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Thermo-Hydraulic Performance of a Curved Solar Air Heater with Different Shaped down Turbulators using CFD

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ABSTRACT

In contrast to the flat plate SAH design, curved designs of solar air heater ducts show substantial improvement in thermal characteristics, with the former showing a slight decrease in hydraulic efficiency. The creation of secondary vortices resulting in the mixing flow is demonstrated by curved SAH due to the centrifugal effect. In addition, the creation of dean vortices increases the rate of heat transfer in curved SAH. In flat plate SAH, these results are absent. In this present work, a three dimensional CFD analysis was carried out in a Curved duct of a solar air heater with a upper roughened wall with down-configuration ribs having shape of half triangular, full triangular, and semi-circular to investigate the heat transfer and flow behavior. The simulation programme ANSYS 17.0 was used for study of the heat transfer physiognomies of a curved duct of a solar air heater. The curved solar air heater with triangular rib roughness on the absorber plate has been found to yield improved results relative to the half-triangular and semi-circular rib and can thus be used to increase the heat transfer. The maximum enhancement in Nusselt number is found to be in triangular shaped ribs, which is 1.112 times that of half-triangular corresponding to at a Reynolds number of 15,000 for the investigated range of parameters.

KEYWORDS: *Artificial roughness, shape of rib, curved solar air heater, heat transfer, friction factor, and CFD*

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I. INTRODUCTION

Thermo-hydraulic efficiency of any device depends on the configuration of the flow path and how the fluid interacts with the heated surfaces within the passageway. The performance of the solar air heating system depends largely on the configuration of the absorber plate and the flow-through duct [1, 2]. This is why many researchers have based their study on different aspects of the SAH structures, primarily the absorber plate and the duct incorporated with different shapes of ribs or turbulators, such as circular and square cross-section ribs, tapered rectangular cross-sections, various combinations of V-shaped ribs, wavy delta winglets, anchor-shaped inserts, perforated winglet vortex generators, etc.

With the energy generation costs through the use of non-renewable fuel resources, such as coal, crude oil, etc., and due to their limited stock and non-renewable nature, it has become necessary to develop effective designs for devices that use renewable energy sources such as solar energy [3]. Since flat plate SAH is commonly used in many domestic and industrial applications such as room heating, agricultural crop drying, desalination and other heating applications, improving designs for better thermal efficiency will make a major contribution to our increasing energy needs.

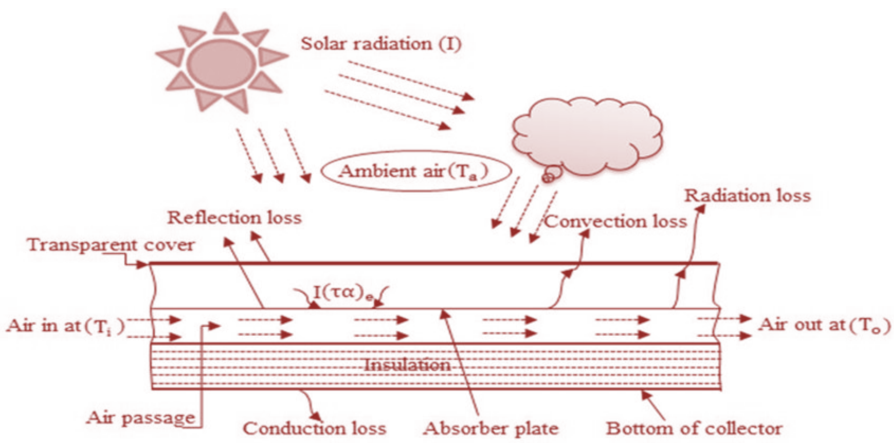

Figure 1 Schematic diagram of conventional solar air heaters

Moreover, provided that the availability of solar insolation is just around 4–6 hours a day, the SAH must be thermally efficient in order to allow use of the full portion of usable solar energy. There are two important facets of the SAH design: the absorber plate and the flow duct, where cold air enters, produces energy from the heated plate and escapes the passage [4].The use of ribs or grooves on the inner surface of the heat exchangers was one of the regular passive approaches to break down the laminar sub-layer and create a turbulent local wall due to the isolation of the flow and the reattachment between the successive corrugation, which decreases thermal resistance and increases the heat transfer rate. A lot of CFD work has been carried out to boost the heat transfer and fluid flow of SAH. The key objective of the present study is to investigate the effect of flow and roughness parameters on the average heat transfer and flow friction characteristics of the artificially roughed curved solar air heater integrated with different shaped ribs.

In contrast to the flat plate SAH design, curved designs of solar air heater ducts show substantial improvement in thermal characteristics, with the former showing a slight decrease in hydraulic efficiency. The creation of secondary vortices resulting in the mixing flow is demonstrated by curved SAH due to the centrifugal effect. In addition, the creation of dean vortices increases the rate of heat transfer in curved SAH. In flat plate SAH, these results are absent.

