our method to solve the problem.

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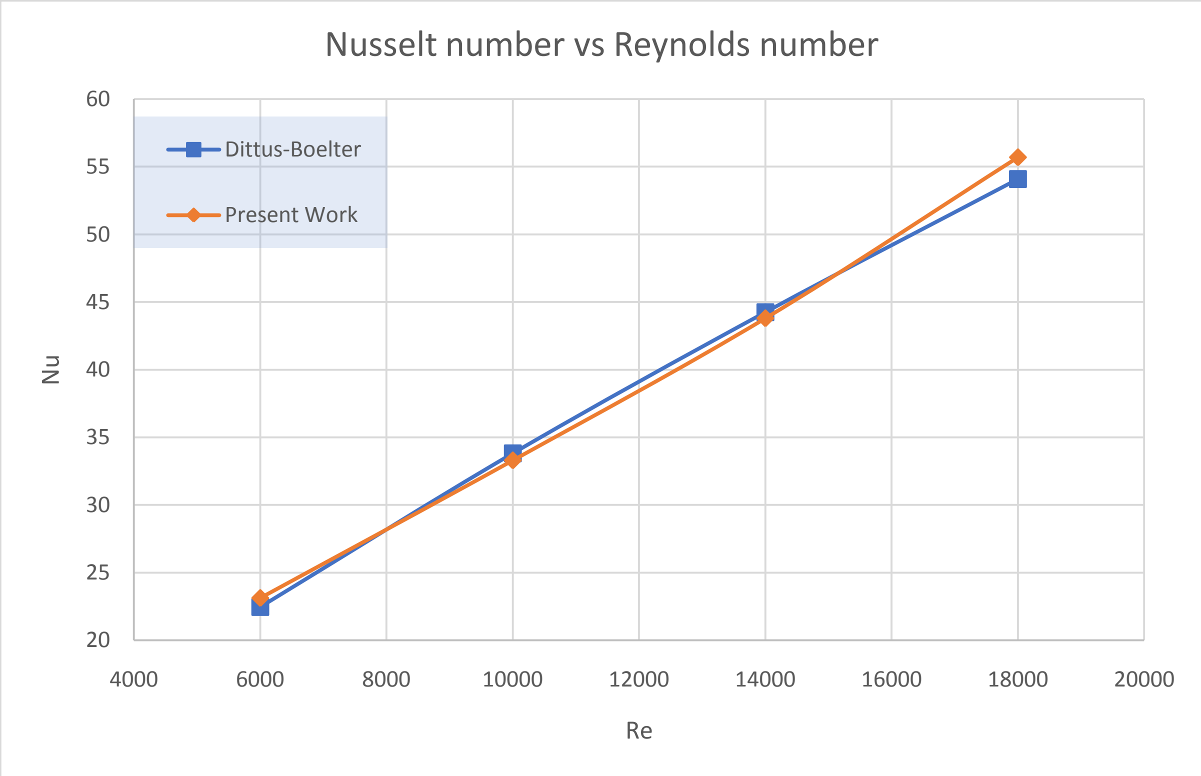

Figure 2.3: Comparison between Nusselt number predictions of CFD model with Dittus-Boelter empirical relationship for smooth duct

III. RESULTS AND DISCUSSION

The numerical investigation has been performed for artificially roughened solar air heater with 'S' shape ribs on the absorber plate and the results are expressed in this section. The average heat transfer as well as flow friction characteristics of the artificially roughened solar air heater are expressed first, and after that the effect of roughness on the flow parameters are discussed below. The results have been compared with those obtained in the case of smooth ducts, operating under similar operating conditions to discuss the enhancement in heat transfer and friction factor on account of artificial roughness. The solution is made to run until the convergence is reached along with the residuals a report plot containing outlet temperature is made to plot for each iteration in order to judge the convergence.

3.1 Heat transfer characteristics:

In the present investigation the heat transfer characteristics for artificially roughened solar air heater are studied in comparison to smooth duct.

