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Solar Air Heater with Artificial Roughness in the Form of U-shaped Turbulators: CFD-based Performance Analysis

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A B S T R A C T

In the present study, a solar air heater U shaped turbulators integrated on the absorber plate with artificial roughness has been subjected to computational fluid dynamics (CFD) analysis. For simulation, Renormalization group (RNG) k- ε model has been used to investigate several fluid flow properties such as flow behaviour, temperature distribution along absorber plate, and velocity distribution. By taking into account the relative roughness height (e/D) varies from 0.018 to 0.038 and a turbulence intensity of 5%, the aforementioned fluid flow properties have been investigated. Reynolds' number has a value varied in between 3800 to 18000. Also, it has been discovered that effective efficiency reaches a maximum value of around 0.7396 for relative roughness height of 0.038 at Reynolds' number of 16000. Further, results obtained from simulation suggested that there has been a considerable rise of about 22°C in temperature of air after passing through the roughened solar air heater.

1. Introduction

Energy has a significant role in the development, as it has been well known for the economic and industrialization of the entire world [1]. There have been various conventional and non-conventional sources from which energy needs have been fulfilled, but given the rate at which our fossil fuels are depleting, it has been imperative that focus is on non-conventional sources of energy in order to meet the energy needs of future generations [2]. The importance of sustainable energy, which

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significantly reduces the consumption of fossil fuels, must be emphasised [3]. Presently main focus of researchers is on making the solar energy as primary energy source. Research has also demonstrated that solar energy, which can supply 8000 times more energy than the world needs, has a significant potential to meet global energy requirement. Solar energy can be used for a variety of purposes, including power generation, water and air heating, solar furnaces, photovoltaic cells, solar refrigeration, photochemical and biological conversion, and more. In recent years, idea of artificial roughness flow pattern roughness geometries utilised in solar air heater ducting, solar air heater thermal efficiency, solar air heater with high efficiency have been examined by various researchers [4]. The laminar sub layer that forms in the heat transfer zone must be broken in order to induce turbulence, which enhanced the heat transfer coefficient and raises the thermal efficiency of the solar air heater [5]. Addition of artificial roughness beneath the absorber plate increases the area of the heat transfer and consequently laminar sublayer has been broken. By including ribs beneath the absorber plate, roughness has been produced on it. There have been many different forms of ribs, including square, V, and wedge-shaped ribs. Undoubtedly, ribs create turbulence, but on the other hand, it has also increased the amount of pumping power needed to propel air into the heater [6]. The shape and placement of the roughness element predicted the turbulence zone, which has been exclusively in the laminar sublayer [7]. Prasad and Saini [8] predicted that friction factor changes as a function of the relative roughness height (e/D) and relative roughness pitch (P/e). Investigation has shown that as the relative roughness height rises, the rate of heat transmission falls while the rate of friction factor rises. Further, friction factor and heat transmission decrease as the relative roughness pitch increases. The effect of the roughness height, angle of attack, and Reynolds number on heat transmission and friction has been examined by Gupta et al. [9] for circular wire ribs. It has been discovered that compared to a smooth duct, heat transfer and friction factor rise by up to 1.8 and 2.7 times for the artificially roughened duct, respectively. Verma and Prasad [10] also looked at different parameters that affect heat transfer and friction for circular ribs, and it has been discovered that the ideal thermo hydraulic performance of around 71%, corresponded to a roughness Reynolds number of 24000. Expanded wire mesh has been studied by Saini and Saini [11] as a roughened element, and it has been shown that heat transmission and friction factor vary with the relative long way length (l/e) and short way length (l/s) of the mesh. Muluwork et al. [12] examined that v-shaped ribs affected the thermal efficiency of a roughened solar air heater. Relative groove position (g/P), a dimensionless measure, has been taken into consideration when comparing various topologies. It has been discovered that the Stanton number rises with the ratio of relative roughness to length. Momin et al. [13] studied about about v-shaped ribs that considerably affected the properties of heat transfer and fluid flow. In this experiment, the relative roughness height ranges from 0.02 to 0.034, the angle of attack runs from 30-90, and the relative pitch has been fixed at 10. Reynolds number ranges from 2500 to 18000. Both the friction factor and the Nusselt number have been seen to grow with the Reynolds number, however the increase in the Nusselt number has been less than that in the friction factor. Using a solar collector with metal grit ribs as the roughness element, Karmare and Tikekar [14] conducted an experiment and looked at the effects of relative roughness pitch (p/e), relative roughness height (e/D), and relative grit length (l/s) on heat transmission and friction. Bopche and Tandale [15] carried out an experiment utilising inverted U-shaped turbulators as the roughness element, and they discovered that heat transfer increased significantly even at relatively low Reynolds numbers (Re5000). In an experiment, Varun et al. [16] used a combination of inclined and transverse ribs as the roughness element. Relative roughness pitch (P/e) of 8 has been discovered to provide the best thermal performance. In an experiment, Layek et al. [17] examined the relationship between heat transfer and friction factor and relative roughness pitch, relative roughness height, relative groove position, and relative chamfer angle in a chamfered rib groove that serves as an artificial roughness for a solar air heater. M.S.W. Potgieter et al. [18] proposed a unique design for soalr air heater . Further, the design has been evaluated in terms of its efficiency via. computational fluid dynamics. The results suggested that efficiency between 23% to 83% has been obtained through proposed design. Milad Shadi et al. [19] analysed the economics, exergy and energy aspects of solar air heater provided with four different types of artificial roughness. For this purpose, nondominated sorting genetic algorithm II and TOPSIS algorithm have been adopted for selectin g the optimum roughness geometry. Farzaneh Sajadipour et al. [20] assessed the flat plate solar water heater thermal behavior by CFD method.

