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Research Article

Effect of Absorber Plate Design on the Air temperature from A Solar Air Heater

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ABSTRACT

This study examines the thermal efficiency of solar air heaters (SAHs) including several absorber plate designs: smooth plates (SP), rectangular ribbed plates (RRP), and square ribbed plates (SRP). The heat transfer and airflow properties of these designs were investigated under controlled settings using computational fluid dynamics (CFD) simulations. The investigated mass flow rate is 0.001 kg/s The RRP exhibited superior thermal efficiency, owing to improved turbulence and heat transfer with little pressure loss. The SRP, although augmenting turbulence, exhibited declining results owing to increased flow resistance. These findings underscore the importance of absorber plate design in enhancing solar air heater performance for sustainable energy applications.

1. INTRODUCTION

Solar energy, which is a renewable resource that is both clean and abundant, is a crucial component in addressing global energy concerns and reducing reliance on fossil fuels. Solar air heaters are a practical and energy-efficient option that may be used for a variety of purposes, including drying activities, ventilation, and heating of rooms. These systems make use of solar energy to warm air, making them an environmentally responsible alternative to conventional methods of heating. Solar air heaters have become an essential component of sustainable energy strategies as a result of their ease of use, cost-effectiveness, and flexibility. They contribute to the reduction of energy expenditures and carbon emissions in residential, commercial, and industrial settings [1-2].

In the field of research on renewable energy, one of the primary focuses has been on the enhancement of energy efficiency in solar air heaters (SAHs). A strategy that is effective involves the utilization of ribs and fins in order to improve the efficiency of heat transfer [3-4]. Altering the patterns of airflow and increasing the surface area that is designated for heat exchange are both outcomes of the utilization of these passive design features. [4].

In spite of the fact that solar air heaters are essential for the collection of solar energy, they frequently have a low thermal efficiency. The efficiency can be attributed to the restricted heat transfer that occurs between the absorber plate and the air, in addition to the laminar flow of air that occurs naturally over the surface [5]. As a consequence of the challenges that have been identified, new designs, such as ribs and fins, have been developed in order to enhance performing capabilities. Ribs are frequently used in heat transfer systems because they possess the ability to induce turbulence, which in turn disrupts the boundary layer and enhances the convective heat transfer . Ribbed absorber plates have been shown to have significant improvements in thermal efficiency, according to academic research. Prasad and Saini [6] demonstrated that the geometry of the ribs, which includes characteristics such as size and spacing, has a considerable impact on performance. In order to significantly improve turbulence, some forms, such as triangular and semicircular ribs, have been demonstrated to be particularly successful. Alam et al.[7] conducted research that brought to light the necessity of utilizing high-conductivity materials in order to enhance the efficiency of heat transfer while simultaneously preserving the integrity of the structure. The integration of ribs has an effect on the patterns of airflow, which ultimately results in a reduction in pressure. The study that was conducted by Karwa and colleagues in 2001 brought to light the need of striking a balance between the control of energy losses caused by turbulence and the enhancement of heat transport.

Fins increase the effective heat transfer surface area, which has the effect of improving the efficiency of the SAH. Through an increase in the amount of contact with airflow, Tiwari et al. [8] shown that the incorporation of longitudinal fins results in an increase in heat absorption. Several other types of fin designs, including straight, helical, and wavy architectures, have been investigated. According to Bhushan and Singh [9], wavy fins have superior performance in comparison to other designs. This is because they are able to generate swirling airflow, which enhances the efficiency of mixing and heat