At first the roughness effect on Nusselt number is presented. Figure (3.1) shows the effect of Reynolds number on average Nusselt number for both smooth and roughened ducts. It can be observed that values of average Nusselt number in the case of roughened duct is always greater than the values obtained in smooth duct. And *Nu* tends to increase with increase in Reynolds number in both the cases. The roughened absorber plate can lead to superior heat transfer performance. This increase in heat transfer is due to the turbulence and recirculation created by ribs present over the plate. Figure (3.2) shows the recirculation happening due to the roughness material below the absorber plate at p/e =7.15, W/w = 3, e/D = 0.02143 and at particular Re number. A significant turbulence is induced because of generate secondary flow which in turn helps in heat transfer. For better understanding the reason behind the increase in performance contour of turbulence intensity at p/e = 7.15, W/w = 3, e/D = 0.02143 and at particular Re number is shown in Figure (3.3). This figure gives you a clear idea about the increase in performance for artificially roughened solar air heater. One can observe the high turbulence intensity caused at the starting of absorber plate and a moderate intensity present over the rest of the plate. This makes the artificially roughened solar air heater to perform well in terms of heat transfer. Figure (3.4) shows the contour of turbulence kinetic energy at p/e = 7.5, W/w = 3, e/D = 0.02143 and at particular Re number. With this figure we can conclude that artificial roughened solar air heater has high heat transfer characteristics when compared to that of smooth duct type solar air heater. Figure (3.5) shows the velocity contour at p/e = 7.5, W/w = 3, e/D = 0.02143 and at particular Re number. One can observe the variation in velocity at the roughness element. A graph plotted between outlet temperature and Reynolds number for both smooth and roughened solar air heater is shown in Figure (3.6). The roughened one has higher outlet temperature as expected. This is because of increased heat transfer in the case of roughened absorber plate. Figure (3.7) shows the graph between temperature difference and Reynolds number, which shows the variation of temperature.

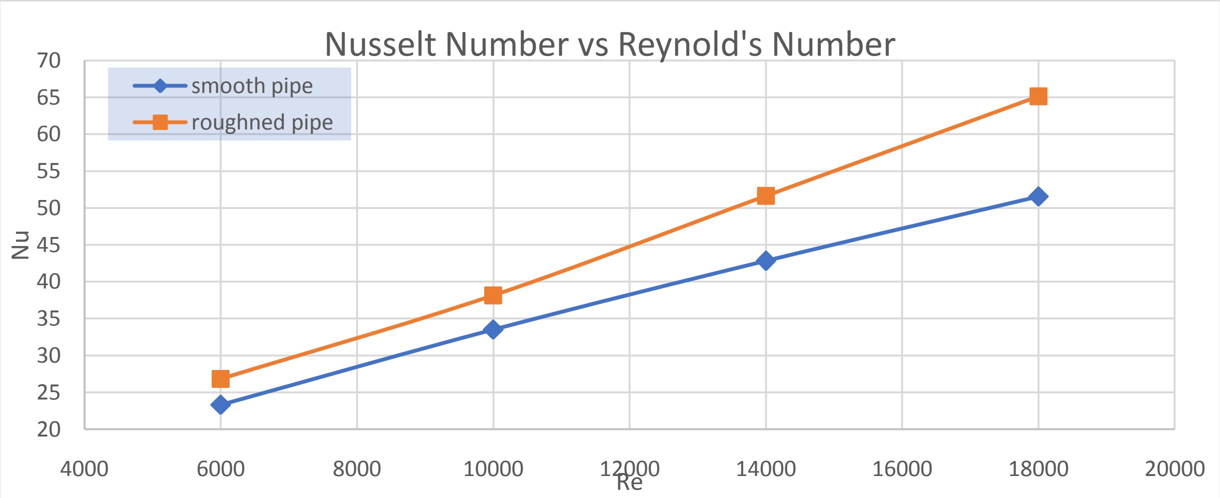

Figure (3.1): Nusselt number variation with Re over relative roughness p/e = 7.5, W/w = 3 and e/D = 0.02143 at Re = 6000-18000.