Further, expermental data has been validated with numerical results. Study revealed 1% to 22% error in simulated results when compared it with experimental results. Azad and Layek [21] predicted the performance of solar air heater having chamfered square elements on its absorber plate. Numerical study has been conducted to find out the value of friction factor and Nusselt number by varying relative roughness pitch. M. Vivekanandan et al. [22] investigated the performance of solar air heater having trapezoidal shaped duct through experimental and CFD analysis. Guide vanes at different inclination angle of 20°, 30°, 40°, 50° and 60° have been provided to develop the flow completely inside the duct. Numerical results have been in good agreement with experimental results.V.B. Gawande [23] et al. utilized reverse L- shaped ribs as a roughness elemet for evaluating performance of solar air heater both numerically and experimentally. Results highlighted significant improvement in friction factor and heat transfer by varying relative roughness pitch and Reynold’s number. Kottayat Nidhul et al. [24] performed numerical and exergy analysis of solar air heater having V shaped triangular ribs. Maximum exergetic efficiency of 23% has been reported against 45° inclination angle and for 7500 value of Reynold’s number. Yadav and Bhagoria [25] investigated performance of artificially roughened (triangular ribs) solar air heater numerically through CFD analysis. Results highlighted that Nusselt number has increased with Reynold’s number. Rohit Misra et al. [26] evaluated performance via. CFD analysis of solar air heater having roughness in the form of V-down ribs and turbulance promoters. In this study, angle of attack and relative roughness pitch have been varied. Results suggested maximum heat transfer has been obtained at 45° inclination angle irrespective of Reynold’s number value. D.S. Thakur et al. [27] evaluated performance of solar air heater having roughness in the form of hyperbolic ribs. Further, results obtained have been compared with smooth duct. It has been found that hyperbolic ribs show better performance compared to rectangular, semi circular and triangular ribs at Reynold’s number value upto 10000. Rajneesh Kumar et al. [28] investigated the effect of chamfered rectangular ribs (firward faced) on heat transfer and friction factor. It was predicted that Nusselt number and friction factor have been significantely improved by varying Reynold’s number and relative roughness height. Further, maximum increase in friction factor was observed for relkative roughness height of 0.043. Harish Kumar Ghritlahre et al. [29] studied the effect of arc shaped ribs on solar air heater thermal performance. In this study, outlet temperature and thermal efficiency have been examined by varying the mass flow rate. Maximum efficiency of 73.2% has been found for apex up shaped ribs. G. Sureandhar et al. [30] analysed solar air heater performance embedded with arc shaped fins. Results show that implementation of ribs provides the better use of solar energy and therefore, maximum outlet temperature has been obtained compared with smooth duct. Anil Singh Yadav et al. [31] analysed circular ribs performance that has been provided on solar air heater. Numerical simulation has been carried out by CFD. Results reported ±5% relative deviation when compared with experimental data. Anil Singh Yadav et al. [32] heat transfer behavior of solar air heater having semi circular ribs. Results reported thermal enhancement factor has a maximum value of 1.76 for Reynold’s number 15000. Ashwini Kumar et al. [33] evaluated performance of solar air heater with corrugated absorber plate. Numerical simulation has been done by CFD. Results shows a significant improvement in Nusselt number and friction factor. Anil Kumar et al. [34] compared different V shaped roughness geometries for predicting flow and heat transfer characteristics. Results revealed that V shaped ribs with groovehas superior thermal performance than other roughness elements being considered. Inderjeet Singh et al. [35] analysed and compared square wave shaped and multiple broken transverse ribs. It has been found that pumping power penalty for square and multiple broken transverse ribs was found to be 3.92 times and 3.85 times, respectively in comparison to smooth duct. Maithani and Saini [36] observed solar air heater having V shaped symmetrical ribs for heat transfer and friction factor, respectively. Friction factor and Nusselt number have been increased by 3.67 and 3.6 times, respectively as reported in obtained results. Singh and Singh [37] performed CFD analysis for solar air heater having roughness element (square wave transverse ribs) on its absorber plate. It has been found that at 15000 Reynold’s number and relative roughness pitch of 10 friction factor and Nusselt number have been increased by 3.55 times and 2.14 times, respectively.