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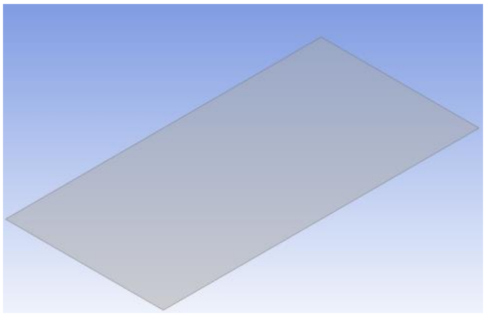
*Corresponding author. engahmed.rahmah@gmail.com transfer. A significant amount of importance is placed on the selection of the material for the fins. Sahu and Bhagoria [10] suggested using materials such as aluminum or copper due to their superior heat conductivity and cost effectiveness. Ribs and fins have been included by researchers in an effort to enhance the effectiveness of SAH. Tests and simulations were carried out by Kumar et al. [11] to demonstrate that hybrid arrangements, which incorporate both elements, result in greater outcomes when compared to the use of either characteristic in isolation. Significant gains in efficiency are brought about as a result of the designs, which increase turbulence and the surface area of heat exchange. Computational Fluid Dynamics (CFD) has become an indispensable instrument in recent years for the purpose of analyzing the flow of air and the transfer of heat in Solar Air Heaters (SAHs) that are equipped with ribs and various fins. For the purpose of determining the most effective design combinations, Jain and Mishra [12] utilized computational fluid dynamics (CFD) to assess the thermal and hydraulic performance of the project. The importance of confirming the results of experiments cannot be overstated. When compared to conventional designs, the thermal efficiency of ribbed and finned solar air heaters (SAHs) was shown to be up to forty percent higher in the laboratory trials that Gupta and Kaushik [13] conducted. Ranjbar [14] conducted a numerical investigation on the impact of a roughened absorber plate with rectangular, triangular, and elliptical fins on the performance of a solar air heater at various inclination angles. The effectiveness of SAH with rectangular fins surpasses that of elliptical and triangular fins by 12.5% and 5.5%, respectively. The optimal angle was observed to be between 50° and 70°.

While the introduction of ribs and fins into SAHs has a great deal of promise, it also raises a number of challenges. Numerous reasons have contributed to this problem, including a rise in the complexity of manufacturing, an increase in the costs of materials, and the possibility of a decline in durability as a result of the inclusion of more structural components. In the future, research should concentrate on finding solutions to these problems by developing production methods that are cost-effective, studying novel materials such as composites or nanomaterials, and developing adaptive systems that can respond to changing environmental conditions. An important step forward in the development of solar energy technology is the incorporation of ribs and fins into solar air heaters. The modifications help to enhance heat transfer and airflow qualities, which in turn helps to address the inherent inefficiencies that are present in conventional systems. The combination of experimental and computational techniques gives a decisive path for the development of solar air heaters that are more efficient and cost-effective, hence boosting the wider use of solar energy systems. This is despite the limits that are now in place.

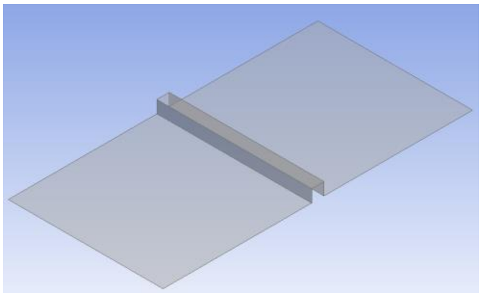
This study seeks to comprehensively examine the thermal and aerodynamic efficiency of solar air heaters using smooth, rectangular ribbed, and square ribbed absorber plate designs. The research use computer simulations to clarify the impact of these designs on heat transfer efficiency and flow dynamics, aiming to uncover ideal combinations that improve energy efficiency and reduce related losses.

2. PHYSICAL MODEL

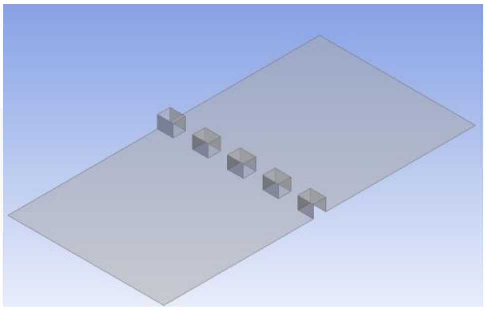
This study examines three design of the absorber plate including : smooth plate, ribbed plate with one rectangular rib and five square ribs as shown in figure (1). The dimensions of the solar air heater are 1000 long, 500 mm width and 120mm height. The height and the length of the ribs is 40 mm for both RPP and SPR plate while the width is 50 mm for SRP.



Smooth absorber plate (SP)



Rectangular ribbed plate (RRP)



Square ribbed plate (SRP)

Fig.1. Tested absorber plates

3. MESH CREATION

Tetrahedron meshing is employed to mesh the domain. The number of elements has a substantial impact on the simulation results. In this study, the element number is crucial primarily, which encompasses fluid flow and heat transfer. To reduce the computational cost , suitable number of mesh elements must be determined carefully. Table (1) present the variation of the outlet temperature of the air with element number. It can be seen the variation of the outlet temperature is insignificant for all the tested elements number. The elements number is chosen to be 786,361. Figure 2 depicts the meshed domain.

