CFD Analysis For Heat Transfer Enhancement of Solar Air Heater Using W-Shaped Roughness

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Abstract - In the present study a Computational Fluid Dynamics (CFD) study was conducted using ANSYS 14.1 SOFTWARE to investigate the heat transfer characteristics in a solar air heater having attachments of W-shaped ribs roughness at an angle of attack 60^o relative to the direction of flow of the absorber plate. The computational study based on the finite volume method using SIMPLE algorithm for the air flow in terms of Reynolds numbers ranging from 4000-14000. The parameter investigated with different relative roughness pitch (p/e) as 10 and 12. It is found that the turbulence created by the W-shaped ribs resulting in greater increase in heat transfer over the test section. The nusselt number increase with increase in Reynolds number. It also varies with the variation of relative roughness pitch. The computational study is also compared with the experimental investigation and found that the CFD results found in agreement with experimental results.

Keywords: Solar air heater; Artificial roughness; Turbulence; CFD; Heat transfer; Fluid flow.

1. INTRODUCTION

Solar air heaters are widely used as energy collection devices to deliver heated air at moderate temperature for drying and heating applications. Because of its lower heat transfer rate between absorber plate and flowing air an effort has been made to increase the heat transfer through absorber plate by using roughness. The presence of artificial roughness increases heat transfer because of creating disturbance to the viscous sub layer. Artificial roughness enhances the turbulence in the flow and reattachment points which results to a higher heat transfer. Number of experimental analysis has been carried out in this area but very few computational analysis and investigation have been done so far. In this study, an attempt is done to predict the temperature which is responsible for heat transfer enhancement. It has been proposed by the investigators that creating artificial roughness on the absorber plate could substantially enhance the heat transfer rate of solar air heater. The application of artificial roughness by using small diameter wire attached with the absorber plate was first introduced by Prasad and Mullick [1] to improve the thermal performance of solar air heater. Prasad and Saini [2] were experimentally investigated the effect of protrusions created at underside of absorber surface in form of small diameter wires on heat transfer for fully developed turbulent flow in a solar heater duct. The effect of transverse wire roughness for three sides of rectangular duct on heat and fluid flow characteristics was investigated by Verma and Prasad [3]. Gupta et al. [4] again studied the effect of transverse wire roughness fixed on underside of an absorber plate by using different operating parameters.

Momin et al. [5] investigated the effect of V-shaped roughness on heat transfer and friction characteristics of solar air heater duct. It was found that V-shape rib roughness gives better performance with an angle of attack of 60^o over inclined ribs as well as smooth plate. V shaped rib geometry develops the secondary flow which creates more turbulence effect as compare to the inclined shaped of roughness. Lanjewar et al. [6] introduced the concept of W shaped rib roughness. In this concept they increases the number of secondary flow developed due to multi inclination of the geometry. The relative roughness pitch they used as 10. W-Shaped rib roughness reported that W-rib arrangement having 60^o angle of attack gives better performance and reported enhancement in Nusselt number as compare to smooth plate. A CFD based 2D investigation of artificial roughness in a solar air heater is carried out by Yadav et al. [7] with square sectioned transverse rib roughness. The 2D analysis of turbulent flow in a rectangular duct is performed using ANSYS FLUENT 12.1 software with RNG k-ε turbulence model. Another numerical investigation using CFD is conducted by Yadav et al. [8] on the solar air heater, using square sectioned transverse ribs with different values of relative roughness pitch. Yadav et al. [9] predicts the effect of roughness having small diameter of transverse wire on heat transfer enhancement in solar air heater. In this analysis also FLUENT 12.1 software is used with the RNG k–ε turbulence model. 2D CFD investigation using different ribs namely rectangular, square, chamfered, triangular etc. is performed by Chaube et al. [10]. FLUENT CFD is used for analyzing the geometries by using the SST k–ε turbulence model. The heat flux of 1100 W/m^2 is provided on the absorber plate and rib, rest of the surrounding surfaces is kept adiabatic. Karmare et al. [11, 13] investigated experimentally as well as numerically the effect of heat transfer performance of a rectangular duct with metal grit ribs as roughness, transferring heat to the air flowing through it. They carried out 3D numerical analysis using CFD on solar air heater roughened with metal ribs of circular, square and triangular cross-section. Many researchers have tried experimentally to optimize the effect of different geometries on the performance of solar air heaters, but experimentation is time consuming and it involves cost. In this present study, roughness element in the form of W shaped ribs for different range of parameter has been taken. The heat transfer and flow analysis of the selected roughness element has been carried out by using 3-D model of ANSYS 14.1 SOFTWARE. The ribs are provided on the one side of rectangular duct whereas other sides are kept smooth. To validate the CFD results, the numerical data is compared with the experimental data obtained from the correlation developed by Lanjewar et al. [6] through his experimental investigation. The results also compared with the previously reported V rib geometry under similar operation conditions.