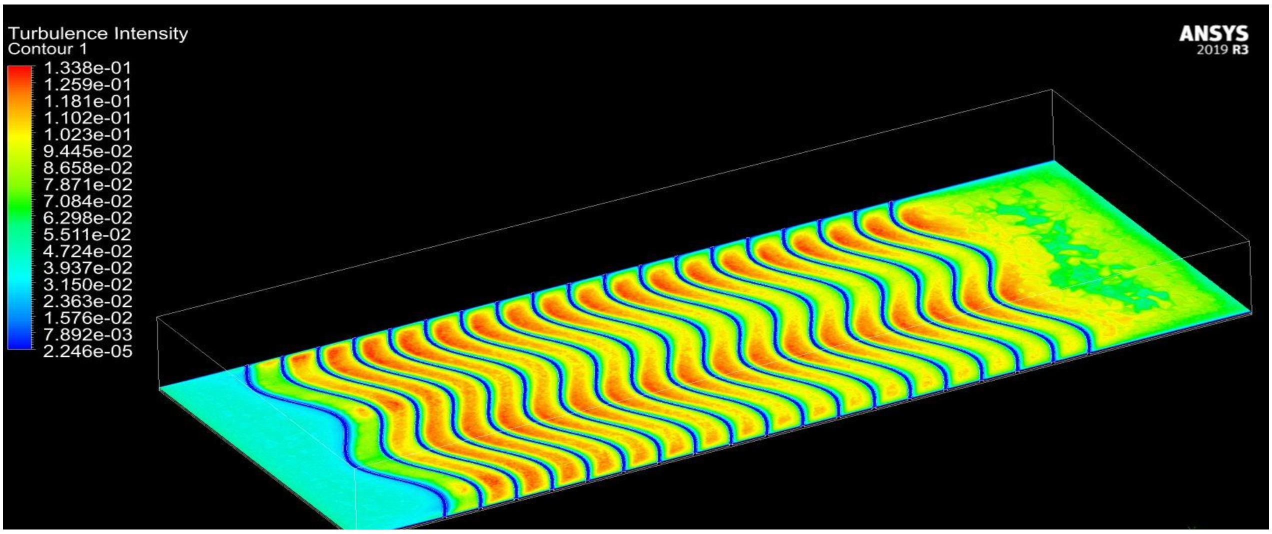

Figure (3.2): Top view of turbulences intensity for relative roughness p/e = 7.5, W/w = 3 and e/D = 0.02143 at Re = 6000-18000.

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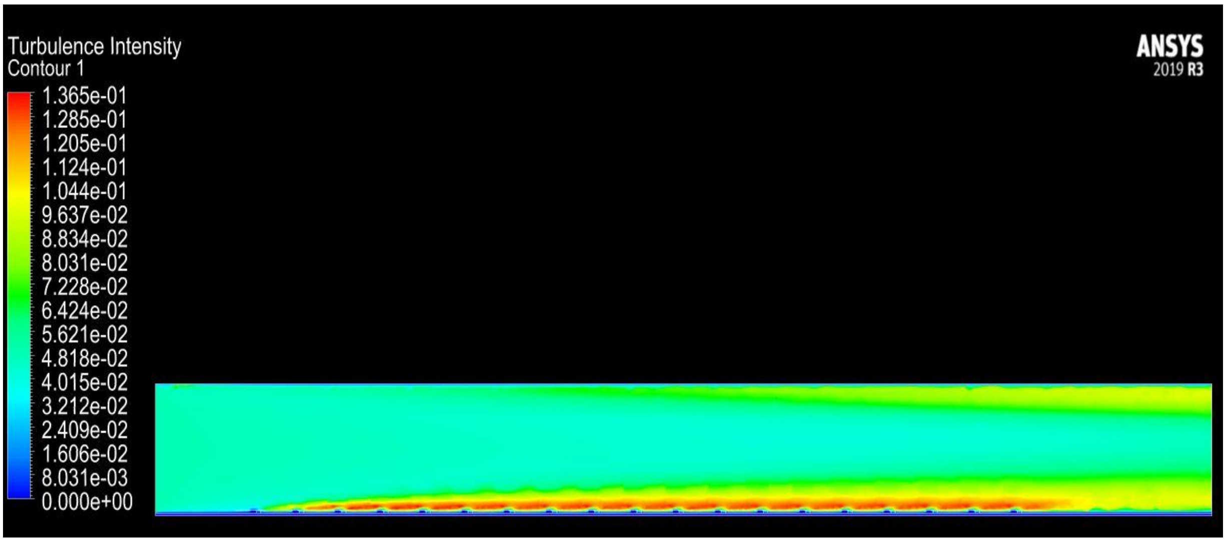

Figure (3.3): The turbulent intensity contour for Re = (6000-18000) at p/e = 7.5, W/w = 3 and e/D = 0.02143.