To the best of the authors' knowledge, there has been no substantial numerical work reported on solar air heaters with U shaped turbulators roughness on the absorber plate in the open literature.

In the present work CFD analysis of solar air heater provided with U shaped turbulators has been performed with an objective to examine the performance (in terms of effective efficiency) of artificially roughened solar air heater by varying the relative roughness height (e/D). Further, flow behaviour in terms of temperature profile, velocity variation and streamline pattern has also been predicted in this research work.

2. Materials and Methods

ANSYS version 12 (workbench mode), a FEM simulation programme, has been employed for the simulation. The current work has made use of the fluid flow (FLUENT) module. The application of thermal loading to the work piece allows the fluid flow (FLUENT) module to forecast the outlet temperature, velocity, and flow behavior with high accuracy. Temperature, convection, radiation, and heat flux are the several thermal loading mechanisms that have been applied to the work piece in the Fluid flow (FLUENT) module. For this analysis few assumptions have been made as listed below [38]:

- The ambient air and inlet air were both at 27 °C.
- On the absorber plate, a uniform 1000W/m^2 constant heat flux has been applied.
- It has been assumed that the air is an ideal gas.
- Perfect insulation throughout the system prevents any heat loss to the environment.
- The airflow was three dimensional, turbulent, and constant.
- Duct wall and roughness material's thermal conductivity have not been temperature-dependent.

As per Figure 1, the duct being evaluated for this investigation has a cross sectional dimension of 200 mm by 20 mm. For this investigation, aspect ratio of 10 has been maintained. A steady heat flux of 1000W/m^2 has been applied to the absorber plate in the flow system's 1000 mm-long test segment.

