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Numerical Analysis of Heat Transfer Performance of Inclined Elliptical Roughness of Roughened Plate Solar Air Heater

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Abstract. *Artificial roughness plays a vital role on heat transfer and fluid flow characteristic on solar air heating system. It promotes economical and effortless approach towards thermal management of solar air heater system a utilization of free radiation energy makes this system cost effective. In present investigation, a solar air heater with inclined ribs of different inclination angle i.e. 12, 14, 18 and 21 degree angle and smooth absorber plate is numerically analyzed. The article emphasizes a CFD based approach to observe thermal behavior of solar air heater, a K – Epsilon turbulence model is used with SIMPLE algorithm. The study is done for different e/D values and Re ranging from 3800 to 18,000 in the turbulent zone. The result demonstrates that the inclined elliptical rib with 14 degree angle exhibits the better thermal enhancement factor. The TEF is observed higher for 1.82 at Reynolds number 15,000.*
Keywords: *Friction factor, Roughness, Inclined Elliptical Ribs, CFD, SAH, Nusselt number.*

1.1 INTRODUCTION

Nowadays, producing clean energy is one of the most difficult areas to govern because to low petrol emissions and the greenhouse effect. The use of coal in production, air conditioning methods, and resource production all contribute to the greenhouse effect in our surroundings, which negatively impacts our ecology. One of our main energy sources that may be used to generate energy in a variety of ways is solar energy. Aircraft systems, solar-powered electricity generating, and solar-powered water heating systems are all in use today. Solar air heaters are currently commonly utilised to achieve the required air temperature in occupied spaces. A country's economy will benefit from it since it will import fewer fossil fuels, including petrol and diesel. The production of job possibilities tends to require a structured framework and frequent rehabilitation for renewable energy. Due to its extremely low carbon emissions, it is one of the key strategies for switching to a very healthy ecosystem way of life [1, 2]. It is therefore simple to manage and isn't typically thought of as an energy-efficient the formation of a laminar sub-layer is primarily to blame for a SAH's reduced efficiency. This lowers the efficiency and supports the total thermal effect. Fins or ribs are taken into account as a surface roughness to degrade this layer in the passive approach of efficiency enhancement [3-11]. An excellent way to maximize system efficiency is to create surface ridges that resemble the surface pattern of a SAH duct by repetition in the form of ribs. It has been determined that different approaches have been taken in analyzing the impact of surface roughness of improved design on heat transfer and friction factor in SAH ducts. Higher heat transmission and plate efficiency are achieved by Prasad and Mullick's study [12] by modifying the protruding wires on the absorber plate surface. According to Prasad and Saini [13], equations for Str and fr were derived from the experimental studies, and flow behaviour in the SAH duct was examined using a protrusion wire acting as a rib. Nusselt number and friction factor values were correlated by Saini and Saini [14] using stretched metal mesh roughened geometry as a starting point. Researchers Gupta et al. [15] conducted a study on roughened SAH ducts and discussed their overall performance as well as how they relate to a conventional smooth SAH duct. The greatest THPP was discovered when Re = 14,000 and e/Dh = 0.033 were used. Karwa et al. [16] determined the wind velocity inside the duct by taking into account an integral rib with a chamfered shape to forecast the relationship between the friction factor and Nusselt number. They determined that a 15° rise in the Nusselt number and friction factor was the most efficient. According to Verma and Prasad [17], an e+ of 24 indicates the maximum THPP of the SAH duct. Sahu and Bhagoria [18] projected a SAH duct with discrete transvers ribs at a 90° angle on the absorber plate. It was projected that the effective result observed in heat transfer