II. LITERATURE REVIEW

2.1. Previous work

In the present framework, the availability of energy is becoming a big issue in everyday life. A quantitative methodology is needed to forecast the supply of energy supplies due to the decline of traditional energy sources and the environmental risks it presents. Solar energy is a cost-effective and feasible renewable energy supply that can satisfy the continuous growth in energy demand. The flat plate solar air heaters (SAHs) are basic in nature and have less maintenance on the thermal route of their application. SAHs are commonly used for a range of industrial and domestic uses, such as room heating, moisture removal of agricultural products, heating of industrial products, wood/timber seasoning, etc.

One of the key problems of the SAH is its poor performance due to lower air transport capacity. A large amount of the thermal energy is lost to the ambient atmosphere from the absorber plate instead of being passed to the moving air. Researchers have reported various methodologies to resolve this. In the last few years, the interest in increasing the thermo-hydraulic efficiency (THEP) of SAH by the use of various active or passive techniques has become very important. The active approach is focused on the full turbulent flow produced and the local turbulence generated in these systems. The passive technique is based on the surface form of the adjusted and enhanced absorber.

Among these research articles, we can cite the work of Alam and Kim (2017), Kalogirou et al. (2016), Sharma, and Kalamkarar, among important review papers dealing with theoretical, computational and experimental studies for new proposed and enhanced prototypes for solar air heaters (2015).

For instance, **Alam and Kim (2017)** gave an analysis of SAH collectors with different criteria and different ribs. They suggested that the use of forced artificial roughness raised the volume of Nusselt but similarly increased the drop in pressure [1].

In their analysis report, **Kalogirou et al. (2016)** listed various groups of collectors of which the first category contains a parabolic dish and parabolic trough collector, and the second classification consists of SAH, evacuated tube collectors and flat-plate collectors. They found that the exergy analysis offers a helpful way of analyzing and assessing the various configurations of SAH [2].

A detailed thermal hydraulic efficiency study of artificially roughened collectors submitted by **Sharma and Kalamkar (2015)** later stated that there are a number of geometric structures that can be used to facilitate the heat transfer in SAH, such as artificial roughness, baffles, ribs, fins, and various shapes and configurations of groves. They also argued that the use of a limited turbulator height increased the number of Nusselt turbulators and reduced the decrease in pressure [3].

A review analysis of SAH with distinct artificial roughness geometry was performed by **Arunkumar, Karanth,** and **Kumar (2020).** The findings obtained indicated that the productive method of using turbulators as ribs roughness raises the temperature of the outlet air but also the friction factor. The THEP of the SAH decreases, however, as the amount of Re increases [4].

Gabhane and **Kanase-Patil (2017)** performed an experimental analysis on a SAH that has a double airflow pass and multiple C shape roughness on the heated wall for experimental studies. For a set height ratio (e/D = 0.02), the characteristics of a duct aspect ratio (W/H) equal to 10, Re number vary from 3000 to 15,000, rib pitch ratio (P/e) varied between 8 and 40 are considered. For a pitch ratio equal to 24, the highest increase in heat transfer (about 2.8 times relative to the smooth plate solar heater) with the lowest friction factor is obtained [5].

Anil Singh Yadav and **J.L. Bhagoria (2017)** performed an analysis on a SAH with square-sectioned transverse ribs considered at the underside of the top wall, where continuous heat flux conditions are applied, a numerical investigation is performed to examine the heat transport and flow friction characteristics. The influence of the relative roughness pitch was investigated on the average number of Nusselt, the average friction factor and the thermo hydraulic efficiency parameter (THPP). Relative roughness pitch in the range of $7.14 \le P/e \le 17.86$ and relevant Reynolds numbers in the range of $3800 \le Re \le 18{,}000$ are protected by this inquiry. With the finite volume process, the two-dimensional steady, turbulent flow, and heat transfer governing equations are solved. In order to analyse the overall influence of the relative pitch of roughness, the THPP under the same pumping power constraint is determined. The overall THPP of 1.82 for the existing set examined is obtained by using the ribs with a P/e of 10.71 [6].

For a SAH that has non-circular holes such as rectangular and square types that are positioned on the V-shaped blockages, **Alam et al. (2014)** experimentally investigated the difference of Nusselt number and friction losses. Findings have shown that for relative pitch P/e = 8 and 4, respectively, maximal flow resistance and Nu number are obtained. In the case of a rectangular hole with a circularity equal to 0.69 and an attack angle similar to 60 °, thermal enhancement may be accomplished [7].

A SAH experimental research was performed by **Aldabbagh** and **Egelioglu (2015)** to test the fluid flow and thermal behavior for single and double-pass airflow with transverse fin for various mass flow values ranging from 11×10^{-3} to 32×10^{-3} kg/s with an angle of inclination of 37 °. In contrast with the single-pass SAH, the authors concluded that double-pass channel thermal efficiency and flow resistance were also higher [8].