2. SOLUTION DOMAIN AND CFD ANALYSIS

The computational domain is designed as it having same dimension as used in experimental test rig of Lanjewar. The computational domain used for CFD analysis having the height (H) of 25mm and width (W) 200mm and length of 1000mm as shown in Fig 1.

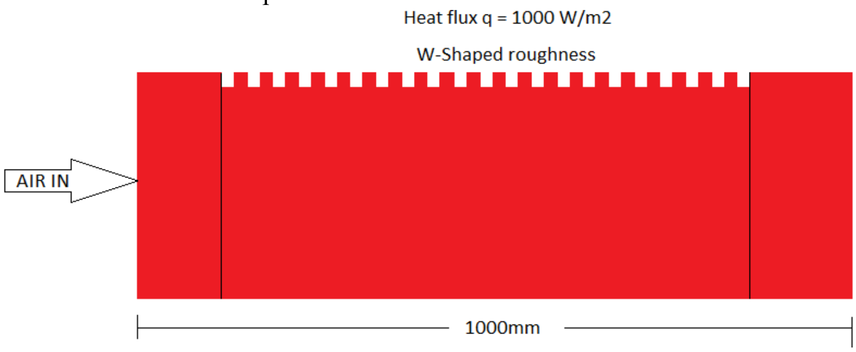

Fig.1. Solution domain of W-rib roughness

The entry and exit length of the flow have been kept as per consideration for fully developed flow and as per recommendation provided in ASHRAE Standard 93-77. The arrangement of roughness elements in the form of W shaped ribs fixed on the inner side of the absorber plate, the dimensions of roughness element and operating parameters are shown below:

Table.1. Data selected for formulate our solution domain

PARAMETERS	VALUE
Duct Height (H)	25mm
Duct Width (W)	200mm
Hydraulic mean diameter (D_h)	44.4 mm
Duct aspect ratio (W/H)	8
Length of Test Section	1000mm
Rib height (e)	2mm
Relative roughness pitch (P/e)	10 & 12
Angle of attack (α)	60º
Reynolds number (Re)	4000-14000
Uniform Heat at bottom Surface	1000W/m^2

Table.2. Thermo-physical properties

PROPERTIES	WORKING FLUID	ABSORBER SURFACE (aluminium)
Density (ρ) Kg/m^3	1.225	2719
Specific heat (Cp) J/Kg.K	1006.43	871
Viscosity (μ) N/m^2	1.789 x 10^{-5}	--
Thermal Conductivity (K) W/m.K	0.0242	202.4

2.1. The assumptions for mathematical model while CFD analyses

i. The flow is fully developed, steady, turbulent and three dimensional.

ii. The thermal conductivity is not changing with temperature.

iii. The working fluid is assumed incompressible

This was assumed in respect of experimentation of solar air heaters by various investigators.

2.2. Boundary condition

The rectangular solution domain of solar air heater has inlet, test and exit sections. The working fluid used in solar air heater duct is air and the absorber plate is made up of aluminum. The thermo physical properties of air and absorber plate material are shown in Table 1. A constant heat flux of 1000 W/m^2 is maintained on the top wall of test section. Uniform velocity boundary condition is applied at the inlet section and constant pressure (1.013 X 10^5 Pa) outlet boundary condition is applied at the exit. The solid surfaces are maintained at no-slip boundary condition and made them as adiabatic.