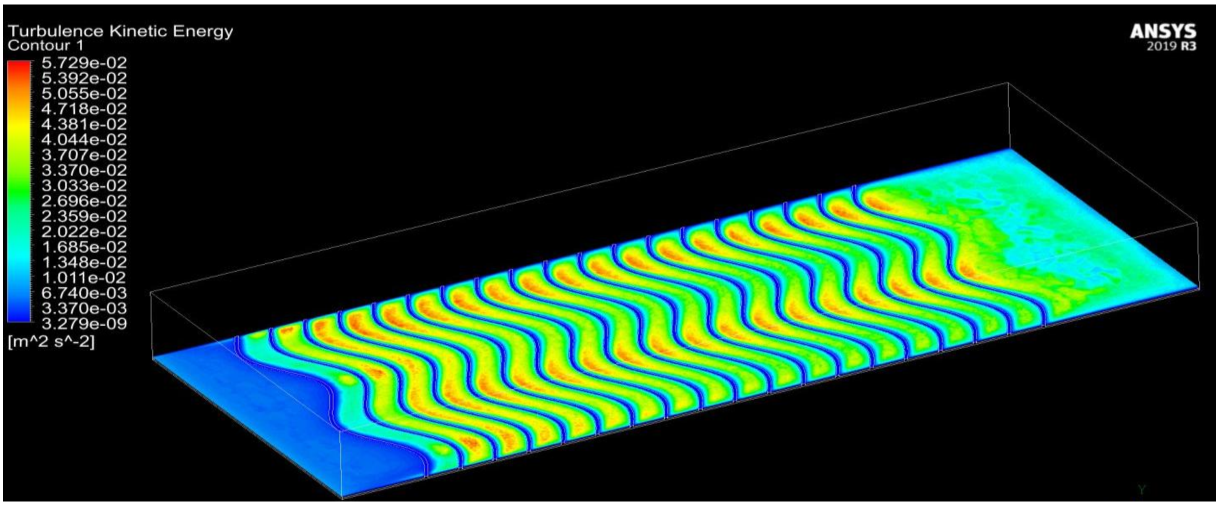

Figure (3.4): The contour of turbulent kinetic energy for Re = (6000-18000) at p/e = 7.5, W/w = 3 and e/D = 0.02143.