achieved at a pitch (p) of 20 mm. The impact of a SAH duct with a rib-grooved shape on the variables Nusselt number, friction factor, and THP was examined by Jaurker et al. [19]. They discovered that a very large increase in heat transfer was produced by a groove design to pitch ratio of 0.4. When Layek et al. [20]analyzed the SAH duct's transversely chamfered rib groove and hypothesized a relationship between the friction factor and Nusselt number. Their findings show that the maximum increase in heat transfer was observed at p/e = 6, and that the relative groove position (g/p) was 0.4. Varun and associates. [21] assessed how combining the roughness parameter impacts the Nusselt number and friction factor values using a transverse and inclined rib roughened arrangement on the plate. They hinted that gth at P/E = 8 may be as high as possible. Aharwal and colleagues [22] investigated the space between ribs in relation to an inclined rib. They finalized that the friction factor and Nusselt number are maximized when gaps are created in an inclined rib. Lau et al. [23] found that the V-shaped rib has the highest value Nu when compared to transverse and inclined ribs. Momin et al. [24] conducted the experimental SAH duct with V-rib roughness and likewise produced a relationship between Nu and f. The highest THPP at e/Dh was found to be 0.034, with a greater value at 60°. Singh et al. conducted an investigation of the SAH duct with V-downrib with gap [25], the roughness is formed by combination between the absorber plate and the shape of roughness. They observed that the maximum nusselt number and decreasing friction factor is found at p/e = 8, e/Dh = 0.043. Maithani et al. [26] performed an experimental analysis with V-shaped ribs consisting of gaps in which they formed a correlation between the Nussult Number and friction factor. Their findings show that at Ng = 3, p/e = 10, g/e = 4, and at angle of 60°, Nu and f grew to their maximums. Deo et al. [27] evaluated the effect on SAH performance of "multiple-gap V-rib interrelated with staggered ribs" in their analysis. They discovered that the greatest increases in thermal hydraulic performance parameter and Nu were 2.45 and 3.34 times, respectively.. Hans et al. [28]studied the surface impacts of the roughness configuration of the V-shaped rib. The formula was designed so that at p/e = 8, a = 60°, and W/w = 6, the maximum rise in Nu and f produced. A hole was created in a multiple-V rib construction by Kumar et al. [29]. The researchers found that THPP is founded at a relative gap distance of Gd/Lv = 0.69 and at a g/e = 1. In order to determine how the SAH functioned, Patel and Lanjewar [30] conducted an experimental analysis taking into account several discrete V-patterns in combination with staggered ribs. The highest Nu and f was observed at 2.27 and 4.28 times, respectively. Aharwal et al. [31] conducted an experimental and computational study to examine the roughness of the SAH duct grooves and ribs. Kumar et al. [32] conducted multi-V-rib with gap tests on the SAH duct. A numerical study of the SAH duct was conducted by Kulkarni and Kim [33] in order to forecast how the flow would change with the augmentation of various forms and shapes. Arc-shaped roughened geometry was considered by Sahu and Prasad [34] in their investigation of the SAH duct.Sahu and Prasad [34]. Kumar et al. [35] employed a multi-V-perforated baffle in their study of the SAH duct. Various ribs have been used in numerous studies to enhance heat transfer while reducing the impact of the friction factor. It is observed in the literature that numerous experimental and analytical studies have been conducted. Numerous researchers have performed experimentation with various rib locations and arrangements. To discover the best configuration of rib shape, some researchers perform CFD analyses multiple times, including roughness for SAH [36–56]. A concentrated approach had been performed by researchers to improve performance of solar air heater by addition of roughness but some deficiency is observed in flow behavior during heat transfer so in this work a comparative computational fluid dynamics (CFD) analysis that employs varying roughness geometry and inclined elliptical ribs to optimise heat transmission and minimise the impact of friction factor.