TABLE I. ELEMENTS NUMBER EFFECT ON THE OUTLET TEMPERATURE

Elements number	**Outlet temperature (K)**
205,658	318.1
458,985	318.5
847,125	318.92
914,785	319.3
1,177,218	319.3

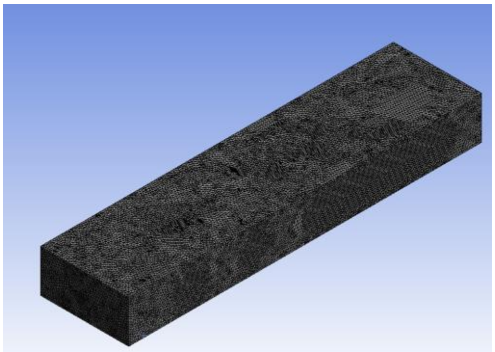


Fig. 2. The meshed domain

4. GOVERNING EQUATIONS

This study utilizes flow to simulate turbulent fluid flow and heat transfer in the proposed simulation, with the governing equations outlined as follows [13] :

Continuity Equation

$$\frac{\partial \overline{u}}{\partial x}+\frac{\partial \overline{v}}{\partial y}+\frac{\partial \overline{w}}{\partial z}=0 \tag{1}$$

Momentum Equation

$$\frac{\partial}{\partial x_i}(\rho\overline{u_i u})=\frac{\partial \overline{p}}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial \overline{u_i}}{\partial \overline{x_j}}+\frac{\partial \overline{u_j}}{\partial \overline{x_i}}-\frac{2}{3}\delta_{ij}\frac{\partial \overline{u_l}}{\partial x_l}\right)\right)-B_i-\frac{\partial}{\partial x_i}\left(\overline{\rho u_i' u_j'}\right) \tag{2}$$

Energy Equation

$$\rho\frac{\partial h}{\partial t}=K_s\left(\frac{\partial^2 T}{\partial n^2}\right)+S_h \tag{3}$$

5. BOUNDARY CONDITIONS

The Governing equations are solved by utilizing the following boundary conditions as in Figure (3):

- Left face: mass flow rate.
- Right face: pressure outlet.
- Glass cover: incident radiation

6. RESULTS

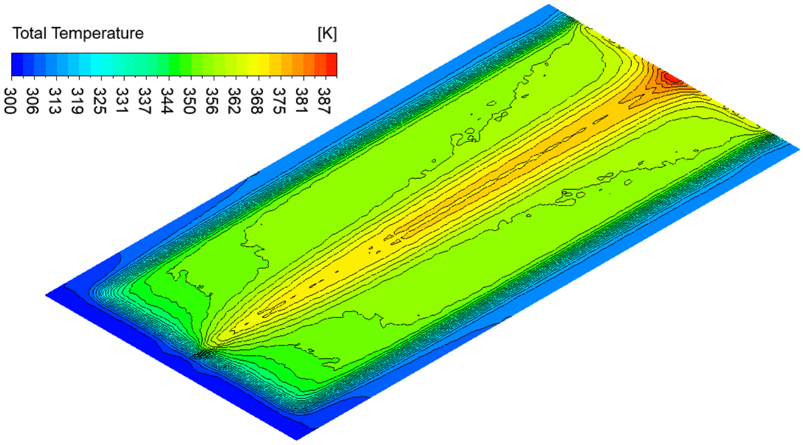
This study quantitatively examined air flow and heat transfer inside three pipe with different cross-section include: circular, square , and triangular. The mass flow rate and temperature are fixed at 0.0004 kg/s and 25 ºC respectively for all cases. The heat flux is set as 300 W/m^2.