Table.3. Boundary conditions

LOCATION	BOUNDARY TYPE	BOUNDARY DETAIL	
		Velocity	Reynolds number
Air inlet	Velocity inlet	1.163636	4000
		1.745455	6000
		2.327273	8000
		2.909091	10000
		3.490909	12000
		4.072727	14000
Outlet	Pressure outlet	Gauge Pressure 0	
Left side, Right side, Bottom	Wall	No slip, Adiabatic insulated wall	
Absorber plate	Wall	Heat flux = 1000 W/m^2 Material = Alluminium	

2.3. Grid/ Mesh Generation

ANSYS 14.1 meshing module is used for creating non-uniform tetrahydral mesh on the computational domain of solar air heater. A very fine mesh size is used at the boundary of smooth rectangular solar air heater duct to resolve the laminar sub layer. The procedure of providing mesh was implemented with different numbers of cells. A marginal variation is found in heat transfer coefficient when the number of cells varies from 250000 cells to 400000. Hence, increasing the number of cells beyond this value has negligible effect on the results.

3. RESULTS AND DISCUSSION

3.1 Validation of setup

In order to validate the numerical solution, the computational analysis have been carried out for forced convection in a smooth rectangular duct having fully developed turbulent flow and it is compared with the exact solution obtained with the Dittus Boelter equation as shown in Fig.3.

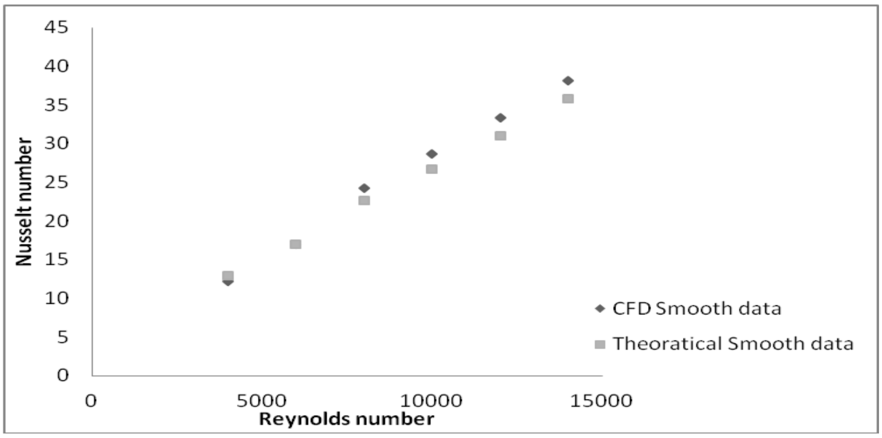

Fig.2. Comparison of computational and formulated value of Nusselt no. vs Reynolds no. for smooth plate

$$Nu_s = 0.024\, Re^{0.8}\, Pr^{0.4}$$

It is found that the present CFD analysis over smooth duct have good agreement with the exact solution for the Nusselt number.

The numerical results of present study i.e. on W-shaped roughness is also compared with the experimental data obtained from the correlations developed by Lanjewar et al. [6] under similar parametric and operating condition to validating the accuracy of numerical solutions. Less than ± 5% deviation is found between the numerical and experimental results as shown in Fig .3.