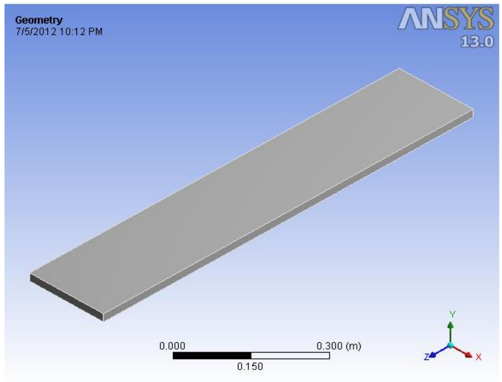

Figure 1. Solar Air Heater Geometry

2.1. Geometric Modeling

As shown in Figure 2, the underside of the absorber plate has been roughened by the creation of U-shaped turbulators, while the other three sides have been thought of as smooth surfaces. Aluminum serves as the material for the absorber plate, and the relative roughness height (e/D) and relative roughness pitch (P/e) values used in this analysis were 0.034 and 57.14, respectively. The range of Reynolds' number varies from 3800 to 18,000.

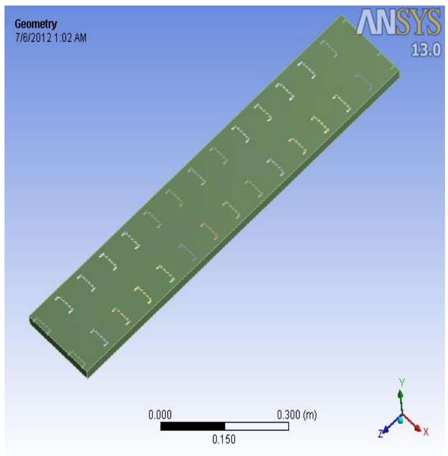

Figure 2. Geometric Model (U Shaped Turbulators)

2.2. Meshing

To ensure correct flow computations, generating a fine mesh has been one of the most significant tasks in the development of 2D CFD simulation. In present work, tetrahedral patch independent technique has been employed for generating mesh. In this meshing technique generation of mesh has been started from inside and those regions where flow has not been taking place within the geometry have been obsoleted. Tetrahedral (patch independent) method provides a non-uniform mesh with fine mesh in the region where artificial roughness has been provided in order to examine the flow and heat transfer behavior. Further, coarser mesh has been employed for the remaining region. As seen in Figure 3, a tetrahedral (Patch independent) mesh technique has been employed. Table 1 provides mesh information.

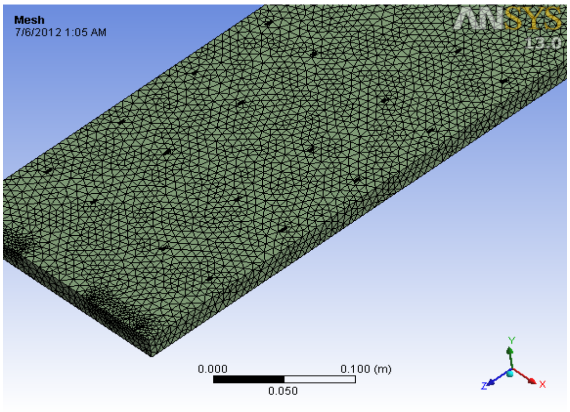

Figure 3. Mesh Details (U Shaped Turbulators)

Table 1. Mesh Characteristics (U Shaped Turbulators)

Type of element	Tetrahedral
Number of nodes	117903
Number of elements	530712

2.3. Boundary Conditions

In present study, a rectangle on x-y plane has been considered as a solution domain imposed with different boundaries condition at inlet, outlet and wall. No slip boundary condition has been applied on wall. The reason is Navier Stokes equation has been computed within the computational domain. A constant heat flux of 1000W/m^2 has been applied on the top surface of absorber plate while bottom surface has been taken as adiabatic. Boundary condition that has been applied at inlet was velocity because it defines the flow velocity along with other associated scaler flow properties at inlet. Mean inlet velocity has been computed using Reynold's number. The temperature of air admitted inside the roughened air heater has been taken as 300K. the various thermophysical properties of roughened element have been provided in Table 2. Table 2 provides the various boundary conditions that have been imposed during simulation.