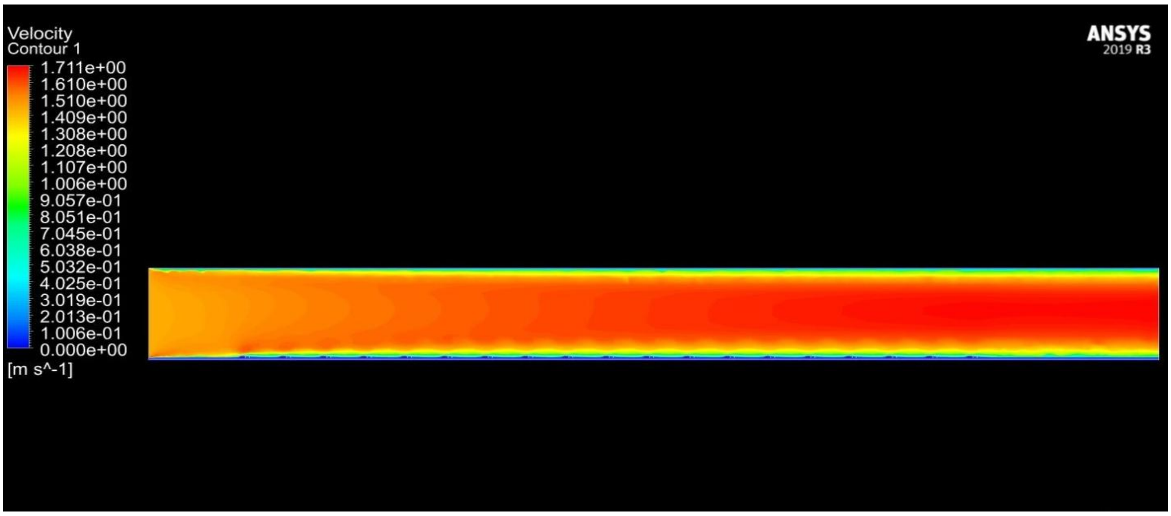

Figure (3.5): The velocity contour profile for Re = (6000-18000) at p/e = 7.50, W/w = 3 and e/D = 0.02143.

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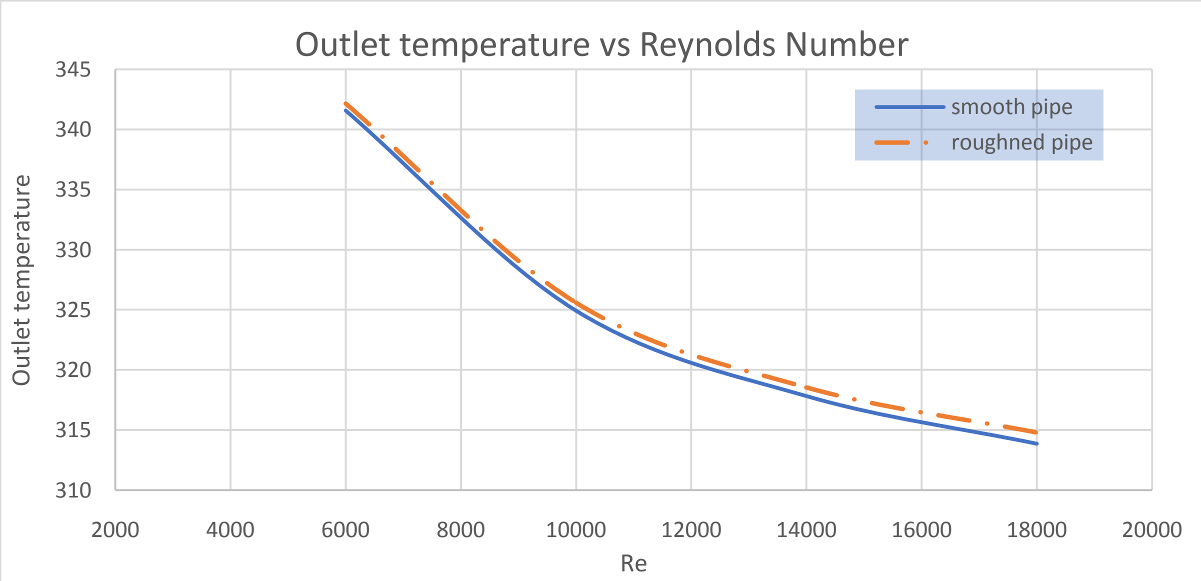

Figure (3.6): Temperature distribution of air along the depth of duct for different Re for relative roughness p/e = 7.50, W/w = 3 and e/D = 0.2143.

