CFD Investigation on Nusselt Number of Solar Air Heater Duct Roughened with Double Arc Shaped Roughness with Different Relative Roughness Pitch

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Abstract- The numerical investigation of heat transfer characteristics of a solar air heater having rectangular duct roughened with double arc shaped rib roughness is conducted in present study. Three dimensional CFD analysis of Double arc shaped roughness is investigated with different relative roughness pitch (P/e) with an angle of attack 60°corresponding to the flow direction using ANSYS FLUENT code. Finite volume method with SIMPLE algorithm is used for the computational numerical study of fluid flow; k–ε turbulence model is used for solving the governing equations. The range of Reynolds number investigated during the investigation of double arc shaped rib roughness is from 6000-14000. The computations are performed with different parameters which are roughness height as 2mm, Hydraulic diameter (D_h) as 0.0461, relative roughness pitch (P/e) varies from 10 to 14(three values) and angle of attack (α) as 60°. The effect of parameters on heat transfer and Nusselt number are analysed. The double arc shaped roughness improves the thermal performance of solar air heater with the generation of more secondary flow along the span. The enhancement in the value of Nusselt number has been obtained with respect to Reynolds number. It is also observed that the heat transfer phenomenon varies with the variation of relative roughness pitch (P/e). 3-D CFD analysis is also compared with the experimental study of arc shaped roughness and found satisfactory agreement of numerical results with the experimental values obtained for investigated range of parameters.

Keywords: Solar air heater; artificial roughness; Turbulence; CFD; Thermal performance.

I. INTRODUCTION

Solar energy is a source of renewable energy which is available freely as clean and cheap form of energy and hence utilizing in various heating applications. Conventional solar air heater is a system using solar energy as a thermal source to increase the thermal characteristics of flowing air and delivers it for many drying and heating applications. The efficiency of conventional solar air heater is low because of lower heat transfer rate between absorber plate and flowing air in solar air heater. Hence the concept of providing artificial roughness geometries over the surface has been introduced to improve the heat transfer rate through heated absorber plate. Artificial roughness disturbs the sub boundary layer developed very near to the surface because of developing turbulence to the viscous sub layer. It increases the heat transfer by increasing the re-attachment points of flow with the heated surface. Numbers of researchers investigated so many types of roughness geometries for improving the heat transfer rate and recommend that creating artificial roughness on the absorber plate give considerably enhance the performance of solar air heater. Prasad and Mullick [1] was first introduced transverse shape of roughness to improve the heat transfer characteristics of solar air heater. Prasad and Saini [2] and Kays [3] use small diameter wires and investigated for the different operating and geometrical parameters. Experimental investigation over transverse rib roughness was studied by Gupta et al. [4] using different operating parameters. Broken type of transverse rib was investigated by Sahu & Bhagoria [5] to analyse the heat transfer characteristics of solar air heater. Momin et al. [6] investigated the effect of V-shaped roughness on heat transfer characteristics of solar air heater duct. It was found that V-shape rib roughness gives better performance with an angle of attack of 60°. Lanjewar et al. [7] uses W shaped rib roughness which increases the number of secondary flow developed due to multi inclination of the geometry having 60° angle of attack. Enhancement in Nusselt number is reported as compare to smooth plate. The concept of discretising the W-shaped of geometry was investigated by A kumar et al. [8] and the effect of operating parameters are compared with the result of smooth surface under similar operating conditions. Performance of solar air heater using arc shaped of roughness was investigated by Saini et al. [9] with relative roughness pitch (P/e) of 10. Further CFD analysis of solar air heater with arc shaped roughness geometry was studied by Kumar et al. [10]. 2D investigation of artificial roughness using CFD in a solar air heater is carried out by Yadav et al. [11]. They use square sectioned transverse rib roughness in a rectangular duct is using ANSYS FLUENT 12.1 software with RNG k-ε turbulence model. Using square sectioned transverse ribs with different values of relative roughness pitch investigated using CFD is conducted by Yadav et al. [12] on the solar air heater. Yadav et al. [13] predicts the effect of roughness having 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 as rectangular, square, chamfered, triangular etc. is performed by Chaube et al. [14]. 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. [15, 16] has done experimental as well as numerical study and analyze the effect of heat transfer performance of a rectangular duct with metal grit ribs as roughness. A 3D numerical analysis has been performed using CFD on solar air heater roughened with metal ribs of circular, square and triangular cross-section.