Table 2. Boundary conditions (U Shaped Turbulators)

Location	Boundary Type	Boundary Details
• Air Inlet	Velocity Inlet	Velocity – 7.04 m/sec Temperature – 300K
• Outlet	Outflow	Temperature – 315.91K
• Insulation	Wall	No slip wall Adiabatic with no heat loss Material used - Wood.
• U Shaped Turbulators	Wall	q – 1000W/m^2 Material used Aluminium ε -1.0 ρ -2719kg/m^3 K 202.4W/m/°C c_p – 871J/kg/°C

3. Results and Discussion

3.1. Effective Efficiency of U Shaped Turbulators

From the Figure 4 it has been clear that effective efficiency increases continuously with Reynolds's number for relative roughness height (e/D) of 0.018 but for all other relative roughness height (e/D) effective efficiency increases continuously up to Reynolds's number of 16000 and after that it starts decreasing slightly for higher values of Reynolds's number. In this case value of relative roughness pitch (P/e) is 57.14 for all the relative roughness height (e/D). It has also been observed that effective efficiency attains a maximum value of approx. 0.7396 at Reynolds's no. of 16000 for relative roughness height of 0.038.

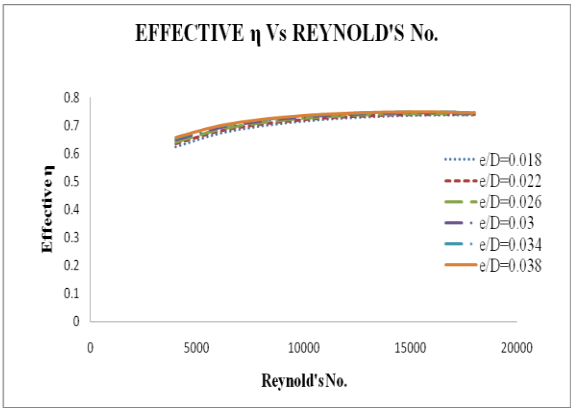

Figure 4. Variation of Effective Efficiency with Reynolds's No. (U Shaped Turbulators)

3.2. Temperature Distribution

From the temperature distribution plot of the system as shown in figures 5 and 6, atmospheric air enters the solar air heater at 27°C and leaves at 49°C. Under the same operating conditions, the outlet temperature obtained by numerical analysis was 43°. Hence it has been concluded that the simulation conducted was quite accurate with + 6°C error.

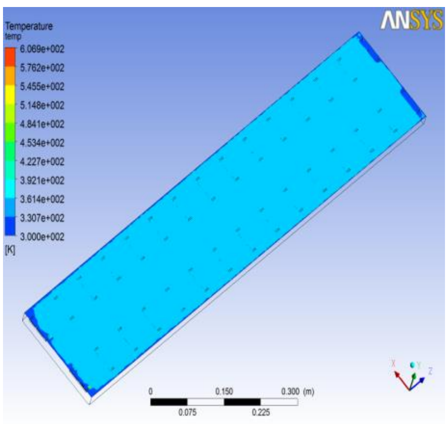

Figure 5. Temperature distribution of Air in Solar Air Heater (U Shaped Turbulators)

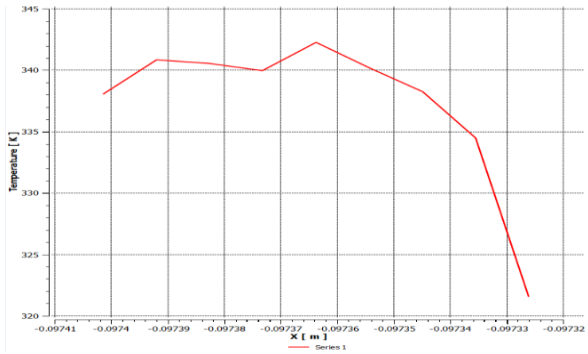

Figure 6. Temperature Plot of Air through Solar Air Heater (U Shaped Turbulators)

3.3. Velocity Distribution

Presence of artificial roughness on absorber plate results in formation of vortices, flow separation and reattachment of fluid layers in the region where artificial roughness has been provided as predicted via. CFD analysis. Figure 7 shows the velocity distribution inside the solar air heater provided with U shaped turbulators. It has been depicted in Figure 7 that velocity has been decreased in region where artificial roughness has been provided due to increase in friction factor. Results suggested that velocity attains a maximum value of 8.085m/sec.