Poongavanam et al. (2018) used a SAH with a modified surface with a form of V-corrugation to perform an experimental analysis of the impact on the Nu number and the pressure drop levels of a rectangular duct of the induced disturbances and enhanced turbulence. They found that the thermal efficiency of the SAH is highly dependent on the absorption of V-corrugation and solar radiation by the SAH. Compared to the smooth absorber layer, the results showed an improved SAH performance with an ideal THEP in the range of 1.35 to 1.56 times [9].

We may cite the work of **Yang** and **Chen (2014)** for numerical studies, who carried out an optimization technique to numerically evaluate a SAH with a vertical partition wall along the absorber plate at the top end. The authors concluded that, relative to the smooth collector, the presence of the partition provides high output and those dimensionless partition parameters such as length (L), thickness (W) and pitch (A) play an important role in the control of the THEP [10].

Gilani et al. (2017) proposed new conical pin protrusions form turbulators to increase the thermal performance of a SAH. The results showed that the ideal inclination value was 45 degrees. Compared with the smooth duct, a rise of up to 26.5% was achieved for the THEP for the roughened wall [11].

A theoretical study of SAH with transverse wavy fins attached to the heated top surface was proposed by **Priyam (2017).** Results demonstrated that with an elevated pressure reduction, the THEP decreases with the rise in the collector length [12].

Theoretical study of artificially roughened SAH with arc-shaped wires arranged under the solar collector's **Yadav et al (2020)** have recently carried out operating conditions**.** The findings showed that, relative to the smooth absorber case, the increase in thermal efficiency for a parallel flow in rough SAH is significant and can achieve a value of about 8 percent to 10 percent [13].

Ajeet et al. (2020) Investigations show that thermo-hydrodynamically curved solar air heaters (SAH) work better compared to the flat SAH design. In addition, down-configurations of turbulators or extended surfaces on a flat plate solar collector have been found to greatly boost thermal efficiency. It was observed that half-trapezoidal and quarter-circular shape ribs display a maximum improvement in thermal performance, i.e. 17% and 16%, respectively, but when compared to trapezoidal shape ribs, frictional loss for quarter-circular ribs was found to be less by around 10% [14].

2.2. Problem finding of literature review

After undertaking a systematic literature review, it is noted that many experimental and computational studies were carried out using artificial roughness in the field of improved thermal efficiency of solar air heaters. However, several C-shape, single and double-pass flow with transverse fin, V-corrugation, delta, stepped cylindrical, oval, square and rectangular ribs were studied in most of the studies studied. Owing to the variation in the shape of the rib and the flow structure, that shows the susceptibility of each design to these parameters, multiple studies note varying degrees of improvements in heat transfer and friction factor. Therefore, the purpose of heat transfer improvement with minimal pressure loss penalty must be based on the choice of any preferred roughness shape and therefore a thermo-hydraulic performance analysis is required.

It is evident from the above discussion that studies are scarce on curved SAH fitted with ribs, which inspired the authors to conduct the present study to investigate the best rib designs for higher thermo-hydraulic efficiency.

In this research a three dimensional CFD analysis was carried out in a Curved duct of a solar air heater with a upper roughened wall with down-configuration ribs having shape of half triangular, full triangular, and semi-circular to investigate the heat transfer and flow behavior. The simulation programme ANSYS 17.0 was used for study of the heat transfer physiognomies of a curved duct of a solar air heater.

The main objective of the present studies is:
- The effect of roughness and flow parameters in a Curved duct of a solar air heater with a upper roughened wall with down-configuration ribs having shape of half triangular, full triangular, and semi-circular on average heat transfer and flow friction properties of artificial rugged solar air heaters.
- To figure out the optimum rib configuration for heat transfer enhancement.
- Investigate the effect of roughness parameters on different SAH thermal properties, such as the number of Reynolds, the number of Nusselt, and the flow friction factor.

III. COMPUTATIONAL MODEL

3.1. Geometrical details of computational model

The geometry for conducting simulation study is drawn from **Ajeet et al. (2020)[14],** a research scholar with exact sizes. The details of the geometry and computational model of conventional design are shown in Table 1 and Figure 2 respectively.

Table 1 Geometric parameters of Curved solar air Heater

Geometrical parameters	Value / Range
length of duct, (mm)	1600
Duct height, H (mm)	40
Curvature angle (◦)	25
Duct hydraulic diameter, Dh (mm)	33.33
Rib height e (mm)	1.4
Pitch P (mm)	50
Relative groove height ratio, 'e/H'	0.125