The heat transfer of solar air heater can further enhance when obtaining number of secondary flows, as the present geometrical design increases the secondary flows by doubling the arc shape. Present numerical study involves CFD analysis using ANSYS SOFTWARE with double arc shaped ribs for different range of parameters. 3-D model of double arc shaped roughness is use to analyze the heat transfer and fluid flow analysis. The present investigation also involves the comparison of numerical analysis of arc shaped roughness with the experimental results of arc shaped roughness obtained from the correlation developed by Kumar et al. [10].

II. DETAIL OF COMPUTATIONAL DOMAIN

2.1. Outline

The solar air heater having duct of rectangular shape, only one side of air passage is considered as a heated section by solar radiations. In order to increase the heat transfer the roughness is provided on the heated side of the rectangular duct. Hence the system is taken as a rectangular channel with one side of artificially roughened and other three sides are taken as insulated smooth surface. As per the experimental studies the domain is divided into three sections as inlet section of 800mm, test section of 1000mm and outlet section of 500mm. Therefore the total length of computational domain is taken as 2300mm. The heated surface is roughened with double arc shape of rib with rib height of 2mm same as seen in experimental studies. The domain having arc shaped of roughness analyzed in CFD is designed similar to the dimensions used in experimental test rig of Kumar et al. [10] as shown in Fig.1. As per the recommendation given in ASHRAE Standard 93-77 the inlet section should be provided to make the flow fully developed. The dimensions of roughness element and operating parameters are shown in Table.1.