Figure (3) illustrates the temperature distribution on the absorber plate of a solar air heater for various absorber plate layouts, emphasizing their impact on heat transfer and output air temperature. For the smooth absorber plate (SP) , The temperature distribution exhibits a consistent gradient, with elevated temperatures centered in the center and diminishing towards the periphery. The uniformity of heat absorption, coupled with the absence of turbulence, diminishes the efficacy of heat transfer to the air, resulting in a mild output air temperature. For the rectangular ribbed plate (RRP), the rib enhances turbulence, creating localized regions of higher heat transfer near the obstacle. This increased turbulence promotes better mixing of the air and improves overall heat absorption, resulting in a significantly higher outlet air temperature compared to the baseline configuration. For the square ribbed plate (SRP), this arrangement has many consecutive barriers on the absorber plate. The impediments create persistent turbulence zones, improving heat transfer over the surface. Nevertheless, the supplementary impediments may induce excessive turbulence, which, although enhancing localized heat transfer, may not provide a higher exit air temperature due to augmented flow resistance and an increased pressure drop. Figure (4) present the outlet temperature of the air for the three tested configurations. The outlet air temperature of the heater with smooth absorber plate (SP) is the lowest of the three configurations. This results from the lack of turbulence-inducing characteristics, leading to laminar airflow that diminishes the efficiency of heat transfer from the absorber plate to the air. The absorber plate facilitates homogeneous yet diminished heating, hence constraining the thermal efficiency of this structure. For the heater with rectangular ribbed absorber plate (SRP) The outlet air temperature is the highest of the three options. The rectangular rib generates localized turbulence, markedly improving heat transfer while minimizing flow resistance and pressure loss. The RRP arrangement is the most efficient in thermal performance due to its perfect mix of enhanced heat transfer and reduced energy losses. The outlet air temperature rises in comparison to the SP setup. The many ribs provide turbulence in the airflow, therefore improving heat transfer between the absorber plate and the air. This arrangement achieves a balance between heightened turbulence and the resultant pressure drop, resulting in improved thermal performance.

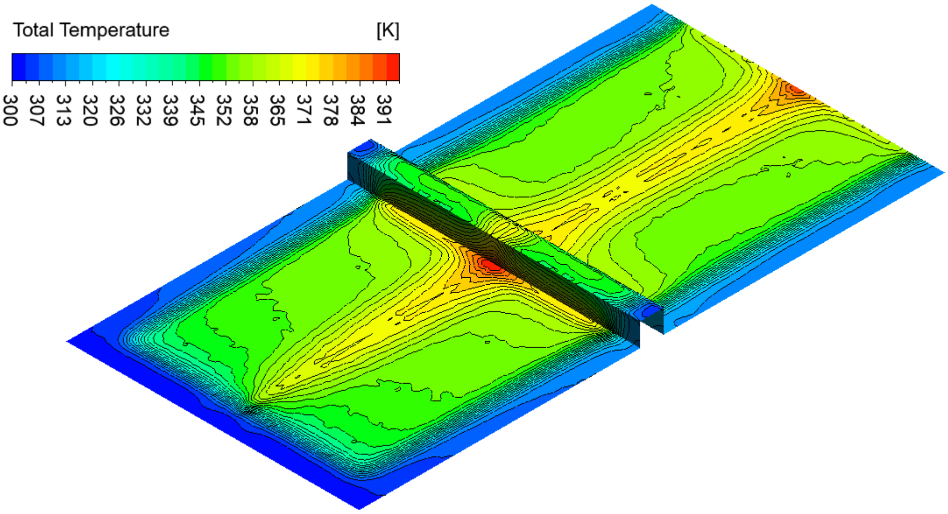
Figure (4) presents Average Nusselt number for the tested pipes. The circular pipe has the greatest average Nusselt number among the three designs, signifying the most effective convective heat transfer. This outcome aligns with existing research, since circular pipes are extensively used for their superior flow dynamics and reduced flow resistance, resulting in well-defined temperature and velocity boundary layers. The square pipe has a somewhat reduced Nusselt number in comparison to the circular pipe. The existence of corners in square cross-sections might interfere with flow patterns, resulting in areas with decreased heat transfer efficiency. Nonetheless, square pipes maintain an equilibrium between the improvement of heat transfer and practical manufacturability in tiny heat exchangers. The triangular pipe demonstrates the lowest Nusselt number among the three shapes. Acute angles in triangle conduits may result in localised stagnation areas and diminished convective heat transfer. Nonetheless, triangular pipes may remain advantageous in scenarios when spatial limitations are paramount, and thermal transfer efficiency is of lesser importance.

Figure (5) demonstrate the turbulence intensity. Turbulence intensity in the circular pipe is reasonably consistent, starting low in the centre and increasing towards the walls. This uniform distribution is due to symmetrical shape, which encourages smooth and predictable flow. Although the circular pipe has lower turbulence intensity than other geometries, its streamlined shape maintains effective boundary layer growth and heat transfer. The square pipe's turbulence intensity is highest in the corners. Sharp edges hinder flow and increase turbulence. Regions that boost mixing might also increase pressure drop. The square pipe's intermediate heat transfer performance is due to increased turbulence than the circular pipe. Triangular pipes have the most turbulence around sharp corners.