1.2 CFD Approach and Simulation

This study is done to provide a description of a two-dimensional numerical simulation in a roughened inclined embossed ellipse. There are tiny ribs that roughen the plate's interior surface. The evaluation of heat transfer by computational fluid dynamics was done for various heights of inclined embossing ribs with a sinusoidal design. ANSYS-Fluent software was utilized to conduct an examination of the RNG k-e turbulent model. In the equations for momentum and energy, the second-order upwind technique was chosen. The SIMPLE algorithm combined pressure and velocity. For each residual, a low convergence threshold was selected in order to accurately forecast various values. In this investigation, a 740 mm-long rectangular segment was taken into consideration. It had an exit length height of 20 mm, a width of 100 mm, and an entry length and test section length. Yadav and Bhagoria's numerical work is the source of this geometry [57]. The inlet section is specified to guarantee that the air flow in the middle test section is fully developed. We utilised ANSYS Fluent for numerical simulation. Chaube and Sahoo [58] ran numerical calculations on their solar air heater. They compared the 3-dimensional and 2-dimensional findings and discovered only slight variations. We conducted a 2D study in support of SAH as a result. Figure 2 shows how the solar air heater's inclined embossed elliptical roughness is arranged. The discre-atization was done using ANSYS meshing domain after modeling the geometrical configuration. Fig. 4 express the mesh generation for inclined embossed elliptical roughness for SAH.

Different conservation equations for turbulent fluid flow are as follows:
Continuity Equation:

$$\frac{d}{dx_i}(\rho u_i) = 0 \quad (1)$$

Momentum Equation:

$$\frac{d}{dx_i}(\rho u_i u_j) = -\frac{dp}{dx_i} + \frac{d}{dx_j}\left[\mu\left(\frac{du_i}{dx_j} + \frac{du_j}{dx_i}\right)\right] + \frac{d}{dx_j}(-\rho\overline{u_i u_j}) \quad (2)$$

Energy Equation:

$$\frac{d}{dx_i}(\rho u_i T) = \frac{d}{dx_j}\left((\Gamma + \Gamma_t)\frac{dT}{dx_j}\right) \quad (3)$$