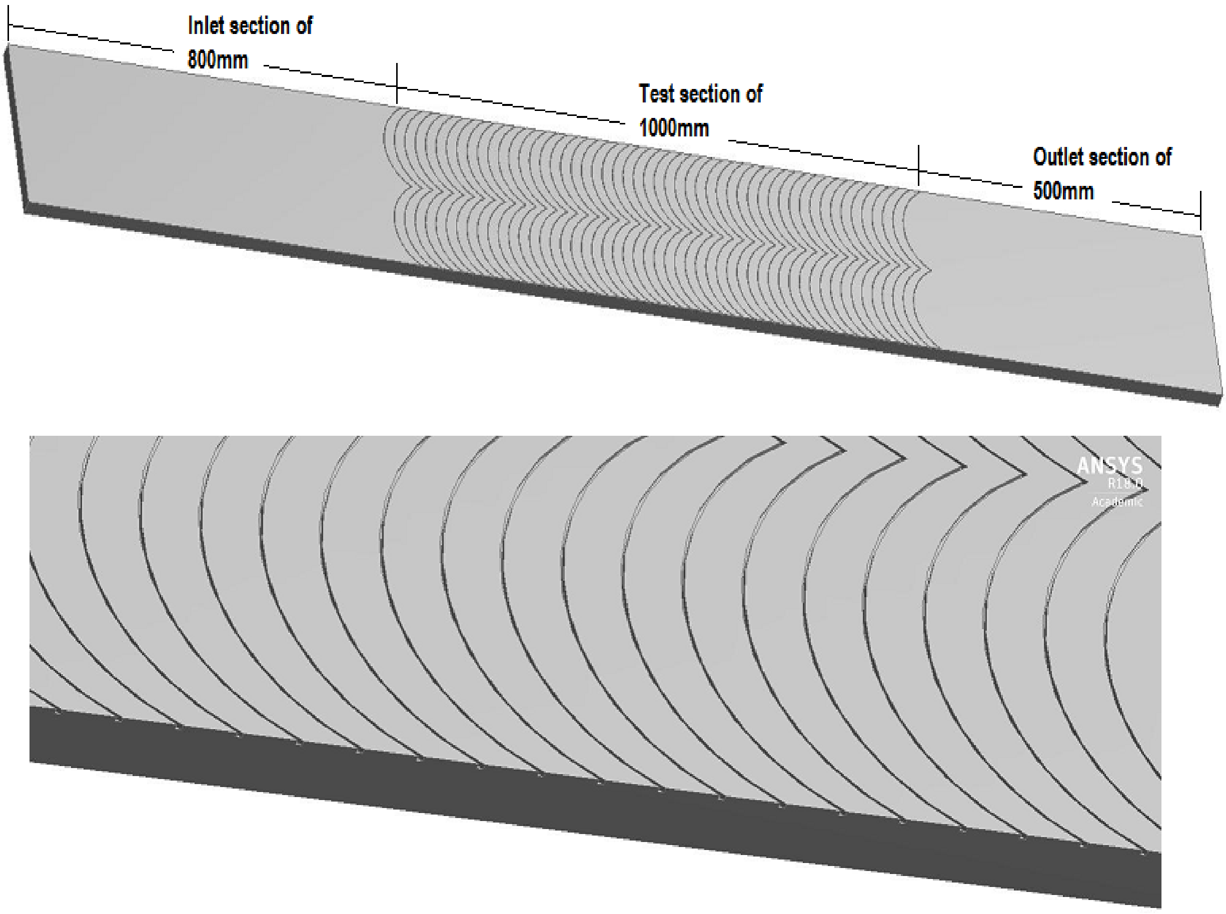

Fig.1. Solution domain roughened solar air heater duct

1.2. Solution domain and mesh generation

In this numerical analysis, a three dimensional computational domain of solar air heater duct is simulated having double arc shaped of roughness. The turbulent flow analysis has been conducted in order to analyze the heat transfer characteristics. A non uniform mesh has been generated to descretize the domain. A very fine grid is generated near the roughened surface whereas the mesh is comparatively coarse type is used far from the boundary wall. The entire solution domain has been meshed with non uniform grid like as shown in Fig.2. Different numbers of cells are provided to obtain the mesh. The grid independence test is carried out by varying elements from 381550 to 577102 in three steps for Re = 14,000, P/e = 10 and e/D = 0.0461. A marginal variation is obtained in heat transfer coefficient when the number of cells varies from 350000 cells to 500000. Hence, increasing the number of cells beyond this value has negligible effect on the results.