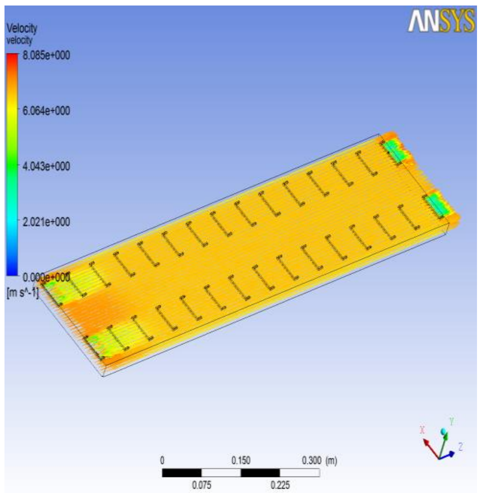

Figure 7. Velocity Distributions (U Shaped Turbulators)

3.4. Velocity Streamline

Results obtained via. CFD simulation depicted that fluid flow has been uniform throughout the duct. The reason is there has been no disruption of fluid layers with one another as depicted in Figure 8. It has been clearly shown that streamlines have equal spacing which suggested that air has been moved with uniform velocity.

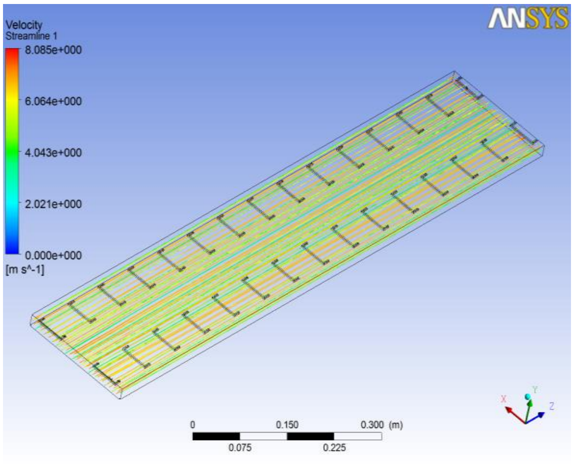

Figure 8. Streamline Pattern (U Shaped Turbulators)

4. Validation

Throughout the past few decades, a number of research investigations on artificially roughened solar air heater for its performance assessments have been conducted. The maximum effective efficiency of 44% has been obtained for hybrid solar air heater [18]. CFD analysis of solar air heater provided with V- shaped ribs predicted an effective efficiency of 74% and an outlet temperature of 37° [39]. In the present work, effective efficiency has a value of 73.9% with an outlet temperature of 43°. Therefore, results reported in present work are in good agreement as reported in existing literature.

5. Conclusions

A CFD analysis has been performed on an air heater with roughness on its absorber surface in the form of (U- shaped Turbulators) ribs in order to predict dynamic fluid characteristics. It has also been noticed that friction factor decreases with increase in relative arc angle (α/60) for a constant value of relative roughness height (e/D) i.e., 0.034. Also, it has been noted that effective efficiency reaches a maximum value of around 0.7396 at a relative roughness height of 0.038 at a Reynolds number of 16000.

In present work, relative roughness height (e/D) has been varied for the roughness geometry under investigation, while the other operating parameters have been kept constant. Therefore, it has been possible to extend this work by adjusting other operating parameters like relative roughness pitch (P/e), to forecast performance in terms of effective efficiency. Further, simulation results predicted the flow behaviour along the length without considering the variation of flow along the height of solar air heater. Therefore, it has been taken into account for future research work in this field.

Nomenclature

ρ	Density
η	Efficiency
ε	Emissivity
q	Heat flux
α/60	Relative arc angle
e/D	Relative roughness height
P/e	Relative roughness pitch
Re	Reynold's number
c_p	Specific heat
K	Thermal Conductivity

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