Where,
$\Gamma=\mu/P_r$ and $\Gamma_t=\mu_t/Pr_t$

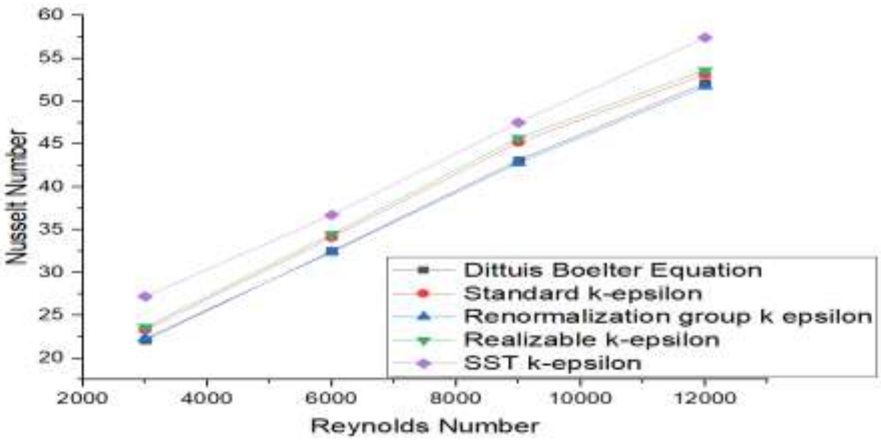

Figure 1 - Validation of Present study

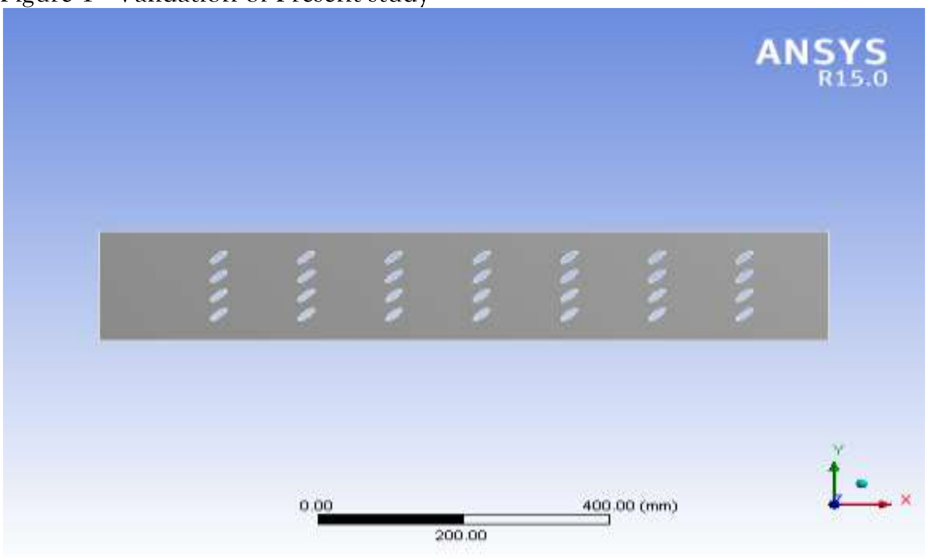

Figure 2 – Inclined elliptical ribs arrangement
Working fluid is considered as a air in this experiment, and aluminium serves as the base plate material. Table 1 displays the material's many attributes. A uniform inlet velocity, uniform atmospheric pressure at

the outlet boundary conditions, and heat flux of 1000 W/m2 on the test zone were demonstrated and are tabulated in table 2

1.3 Data reduction

The equations below determine Nur and fr for ribbed SAH ducts:

$Nu_r = hD/k$ (4)

The equations below determine nusselt number and friction factor for smooth solar air heater ducts dittus – boelter equation [59]

$Nu_s = 0.023Re^{0.8}Pr^{0.4}$ (5)

Blasius equation [60]

$fs = 0.0791Re^{-0.25}$ (6)

Thermal Enhancement Factor

$$TEF = \frac{\left(\frac{Nu_r}{Nu_s}\right)}{\left(\frac{fr}{fs}\right)^{\frac{1}{3}}} \quad (7)$$

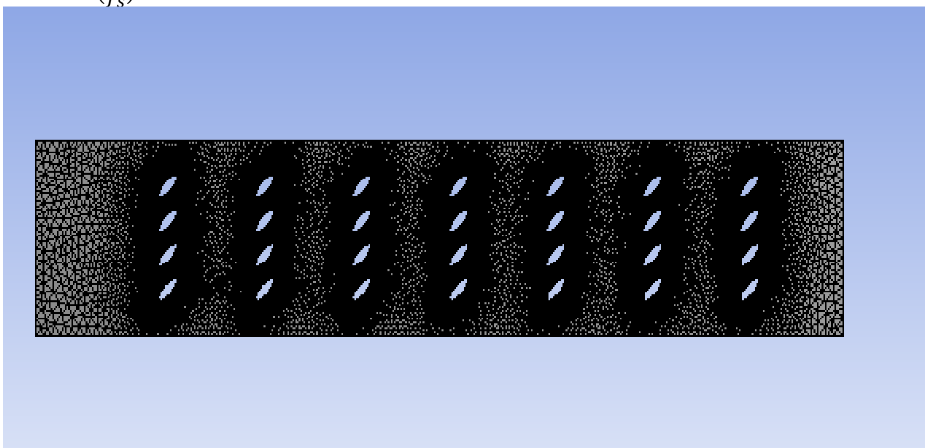

Fig 3 - 2-D model grid of inclined elliptical ribs.

Table 1. Thermo-physical properties of absorber plates and air.

Properties	Working fluid (Air)	Absorber plate (Aluminum)
Density,'q'(kgm^{-3})	1.225	2719
Specificheat, 'C_p' ($Jkg^{-1}K^{-1}$)	1006.43	871
Viscosity,'l'(Nm^{-2})	1.79E-05	–
Thermal conductivity, 'k'($Wm^{-1}K^{-1}$)	0.0242	202.4

Table 2. Boundary conditions used in the present simulation.