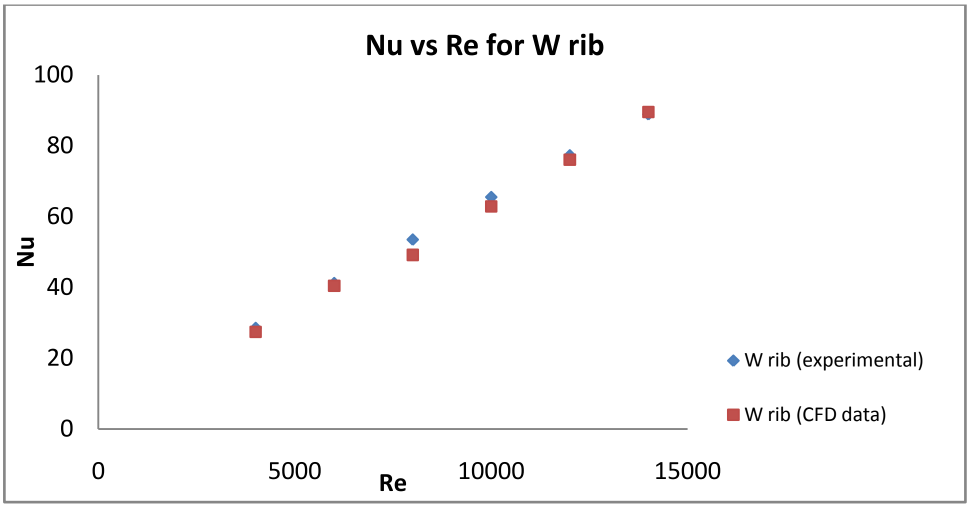

Fig.3. Comparison of computational and experimental results of Nusselt no. vs Reynolds no. for W shaped rib roughness

3.2. Heat transfer in roughened solar air heater duct

The heat transfer and fluid flow gets affected by providing artificial roughness on the rectangular duct of solar air heater. Nusselt number has been found to be low just at the vicinity of rib because heat transfer takes place at that rib area is due to conduction only, while at point where the flow get reattached with the heated surface Nusselt Number will get incrreased. The increase in the value of Nusselt number is due to the variation in flow pattern. The presence of roughness along the flow direction creates turbulence and the fluid flow also separates from the wall. Heat transfer decreases with the separation of flow whereas vortices generated because of turbulence makes the fluid to mix and hence increasing heat transfer. Temperature profile of V shaped rib roughness and W shaped rib roughness is shown in the Fig.4 and 5.