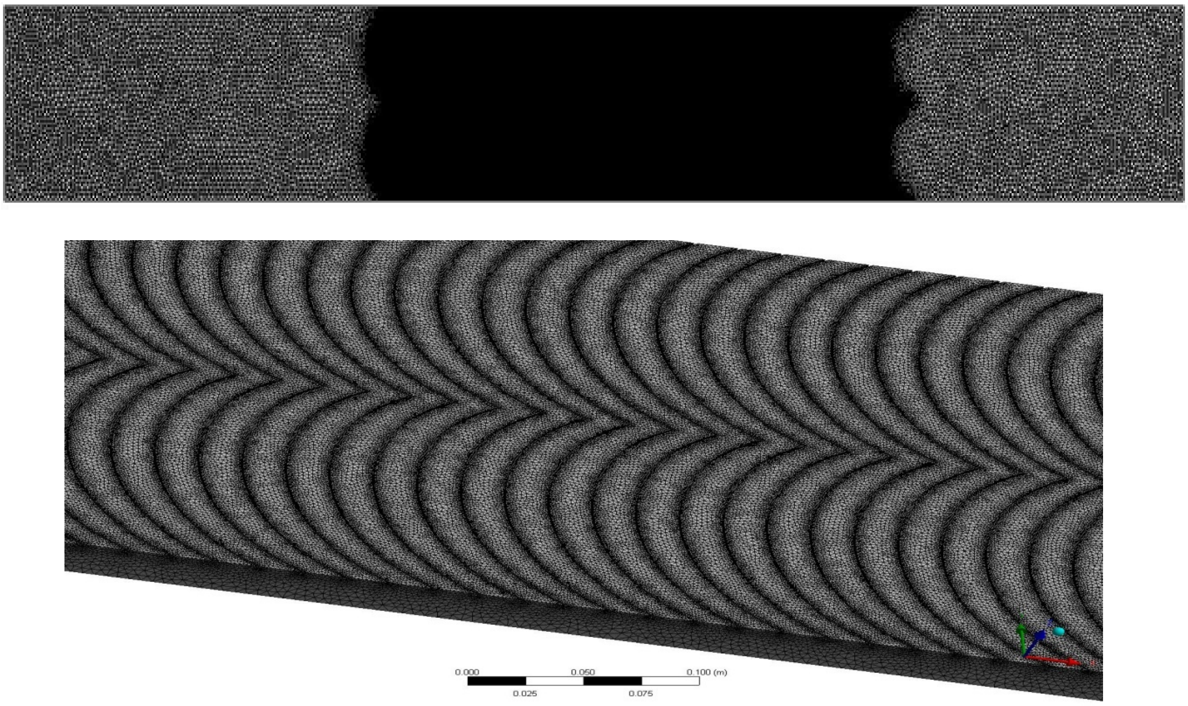

Fig.2. Grid generation over the computational domain

Table.1. Operating dimensions used in computational domain

PARAMETERS	VALUE
Duct Height (H)	25mm
Duct Width (W)	300mm
Hydraulic mean diameter (D_h)	46.1 mm
Duct aspect ratio (W/H)	12:1
Rib height (e)	2mm
Relative roughness pitch (P/e)	10,12,14
Angle of attack (α)	60º
Reynolds number (Re)	4000-14000
Uniform Heat at bottom Surface	1000W/m^2

1.3. Boundary condition and fluid properties

The rectangular computational domain of solar air heater is divided into three sections as inlet, test and exit sections. Air is used as a working fluid solar air heater duct and the absorber plate is made up of aluminum. The thermo physical properties of flowing fluid and absorber plate material are shown in Table 2. A constant heat flux of 1000 W/m^2 is generated over the heated wall of test section. Uniform velocity is taken as the inlet boundary condition for the inlet section and constant pressure (1.013 X 10^5 Pa or 0 gauge) is considered as outlet boundary condition applied at the exit. The upper roughened surface of domain is maintained at no-slip boundary condition and all the surrounding wall is maintained as adiabatic.

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	1.789×10^{-5}	--
Thermal Conductivity (K) W/m.K	0.0242	202.4

Table.3. Boundary conditions

LOCATION	BOUNDARY TYPE	BOUNDARY DETAIL	
Air inlet	Velocity inlet	Velocity	Reynolds number
		1.745455	6000
		2.327273	8000
		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 = Aluminium	

1.4. The assumptions made to solve the mathematical model while CFD analyses

In order to analyze the artificial roughness domain using CFD following assumption has been considered

i. Steady Flow
ii. Incompressible flow
iii. Two-dimensional flow.
iv. Constant thermo physical properties of the fluid.
v. Neglecting conduction resistance of the heated absorber plate.
vi. Neglecting viscous dissipation in the energy equation as significance of viscous dissipation only for flows at high velocities.

1.5. Solution method and turbulent model

The CFD analysis of solar air heater duct with double arc shaped artificial roughness is carried out using CFD code ANSYS FLUENT 16.1. The steps involving for the numerical simulation using CFD in solar air heater is as follows:

- ✓ Developing model
- ✓ Computational domain
- ✓ Create 3-D model of the domain
- ✓ Generating mesh
- ✓ Set up and compute the solution
- ✓ Examine the results

Initial step is to develop the 3-D model, in present study 3-D double arc shaped model is selected to analyze because it is time saving and obtained results exact to the experimental testing as compare to the 2-D model. A 3-D computational domain is prepared like as shown in Fig.1. Non-uniform grid or mesh is generated over the domain in order to capture the gradients by using CAD model. Computational domain is prepared in ANSYS modeler 16.1. The properties of Material, operating conditions, boundary conditions, solver controls and convergence monitors are set up in solver. Finite volume method is used to discretize the governing equations of continuity; momentum and energy. RNG K-ε turbulence model is used to solve the flow equations.

2.6. Effect of Double arc shaped roughness.

By applying Double arc shaped of artificial roughness over the span of heated area increases the heat transfer coefficient of solar air heater by developing number of secondary flows over the span which in turn increases the turbulence inside the duct. The roughness is provided repeatedly over the streamwise as well as span wise direction due to which a local turbulence is created along the flow as well as in span wise direction to cover more heated space provided between the two consecutive roughnesses.

III. RESULTS AND DISCUSSION

3.1 Validation of setup

For the 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. In CFD analysis, Nusselt number for smooth duct (Nu_s) of a solar air heater can be obtained by the Dittus–Bolter

equation (McAdams, 1942),

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

It is obtained from the results that the present study of CFD analysis over smooth duct has good agreement with the exact solution for the Nusselt number.