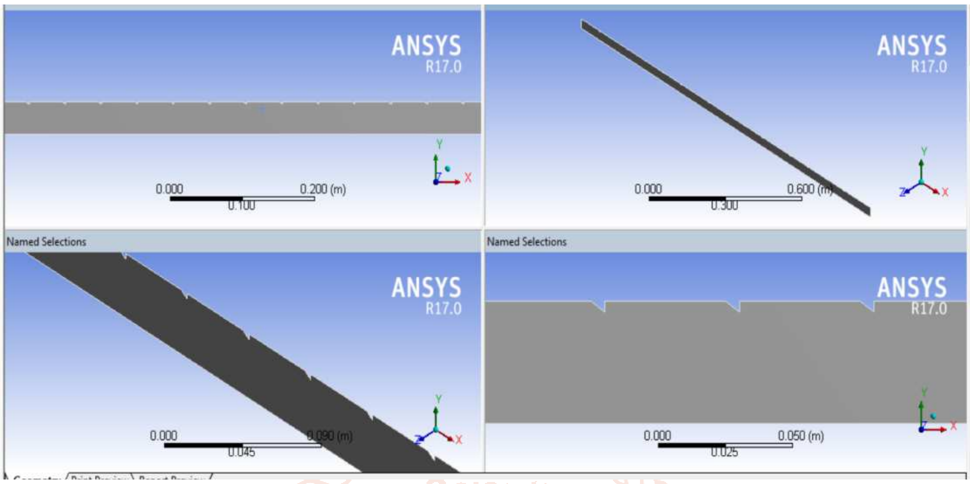

Figure 2 Geometry of a curved SAH having25° curvature angle with the half-triangular grooved absorber plate (Conventional design)

After than in the proposed designs, 'full triangular and semi-circular' section rib is employed on the absorber plate. The part of the model designed in ANSYS (fluent) workbench 17.0 software.

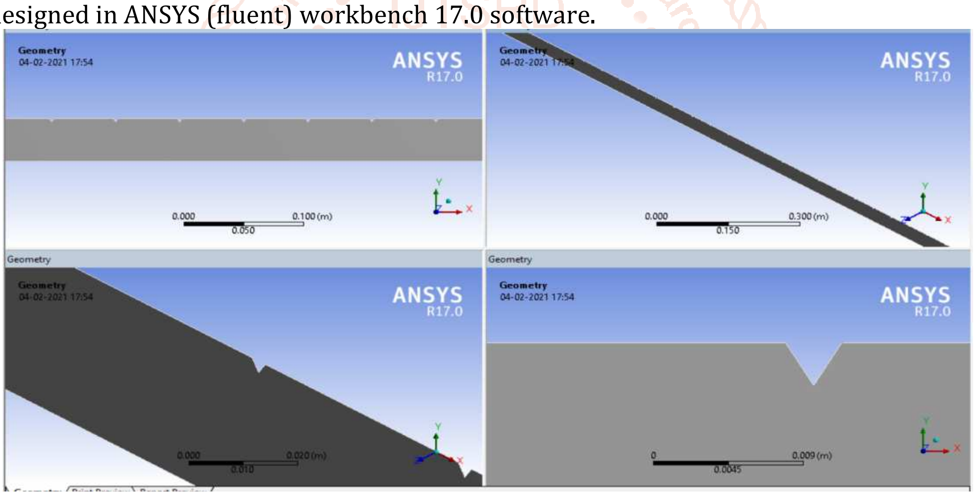

Figure 3 Geometry of a curved SAH having25° curvature angle with the triangular grooved absorber plate (Proposed design)

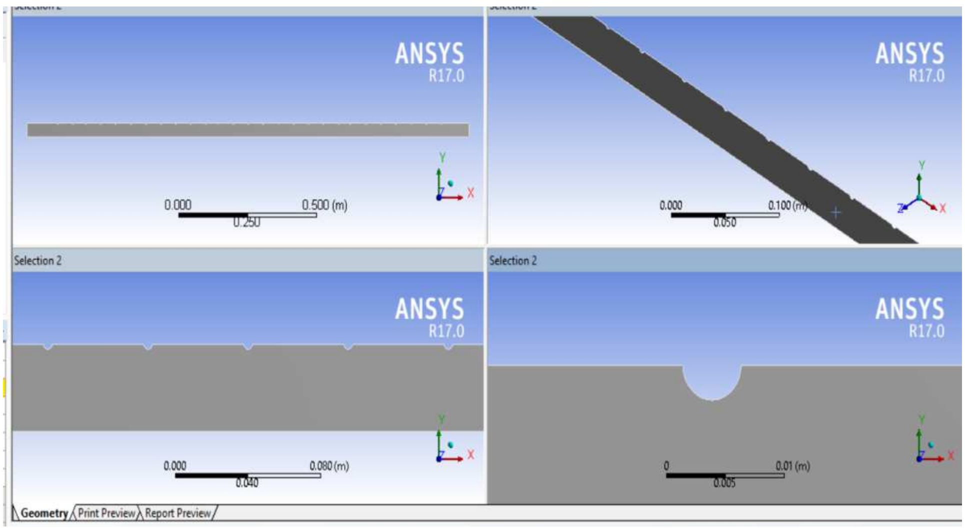

Figure 4 Geometry of a curved SAH having25° curvature angle with the semi-circular grooved absorber plate (Proposed design).

3.2. Meshing

In the pre-processor step of ANSYS FLUENT R 14.5, a three-dimensional discretized model was developed. Although the styles of grids are connected to simulation performance, the entire structure is discretized in the finite volume by, default; a coarse mesh is generated by ANSYS software. Mesh contains mixed cells per unit area (ICEM Tetrahedral cells) having triangular faces at the boundaries. The meshing that has used in this analysis is mesh metric with medium smooth curvature.