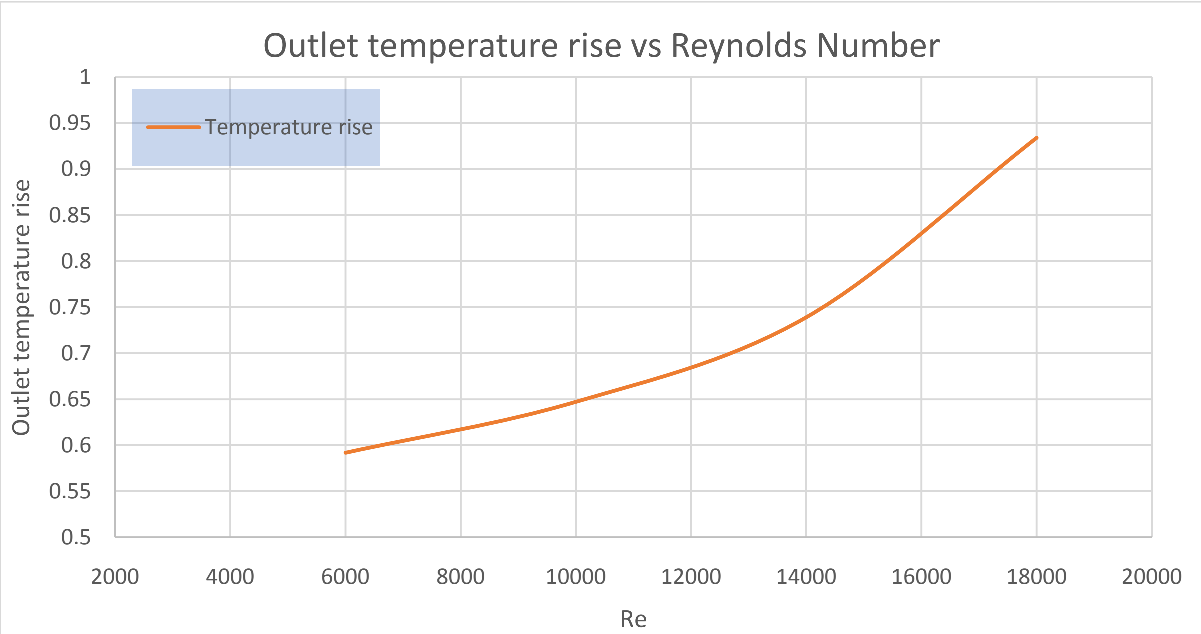

Figure (3.7): Temperature difference distribution of air along the depth of duct for different Re for relative roughness p/e = 7.50, W/w = 3 and e/D = 0.2143.

3.2 Flow friction characteristics:

Because of this roughness, pressure drop increases drastically. Because of this increased pressure drop the friction factor increase which is not desirable. From the above analysis we can conclude that with the inclusion of artificial roughness above the absorber plate in the duct there will be enhancement in pumping power requirement. So, we need to design the roughness in such a way that the pumping power should not be rise. Figure (3.8) shows the trend of friction factor with increasing Reynolds number for both smooth and rough cases. From the graph one can observe that there is a lot of increase in the friction factor for artificially roughened solar air heater this is due to the inclusion of obstructions in the flow field to create turbulence. It is, therefore, desirable to choose the roughness geometry such that the heat transfer is maximized while keeping the pumping losses at the least possible value. In order to analyze overall performance of a solar air heater, thermo-hydraulic performance should be evaluated by simultaneously consideration of thermo hydraulic performance.