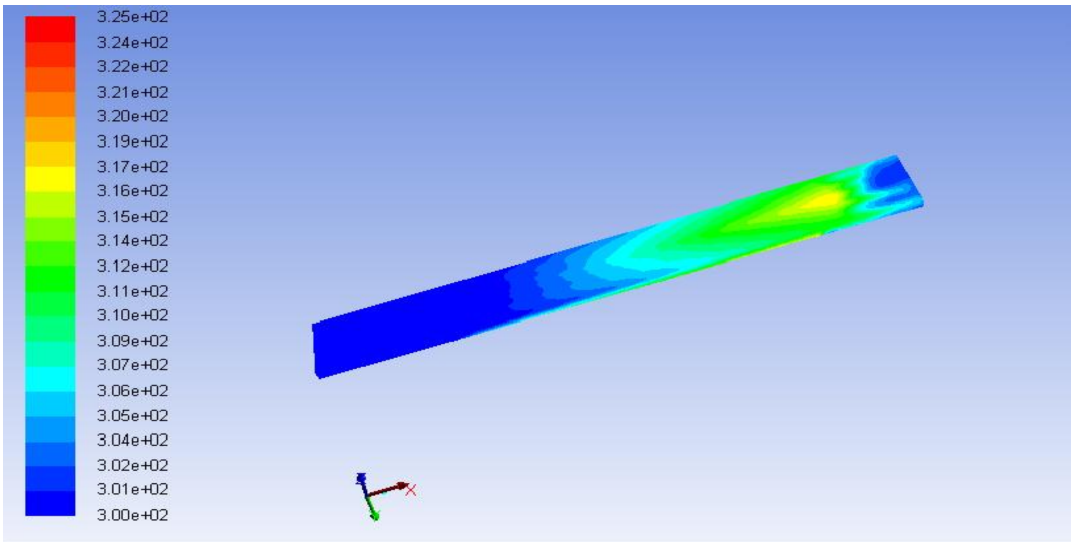

Fig.4. Temperature contour of computational domains of V rib

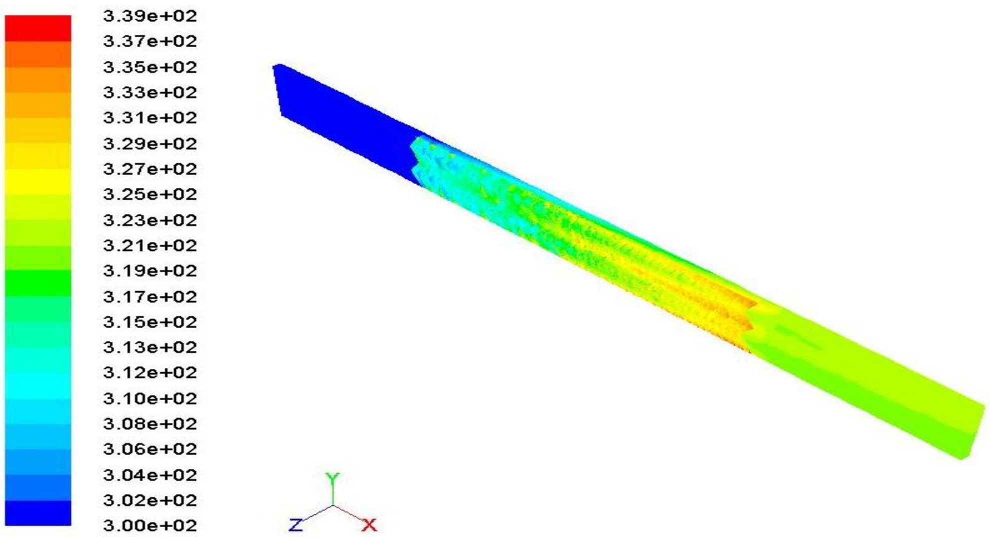

Fig.5. Temperature contour of computational domain of W rib

2.4. Comparison with earlier reported V rib roughness

The enhancement in the value of Nusselt number by using W-shaped rib roughness is found to be more than that of earlier reported V-shaped roughness geometry as well as smooth rectangular duct simulated under similar parametric and operating conditions as shown in Fig.6. This is because of more secondary flow generation in W-shaped roughness as compare to the V-shaped roughness. Heat transfer and Nusselt number increase with the increase in turbulence which is affected by the number of inclinations provided in the geometry which is more in W shaped rib roughness as compared to V shaped rib.

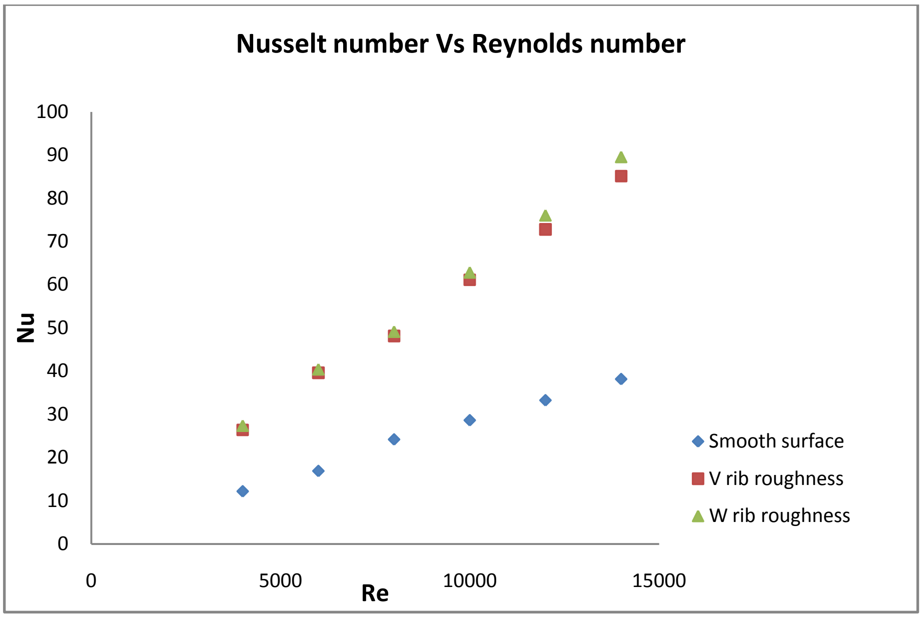

Fig.6. Comparison of Nusselt number Vs Reynolds number for W-rib and V-rib roughness

2.5. Comparison between various ribs at different p/e

The variation in Nusselt number for W shaped rib roughness has been plotted as function of relative roughness pitch (P/e) for the range of Reynolds number varies from 4000-14000 shown in Fig.9. It has been observed that for any particular value of Reynolds number, Nusselt number attain maximum value corresponding to relative roughness pitch (P/e) value of 10 and on increasing this value as 12, decrease in Nusselt number has been observed. It is due to the fact that flow separation occurs on a rib at relative roughness pitch (P/e) as 12 the reattachment points decreases with the heated surface and also reduces the turbulence and vortices. The temperature contour of W-rib roughness having relative roughness pitch (P/e) as 10 and 12 is shown in Fig.7 and 8.