Geometry Position	Conditions	
Left	Inlet	Velocity Inlet
Right	Outlet	Pressure outlet
Top Side wall	Wall	Wall
Base wall	Heated Section	Wall

1.4 RESULT AND DISCUSSION

The précised result was observed by choosing the good mesh quality which have greater significance the validated result is shown in figure 1. Hence, grid independence tests were carried out at Re 3800 in order to choose an appropriate mesh size for carrying out the numerical simulations. Figure 5 illustrates how, for various rib geometries and smooth plates with uniform heat flux, the Nusselt number of the roughened plate changes with Reynolds number. Nusselt number is primarily dependent on velocity and other geometric factors. As the Reynolds number increases, the average wind velocity also rises, correlating with a rise in the Nusselt number of the roughened plate. A solar air duct with ribs has a maximum Nusselt number of roughened plates compared to one with a smooth channel. It has been discovered that an ellipse with a sinusoidal-shaped rib has a highest Nusselt number of 168.38 at Re 15,000. The typical Reynolds number for an ellipse with a sinusoidal-shaped rib span from 3800 to 18,000.

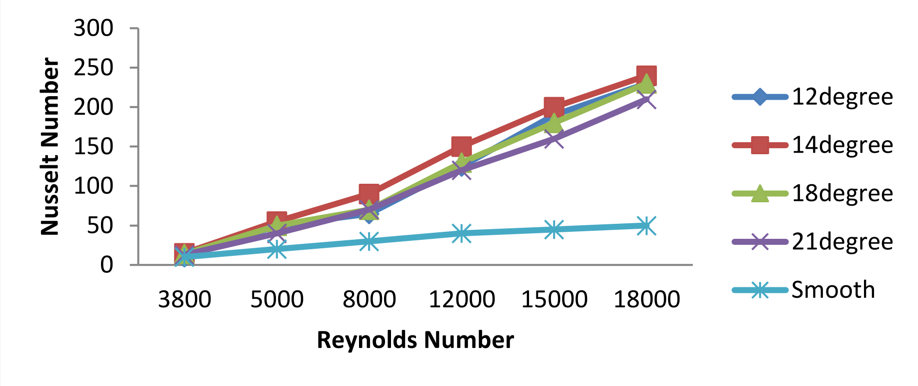

Figure.4.Variation of Nusselt number with Reynolds number.

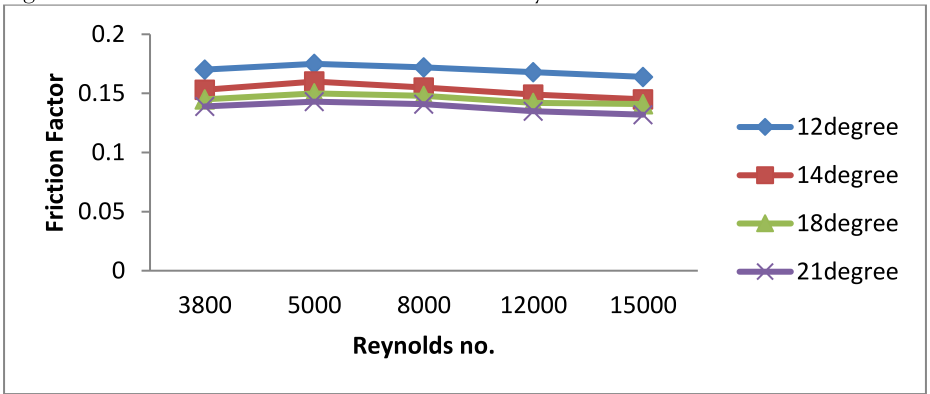

Figure5.Variation of Friction Factor with Reynolds number.