Table 2 Meshing detail of various models

S. No.	Parameters	Semi-triangular rib (Conventional design)	triangular rib (Proposed design	Semi-circular rib (Proposed design)
1	Curvature	On	On	On
2	Smooth	Medium	Medium	Medium
3	Number of nodes	64767	64808	64943
4	Number of elements	63134	63174	63207
5	Mesh metric	None	None	None
6	Meshing type	Tetrahedral	Tetrahedral	Tetrahedral

IV. NUMERICAL PROCEDURE

The RNG k-ε model was chosen as the turbulence model for the further study of the problem because the flow is turbulent. As a heat transfer model, the energy equation is also kept ON.The numerical model for fluid flow and heat transfer through an artificially roughened solar air heater is developed under the following assumptions:

- The fluids sustain a single-phase, turbulent flow through the duct.
- 3D steady heat transfer fluid flow.
- Flow thoroughly formed both thermally and hydraulically (steady-state conditions).
- Both the fluid (air) and rigid absorber (aluminium) have continuous thermo-physical characteristics (temperature independent).
- Refused heat transfer by radiation.

The heat transfer equations and fluid flow structure contains the mass, momentum and energy conservation equation. The equations are as follows:

The mass conservation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0$$

The momentum conservation:

$$\frac{\partial(\rho \overline{u_i u_j})}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial\left(\mu + \mu_t\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)\right)}{\partial x_j}$$

The energy conservation:

$$C_p \overline{u_i} \frac{\partial(\rho \bar{T})}{\partial x_i} = \frac{\partial\left(\lambda \frac{\partial \bar{T}}{\partial x_i}\right)}{\partial x_i} - C_p \frac{\partial\left(\frac{\mu_t}{Pr_t}\frac{\partial \bar{T}}{\partial x_i}\right)}{\partial x_i}$$

All governing equations are discretized by a second-order upwind-biased scheme using a finite volume approach and then solved in a segregated manner. The SIMPLE algorithm to couple pressure and velocity is selected for the in compressible flow computation. Convergence criteria are defined as 0.001 for all dependent variables. Whenever issues of integration are found, the solution starts with the upwind discretization system of first order and ends with the upwind system of second order.

After setting all necessary input conditions, theproblemissettoiteratefor1000iterationswithinwhich it gives well converged according to the set convergence criteria so that we can get accurate results.

4.1. Material Property

For any kind of analysis property are the main things which must be defined before moving further analysis .There are thousands of materials available in the ANSYS environment and if required library is not available in ANSYS directory the new material directory can be created as per requirement.

Table 3 Thermo-physical Properties of Air and Aluminium

Properties	Air	Absorber plate (Aluminium)
Density, 'ρ' (Kg/ m^3)	1.184	2719
Specific heat, 'c_p' (J-Kg/K)	1003.62	871
Thermal conductivity, 'k'(W/ m-K)	0.026	202.4
Viscosity, 'μ' (N-s/m^2)	1.855×10^{-5}	---
Prandtl number	0.71	---

4.2. Boundary Conditions

All the cases considered were simulated under a set heat flux absorber value, q=1000 W/m^2. A flow velocity value corresponding to a basic Reynolds number, Re was assigned. At the outlet section, the atmospheric condition was maintained by assigning the gauge pressure value to zero (i.e. atmospheric condition) and rest walls were believed to be adiabatic (i.e. assuming no heat loss to ambient). The walls are subject to the boundary state of no-slip. For the Re 11,000-15000 scale, each case has been simulated. The flow was known as an incompressible flow, meaning that the density of the fluid was independent of changes in the pressure values.

For inlet flow to the duct and the outlet flow from the duct is regulated by a uniform velocity inlet boundary state. The air reaches the duct with a uniform velocity at room temperature (T_0 = 300 K) (U_0). A pressure outlet condition with fixed atmospheric pressure of 1.013×10^5 Pa is applied at the exit. Impermeable boundary and slip-free wall conditions over the walls of the duct are applied.

V. RESULTS AND DISCUSSIONS

The purpose of the present work of CFD is to research the impact that a rib shape has on average Nusselt numbers as well as average friction factor, and THPPs on the underside of the absorber plate in artificially roughened solar air heaters with transverse ribs.

The average Nusselt number for artificially roughened solar air heaters is defined as:

$$\boldsymbol{Nu} = \frac{h\,D_h}{K_a}$$

Reynolds number is defined as:

$$\boldsymbol{Re} = \frac{\rho u D_h}{\mu}$$

where $\boldsymbol{\rho}$ is the density of the air inlet, $\boldsymbol{u}$ is the average velocity of the air inlet, $\boldsymbol{D_h}$ is the hydraulic diameter of the wedge duct inlet, and $\boldsymbol{\mu}$ is the dynamic viscosity of air at the inlet.