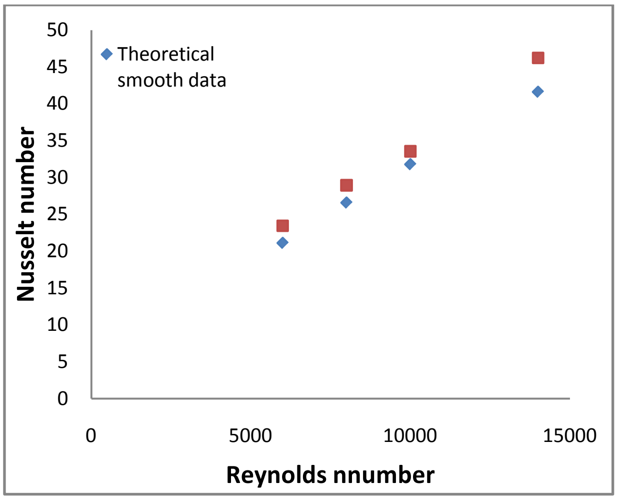

Fig.2. Comparison of computational and formulated value of Nusselt no. vs Reynolds no. for smooth plate

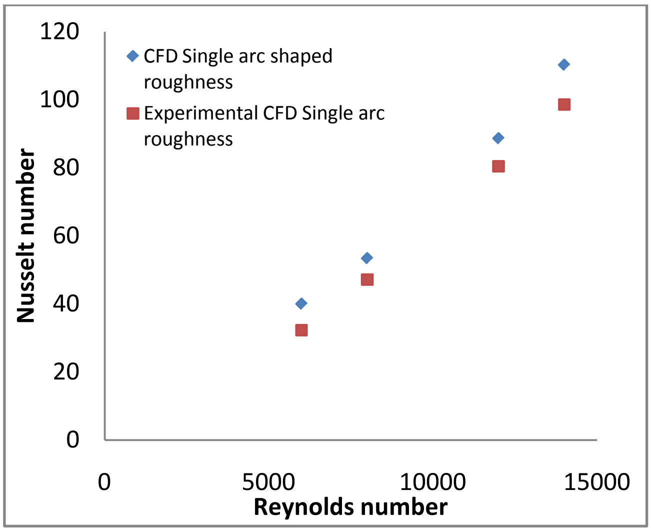

Fig.3. Comparison of computational and experimental results of Nusselt no. vs Reynolds no.

In order to validating the accuracy of numerical solutions CFD analysis of present roughness geometry i.e. double arc shaped is also compared with the experimental results obtained from the correlations developed by Kumar et al. [10] under similar parametric and operating condition. Less than ± 10% deviation is obtained between the numerical and experimental results as shown in Fig .3.

3.2. Heat transfer in roughened solar air heater duct

Artificial roughness on a side of rectangular duct of solar air heater affects the heat transfer and fluid flow characteristics. Heat transfer takes place at that rib area is due to conduction only hence Nusselt number has been found to be low nearer to the rib, while at the point where the flow get reattached with the heated surface Nusselt Number will get increased. 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 single arc shaped rib roughness and double arc shaped rib roughness is shown in the Fig.4 and 5.

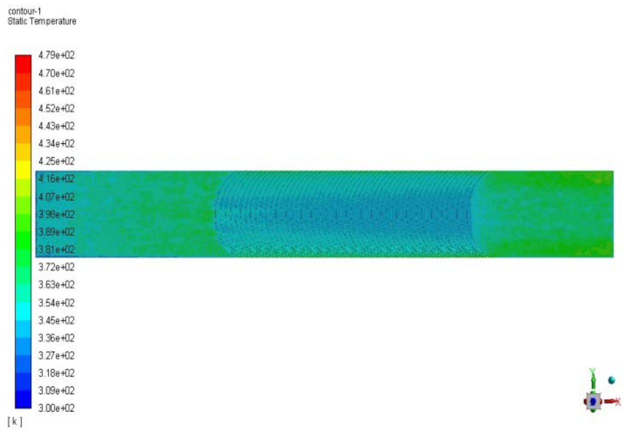

Fig.4. Temperature contour of computational domains of Arc shaped roughness at Re=14000