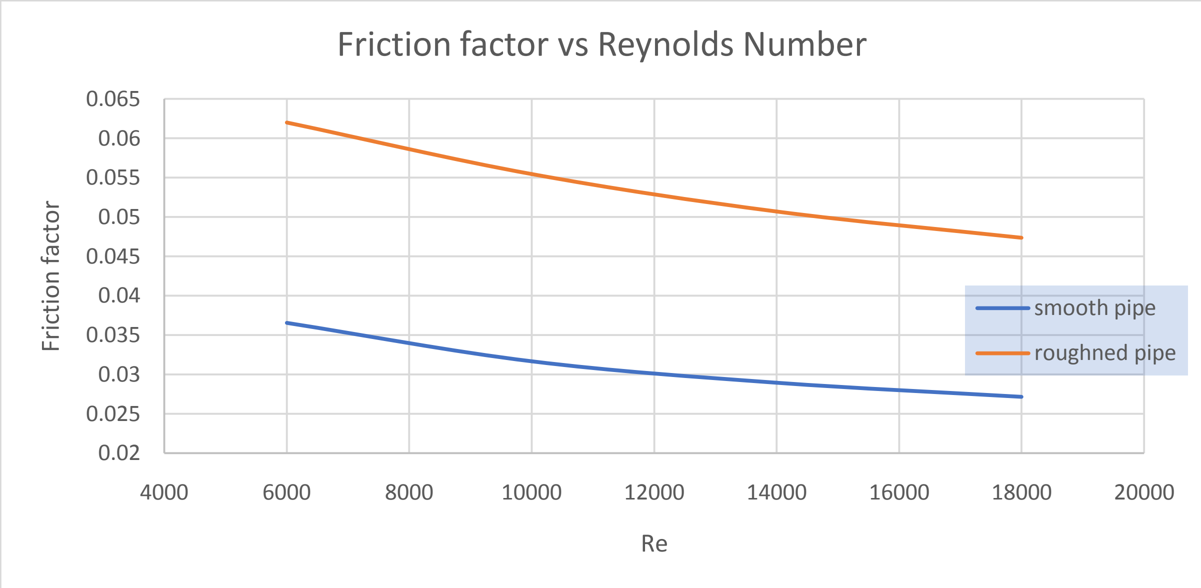

Figure (3.8): Variation of friction factor with different Reynolds number for relative roughness p/e = 7.50, W/w = 3 and e/D = 0.0213.

3.3 Thermo hydraulic performance of roughened duct:

The thermo-hydraulic performance parameter is used to estimate how effectively an artificially roughened surface enhances the heat transfer rate. Thermo hydraulic performance parameter is calculated by Eq (12). THPP is the parameter which correlates both thermal and hydraulic performance. From various researches, it is evident that solar air heater with THPP should be greater than unity is only useful for the better performance. Figure (3.9) shows the thermo-hydraulic performance of artificially roughened solar air heater with respect to Reynolds number. As you can see that the enhancement factor first increases and decreases in this case. The peak point is the point at which maximum enhancement is possible. It has achieved a maximum value of 1.48 at Reynolds number equal to 11000.

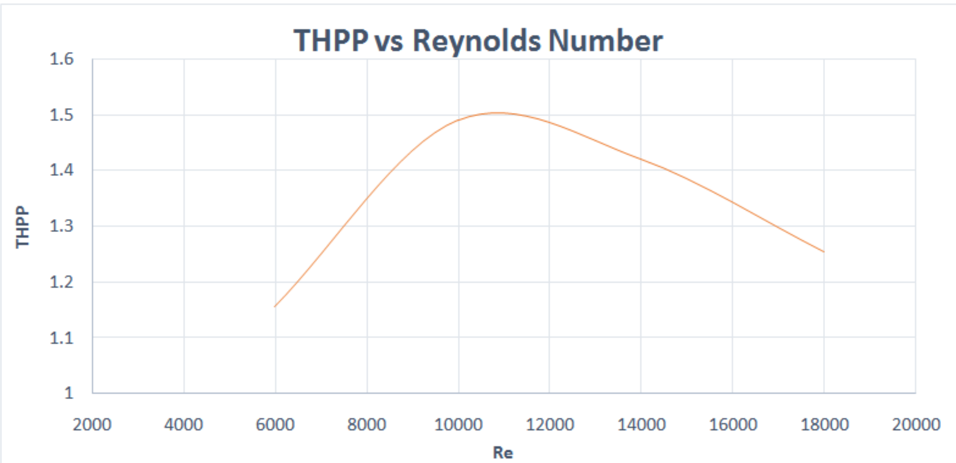

Figure (3.9): Overall enhancement ratio with Re = 6000-18000 for relative roughness p/e = 7.5, W/w = 3 and e/D = 0.02134.

IV. CONCLUSIONS

In this study, ANYSY FLUENT 19.2 has been used for numerical simulation of fluid flow and heat transfer characteristics of artificially roughened solar air heater. CFD result have been validated with Dittus-Boelter empirical relationship for smooth duct. And it is found that the values obtained through CFD analysis are in good agreement with Dittus-Boelter equation. The effect of the relative roughness width, relative roughness pitch and relative roughness height (e/D) on heat transfer (Nusselt number) and friction factor has been studied. Based on this investigation the following conclusions were made.

- Significant enhancement in heat transfer and friction factor can be achieved by creating the artificial roughness in the solar air heater as compared to the smooth duct.
- Reynolds number has strong impact on both Nusselt number and friction factor as Nusselt number increases while friction factor decreases with increase in Reynolds number.
- Overall enhancement ratio with a maximum value of 1.48 has been observed for roughness geometry corresponding to relative roughness p/e = 7.5, W/w = 3 and e/D = 0.021 at Re = 11000.

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