For artificial solar air heaters the average friction factor is determined by:

$$\boldsymbol{f_r} = \frac{\left(\frac{\Delta P}{l}\right)D}{2\rho\vartheta U^2}$$

Where $\Delta\boldsymbol{P}$ is pressure drop across the duct of an artificially roughened solar air heater.

The temperature factor for artificially roughened solar air heaters is defined as:

$$Temperature\ factor = \frac{T_o - T_i}{I}$$

5.1. CFD validation

Comprehensive and very settled results are promised in computational models. Numerical models of physical dimensions need to be checked, however. The simulation of artificially roughened solar air heaters is conducted with the objective of validating the numerical model, and the results are correlated with the data from **Ajeet et al. (2020)[14],** who studied the influence of semi-down turbulators on curved roughened frictional factors and heat transfer.

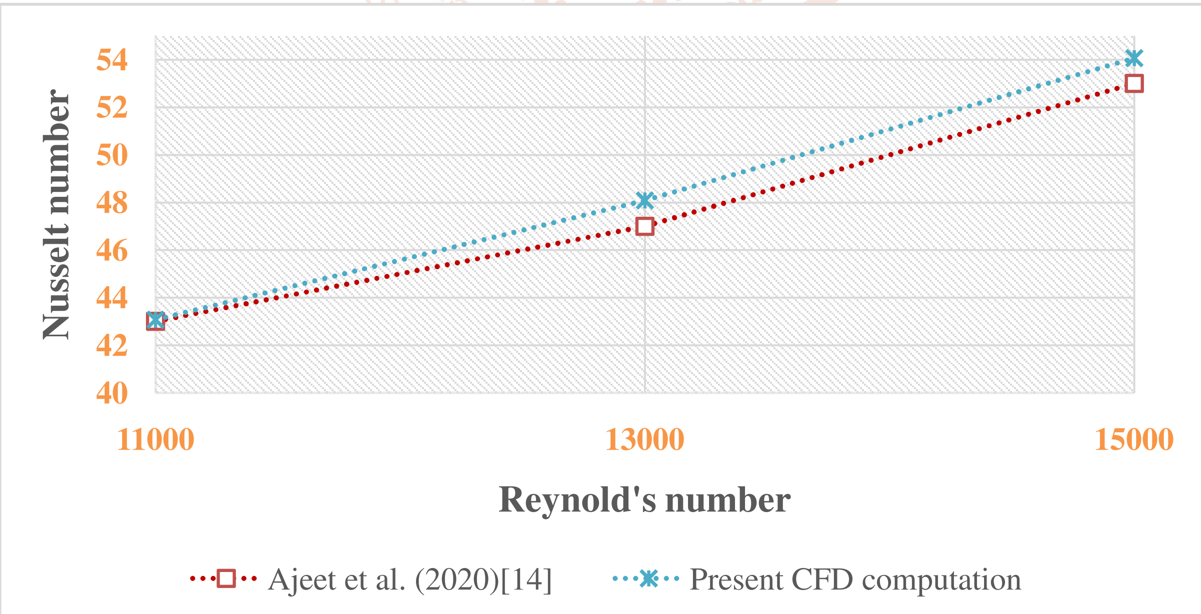

Figure 5 Comparison of the Nusselt number derived from CFD results and the Ajeet et al. (2020) [14] results

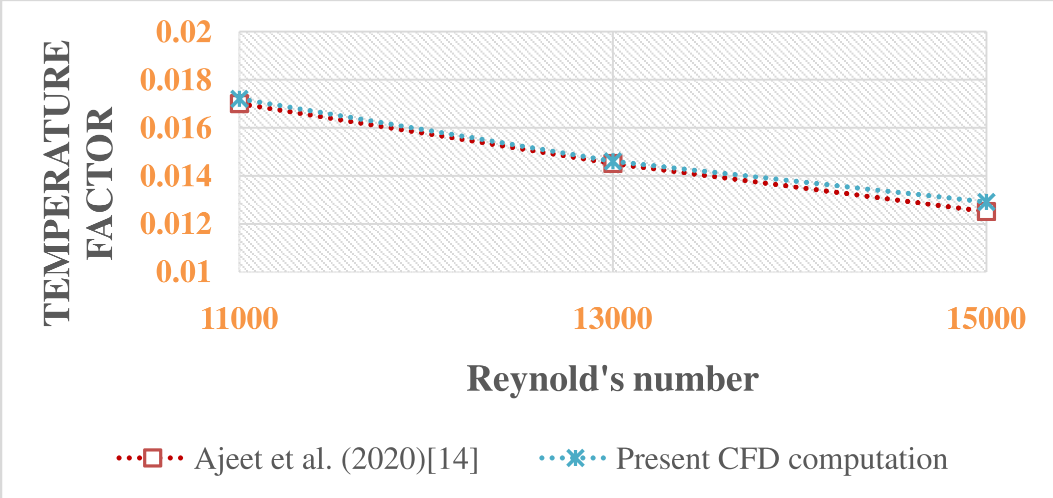

Figure 6 Comparison of the temperature factor values derived from CFD results and the Ajeet et al. (2020) [14] results