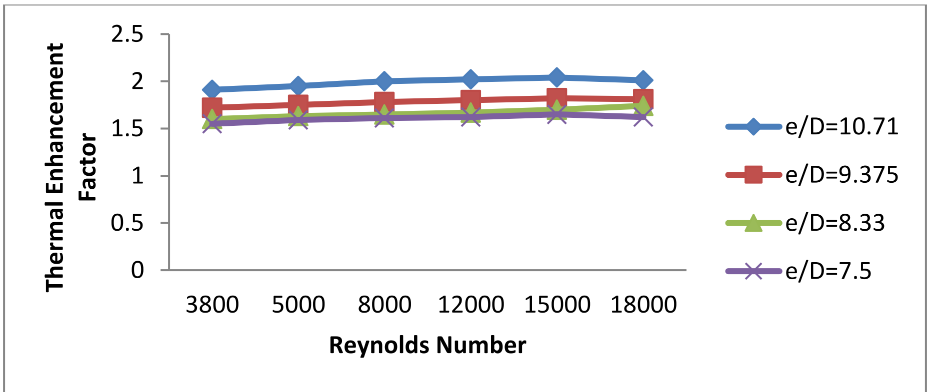

Figure 6.Variation of Thermal enhancement factor with Reynolds number.

Maximization in Nusselt number is found as compared to a solar absorber plate with no roughness is 1.95–3.85. An elliptical rib with a 14-degree angle and inclined elliptical roughness has a higher Nusselt number of 238 at Reynolds number 18,000. For inclined elliptical ribs, the Reynolds ranges between 3800 to 18,000, and a roughened plate has an average increase in Nusselt number of 1.88–2.96 relative to the smooth channel. For inclined elliptical roughness of solar air heater, Fig. 5 also shows the Nusselt number of roughened plate difference with Reynolds number at different e/D value, with the value of e/D shifting from 7.5 to 10.71. The outcome shows that, for various roughened ribs at Re 18,000, a greater average Nusselt number for roughened plate is observed at e/D = 10.71. Fig. 5 shows the impact of the Reynolds number on the roughened plate's friction factor for various roughened geometries. For the entire value of e/D, the friction factor of a roughened plate is entirely dependent on the Reynolds number, which falls as the flow maximizes. The Reynolds number and the friction factor are inversely related. The friction factor of roughened plate fluctuation with Reynolds number for different rib shapes is shown in Fig. 5. This approaches the roughened plate maximum friction factor, which for an inclined elliptical rib has a value of 0.14 at Re = 3800. A smooth plate has a greater friction factor than a roughened plate (0.059) at Re 3800. For different ribs, the Reynolds number varies from 3800 to 18,000, and the roughened plate's average increase in friction factor is 2.5–5.06 times higher than that of the smooth plate. The highest friction factor of an inclined elliptical rib profile is 0.176 at Reynolds number 18,000. The average increase in friction factor for inclined elliptical ribs with Reynolds numbers ranging from 3800 to 18,000 is 3.05–4.96 times than the smooth plate. Lastly, at a Re of 15,000, a roughened duct with an e/D of 10.71 has a maximum Thermal enhancement factor of 1.82.

CONCLUSIONS

In order to analyses the thermal behaviour of various profiled ribs and discrete ellipticals, including sinusoidal ribbed type of rib forms placed in various configurations, a two-dimensional computational domain was built. In turbulent flow zones, the analysis was done for various Reynolds number values. The findings of the numerical investigation of the solar air heater lead to the following observations.

- The CFD approach emphasizes the Nusselt number for Roughened solar air heater is greater than the Nusselt number for smooth SAH.
- Friction factor for rectangular channel with inclusion of rib is found to be maximum than the absorber plate without roughness.
- As per results obtained from the CFD analysis, it has been concluded that the discrete elliptical with rib generates higher Nusselt number and lower friction factor as increase in Reynolds number.
- The Nusselt number observed to be high for an absorber plate having ribs of e/D equal to 10.71.
- The Nusselt number have a higher value of 238.34 at Reynolds number 18,000 for the other rib profiles.
- The thermal enhancement factor has been observed to have a maximum value of 1.82 at Re = 15,000 for the discrete elliptical profiled rib.
- It is observed that inclined elliptical rib of 14 degree angle shows good results in all parameters.
- The following proposed rib geometry induces better thermal enhancement, this rib geometry enhances vorticity in flow. This could be compared with other rib geometries with different process parameters in context of turbulence and parametric evaluation.

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