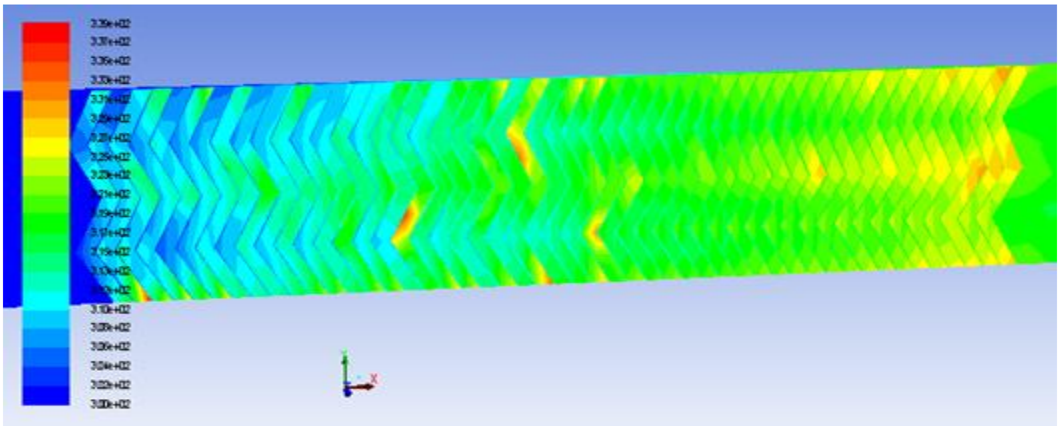

Fig.7. Temperature contour of W-rib roughness having P/e = 10

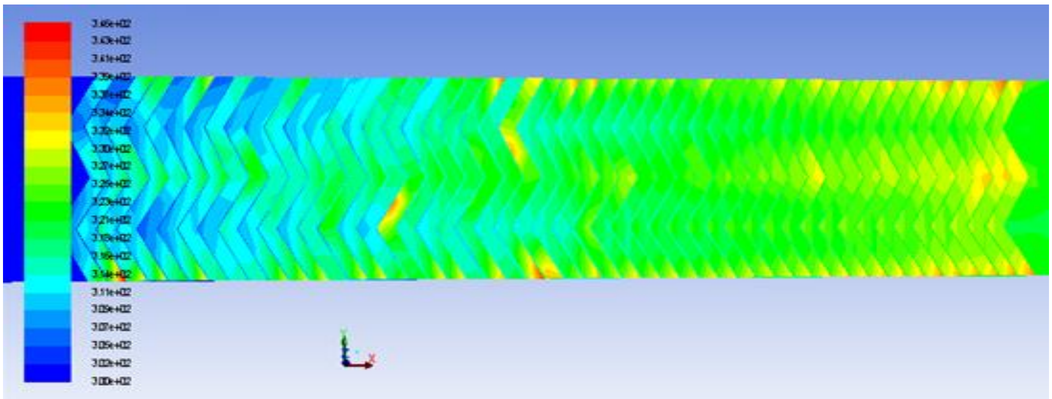

Fig.8. Temperature contour of W-rib roughness having P/e = 12

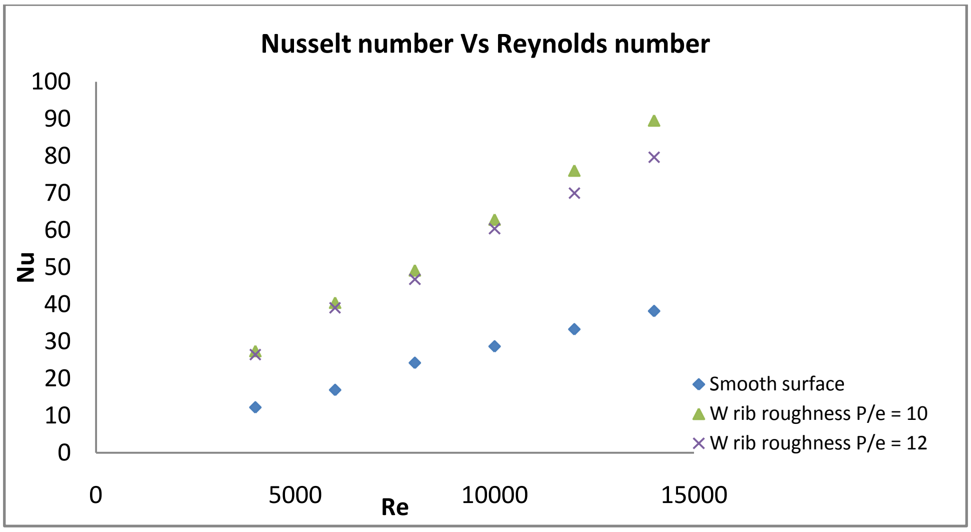

Fig.9. Comparative graph of W-rib roughness with different relative roughness pitch

The present numerical study of using W-shaped roughness with different relative roughness pitch (P/e) in a rectangular duct shows that the W-shaped rib roughness having relative roughness pitch (P/e) of 10 gives better performance as compare to the V-shaped roughness under similar operating conditions as well as the smooth rectangular duct of solar air heater. The overall comparative chart of W shaped rib roughness is shown in Fig.10.

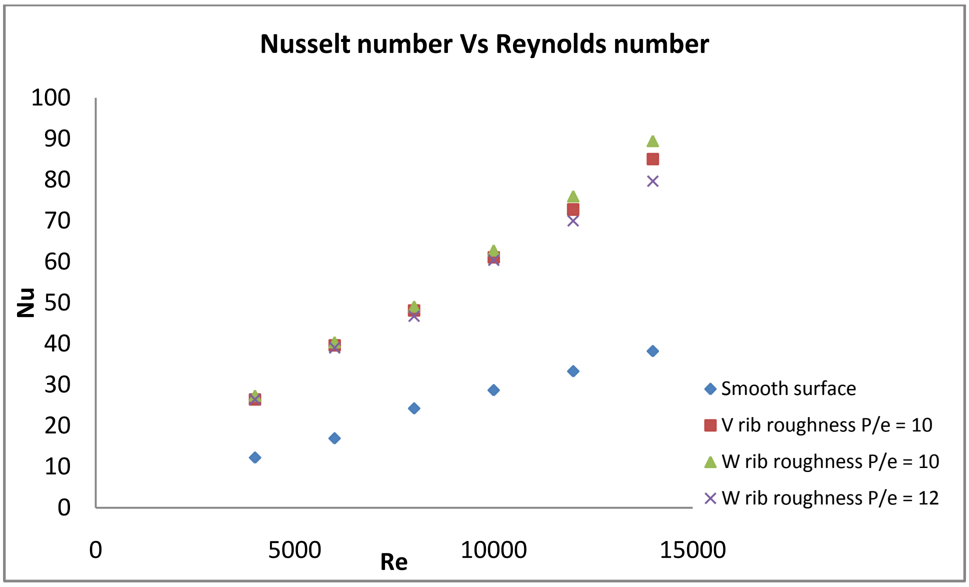

Fig.10. Comparative chart of W shaped roughness

4. CONCLUSION

The present CFD based study carried out by using W-shaped roughened solar air heater for analyzing fluid flow and heat transfer characteristics and it also shows that the CFD results found in agreement with experimental results. As we increase the Reynolds number the Boundary layer thickness decreases which increase the convective heat transfer between the absorbing plate and the air by decrease the convective resistance it results increase in Nusselt number. W-shaped roughness gives better heat transfer rate as compare to the V rib roughness because of more secondary flow development in W rib under similar operating conditions. The maximum value of Nusselt number for W-shaped roughness is obtained with the relative roughness pitch (P/e) of 10 beyond that it starts decreasing i.e. at P/e = 12. The maximum increment in Nusselt number is found to be 2.34 times as compare to the smooth surface at Re = 14000. The maximum increment in Nusselt number is found to be 1.15 times as compare to the V rib roughness at Re = 14000.

5. REFERENCES

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