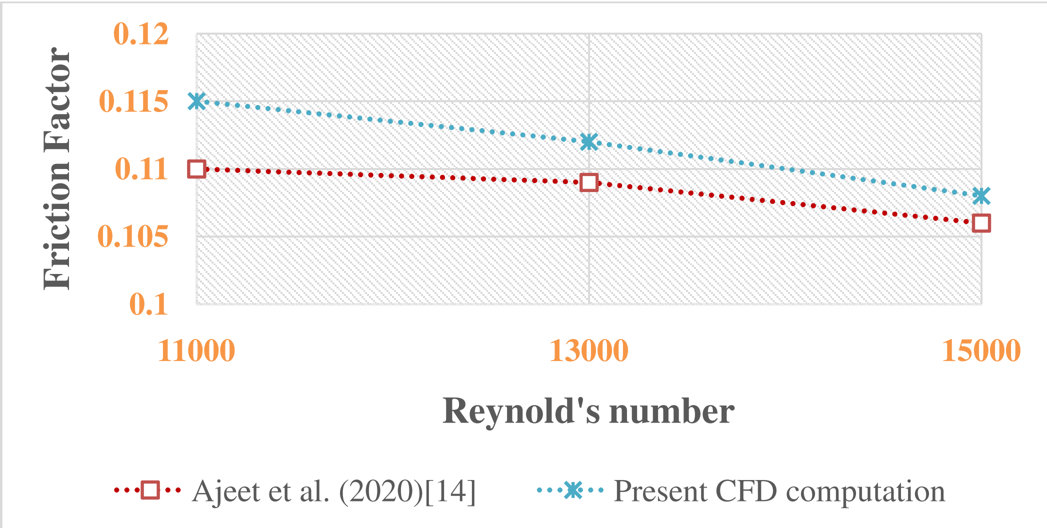

Figure 7 Comparison of the friction factor values derived from CFD results and the Ajeet et al. (2020) [14] results

From the above graph, it is found that the value of **Nusselt number, Friction factor**, and **Temperature factor** calculated from numerical analysis is closer to value **Nusselt number, Friction factor**, and **Temperature factor** obtained from the base paper, which means that numerical model is correct.

5.2. Comparison between the value of the Nusselt number, Friction factor ratio, and Temperature factor for half-triangular, triangular, and semi-circular rib on the absorber plate

To improve previous understandings and to distinct the contribution of providing a half-triangular, triangular, and semi-circular rib on the absorber plate to the overall thermal enhancement of proposed design, absorber plate with half-triangular, triangular, and semi-circular rib on the absorber plate are compared in this section.

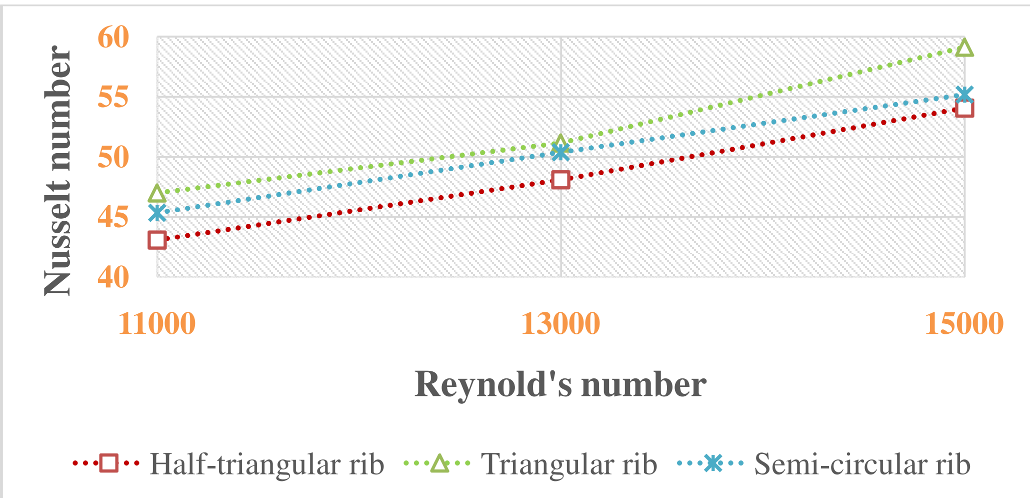

Figure 8 Comparison of the Nusselt number values with half-triangular, triangular, and semi-circular rib on the absorber plate

Figure 8. shows the variation of Nusselt number as a function of Reynolds number. In this case, the Nusselt number ratio increases with increase in Reynold's number for all the cases.