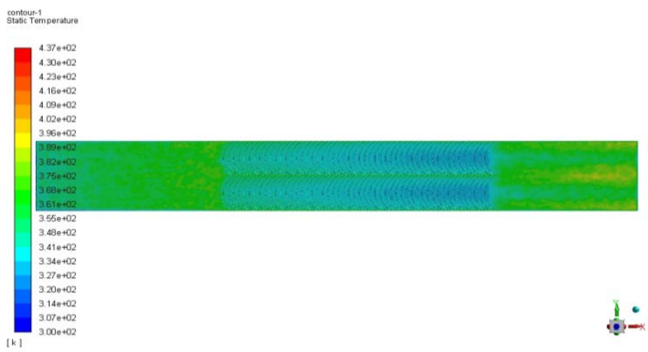

Fig.5. Temperature contour of computational domain of double arc shaped roughness at Re=14000

1.6. Comparison of present roughness with earlier reported rib

The enhancement in the value of Nusselt number by using double arc shaped roughness is found to be more than that of earlier reported arc shaped roughness geometry as well as smooth surface simulated under similar parametric and operating conditions as shown in Fig.6. By applying Double arc shaped of artificial roughness over the span of heated area increases the heat transfer coefficient of solar air heater by developing number of secondary flows over the span which in turn increases the turbulence inside the duct. The roughness is provided repeatedly over the streamwise as well as span wise direction due to which a local turbulence is created along the flow as well as in span wise direction to cover more heated space provided between the two consecutive roughnesses. Heat transfer and Nusselt number increase with the increase in turbulence intensity of flow which is more in double arc shaped rib roughness as compared to single arc shaped rib roughness.

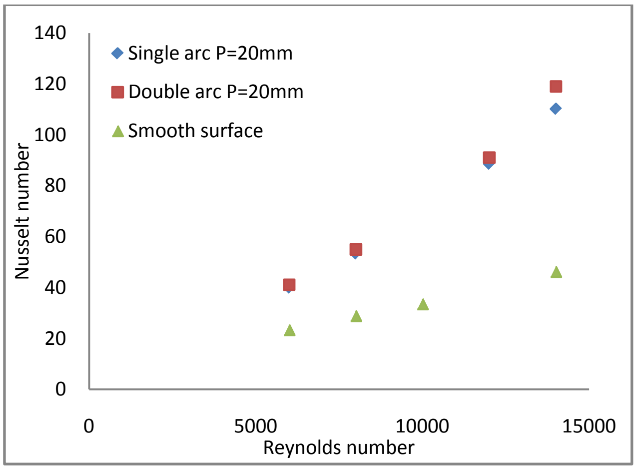

Fig.6. Comparison of Nusselt number Vs Reynolds number for W-rib and V-rib roughness

1.7. Effect of different relative roughness pitch on heat transfer

The variation in the value of Nusselt number for different relative roughness pitch (P/e) of double arc shaped roughness has been displayed in graph for the range of Reynolds number varies from 6000-14000 shown in Fig.10. It is observed from the analysis that for any particular value of Reynolds number, Nusselt number attains maximum value corresponding to relative roughness pitch (P/e) value of 10 and on increasing this value as 12 or 14 results decrease in Nusselt number. It is due to the fact that flow separation occurs on a rib at relative roughness pitch (P/e) as 12 decreases and the reattachment points also decreases with the heated surface because of less number of elements. The temperature contour of double arc shaped roughness having relative roughness pitch (P/e) as 10, 12 and 14 is shown in Fig.7, 8 and 9.

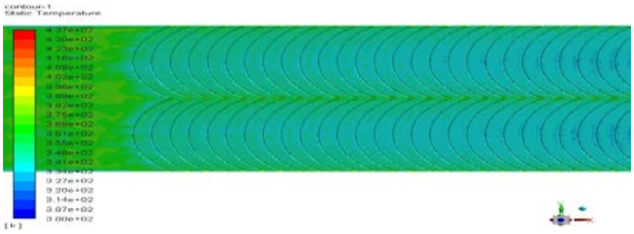

Fig.7. Temperature contour of Double arc shaped roughness having P/e = 10 at Re=14000

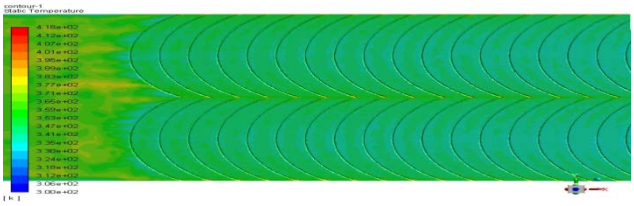

Fig.8. Temperature contour of Double arc shaped roughness having P/e = 12 at Re=14000