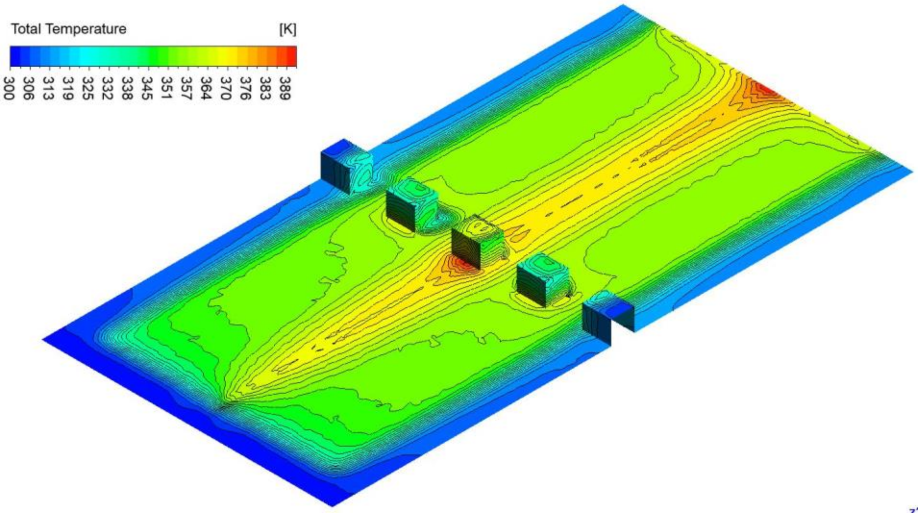
Sharp triangular angles disturb flow, causing considerable turbulence in certain places. Pressure drop and flow resistance may rise as mixing improves. Due to decreased mixing in the pipe centre, uneven turbulence intensity reduces heat transfer compared to circular and square pipes.



SP



RRP



SRP

Fig. 3. Temperture distributino on the absorber plate.

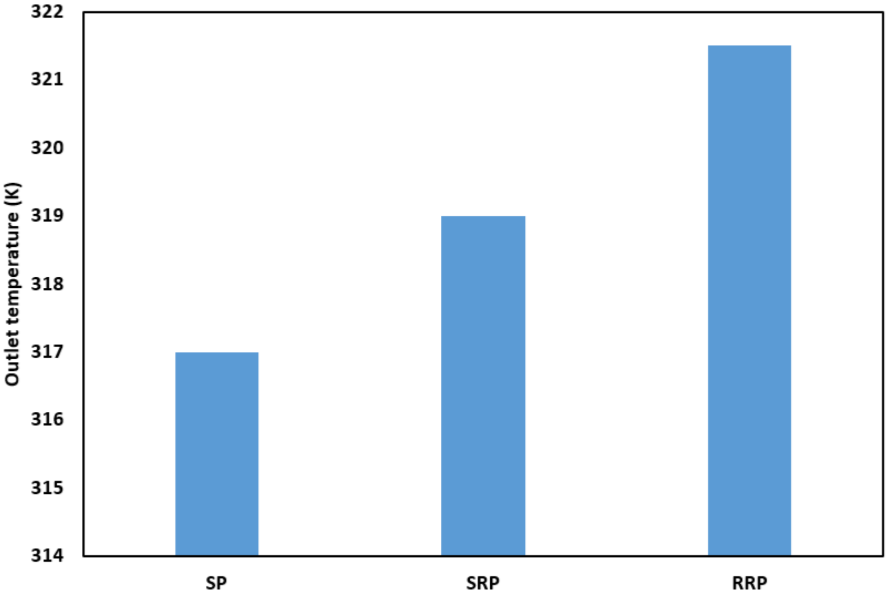


Fig. 4. Outlet temperture for the different configurations

5. CONCLUSIONS

The present work investigated the performance of a solar air heater for different absorber plate designs including : smooth plate, rectangular ribbed plate, and square ribbed plate. The main conclusions can be summarized as :

- The rectangular ribbed plate (RRP) design demonstrated enhanced thermal efficiency by promoting appropriate turbulence, hence improving heat transfer and reducing flow resistance.
- The smooth plate (SP) configuration had the worst performance, since laminar airflow constrained heat transfer efficacy.
- The square ribbed plate (SRP) enhanced turbulence and localized heat transfer; nevertheless, its considerable flow resistance diminished its overall efficiency relative to the RRP.

- The work highlights the necessity of equilibrating turbulence induction and flow resistance for optimal SAH design, offering insights for enhancing solar energy systems.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

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