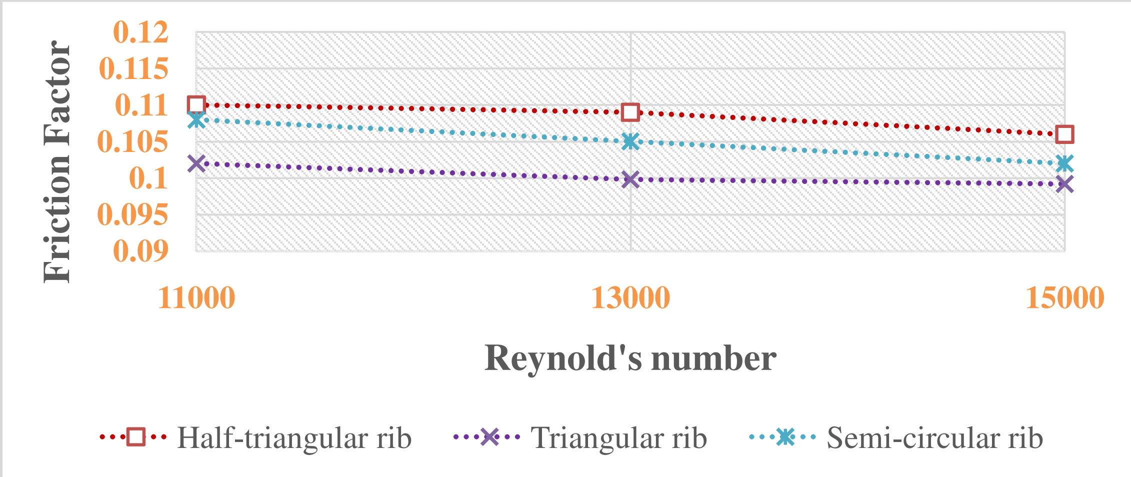

Figure 9 Comparison of the friction factor values with half-triangular, triangular, and semi-circular rib on the absorber plate

Figure 9shows the variation of friction factor as a function of Reynolds number. In this case, the friction factor ratio decreases with increase in Reynold's number for all the cases.

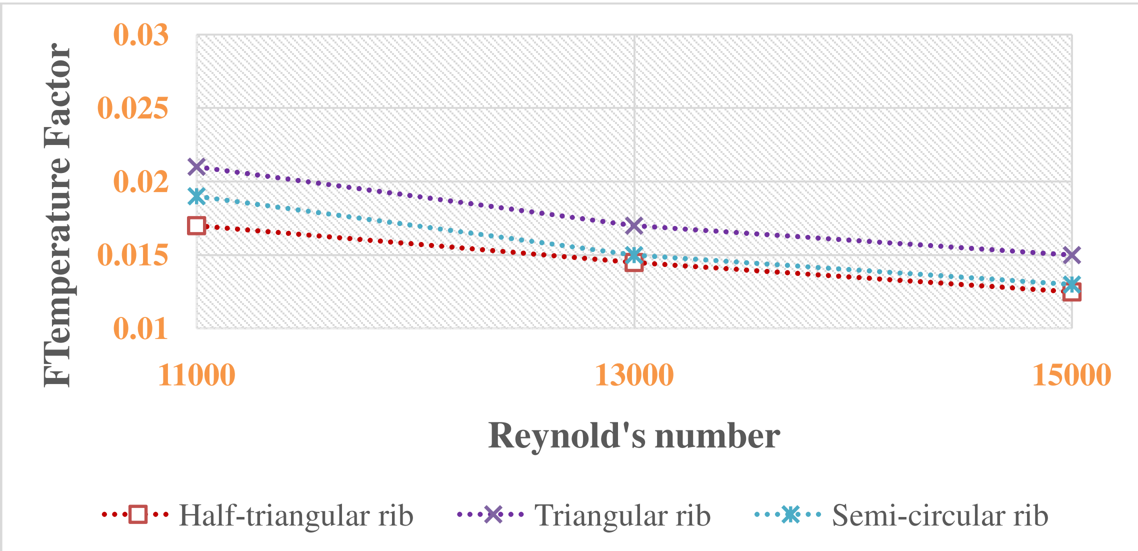

Figure 10 Comparison of the Temperature factor values with half-triangular, triangular, and semi-circular rib on the absorber plate

VI. CONCLUSIONS

Based on the CFD provision currently in operation, the following related results can be reached by analyzing a 3D curved solar air heater with half-triangular, triangular, and semi-circular rib on the absorber plate rib with the heat transfer and flow friction, the following conclusions can be drawn:

- The maximum enhancement in **Nusselt number** is found to be in triangular shaped ribs, which is 1.112 times that of half-triangular corresponding to ata Reynolds number of 15,000 for the investigated range of parameters.
- The minimum **friction factor** is found to be in triangular shaped ribs, which is 0.89 times that of half-triangular corresponding to ata Reynolds number of 15,000 for the investigated range of parameters.
- The maximum enhancement in **Temperature factor** is found to be in triangular shaped ribs, which is 1.28 times that of half-triangular corresponding to ata Reynolds number of 15,000 for the investigated range of parameters.
- The curved solar air heater with triangular rib roughness on the absorber plate has been found to yield improved results relative to the half-triangular, and semi-circular rib and can thus be used to increase the heat transfer.

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