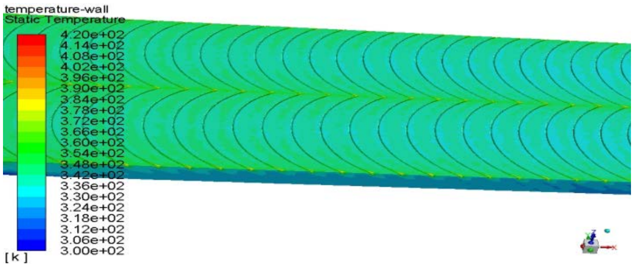

Fig.9. Temperature contour of Double arc shaped roughness having P/e = 14 at Re=14000

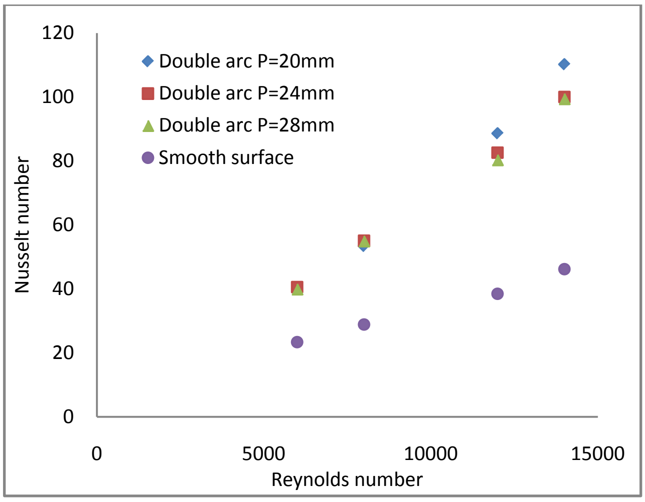

Fig.10. Comparative graph of W-rib roughness with different relative roughness pitch

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

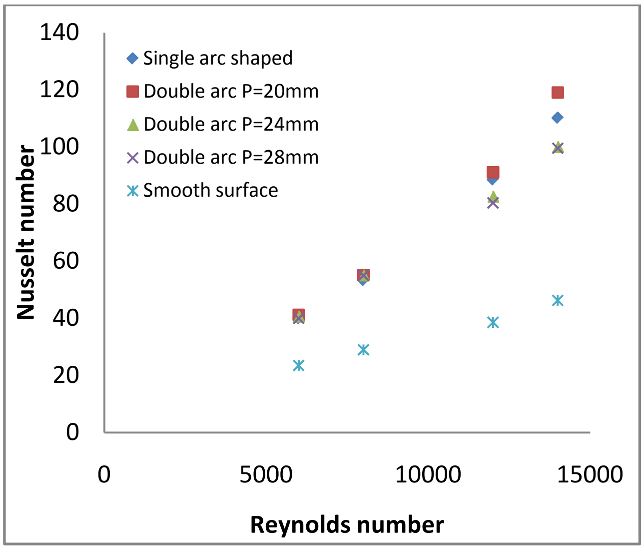

Fig.10. Comparative chart of Discrete and Single arc shaped roughness

IV. CONCLUSION

The present numerical study using CFD carried out by using Double arc shaped roughened solar air heater to evaluate fluid flow and heat transfer characteristics. It shows that the CFD results found in better agreement with experimental results. As we increase the Reynolds number the thickness of boundary layer reduces which improves the convective heat transfer between the heated plate and the air by decreasing the convective resistance, it results increase in Nusselt number. Double arc shaped roughness gives better heat transfer rate as compare to the single arc shaped roughness because of more separation of flow in double arc shaped roughness under similar operating conditions. Double arc shaped roughness also increases the secondary flow which generates more turbulence as compare to the single arc. The maximum value of Nusselt number for double arc shaped roughness is obtained with the relative roughness pitch (P/e) of 10. It starts decreasing on increasing the relative roughness pitch as 12 and 14. The maximum increment in Nusselt number is found to be 2.58 times as compare to the smooth surface at Re = 14000. The maximum increment in Nusselt number is found to be 1.10 times as compare to the arc shaped roughness at Re = 14000.

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