

Research Article

Numerical Study of heat transfer characteristics of Rectangular channel with combined roughness

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Abstract:

The study numerically investigates convective heat transfer enhancement in a solar air heater (SAH) duct using semi-circular roughness elements on the absorber plate. A three-dimensional, turbulent airflow model is analyzed with fixed heat flux and validated against the Dittus–Boelter correlation for smooth ducts. The flow in the rectangular channel is steady, incompressible, and turbulent, with constant properties throughout. Air properties such as density and viscosity remain uniform, and the solar radiation over the absorber plate is also uniform, facilitating calculations. The no-slip condition applies as a boundary condition in CFD simulations; minor heat losses to the environment can be neglected. It examined the influence of geometric configuration, particularly the $p/e = 7, 8, 9, 10$ and 11 relative pitch ratio between roughness elements, on the duct's thermal performance. These variables are investigated in turbulent flow conditions with Reynolds numbers (Re) between 3000 and $24,000$. Results indicate that these roughness elements increase heat transfer rates by up to 262% compared to smooth ducts at a Reynolds number of $24,000$, with optimal configurations yielding a Nusselt number approximately 2.3 times higher and a maximum thermal–hydraulic performance parameter of 1.61 at specific geometric conditions as under specific conditions at $Re = 24,000$, $P = 22$ mm, and $P/e = 10$.

Keywords: Semicircular roughness, Nusselt Number, Friction Factor, Heat Transfer performance, Solar air Heater (SAH)

1. Introduction

A solar air heater is a sustainable device that converts sunlight directly into warm air for heating buildings or industrial processes. It typically consists of a solar collector, which absorbs sunlight and transfers the heat to the air flowing through or over it. The warm air from solar air heater can be applied immediately for building heating, to reduce reliance on conventional heating systems, thereby lowering energy costs and carbon emissions.

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They play a vital role in sustainable energy systems and contribute to energy conservation by utilizing an abundant and renewable resource—the sun. Solar air heaters offer a cost-effective way to supplement traditional indoor heating systems. However, their efficiency can decrease under cloudy conditions due to reduced sunlight availability. It has been discussed that the effect of various ribs, which were used by various researchers. This review basically states and concentrates on the design which have used by many researchers, and even its location on the solar air heater panel. The laminar sub-layer develops in thickness along the stream course; subsequently, warm execution of ordinary SAH is unfavorably influenced. Among these, the intermittent rib roughness technique is often considered reliable, as it introduces turbulence in the airflow and alters the heat transfer surface of the absorber plate, disrupting the laminar sublayer. Singh et al [1] reviewed effects across the plate that absorbs functional roughness of heat transfer & friction characteristics having several roughness of arc-shaped features. Alam et al [2] examined the effects of non-circulation perforations in the V-shaped obstructions to which a single rectangular heated wall duct is connected. Momin et al. [3] A distinct benefit over predisposed rib plates under comparable operating conditions is demonstrated by the V-shaped ribs with smooth plate cases at Reynolds number 17034, which raise Nusselt number values by 1.14 and 2.30 times with an average roughness height of 0.034 at an angle of attack of 60°. Prasad, B. N., Behura, A. K., & Prasad [4]. The fluid & transferring heat study was conducted for transferring heat improvement in the three-side, consequently roughened SAH at the top & side walls using a small-scale diameter. Khatri et al. [5] conducted an experimental-based analysis looking to study characteristics of heat transfer & friction in SAHS having a dimple shape element arrangement with an angular manner. Saini, R. P., & Verma [6]. the effect of rough geometries investigated & function parameters of heat transfer in a rough duct provide roughness geometry for the dimple form. Singh S, Chander S, Saini JS [7] in experimental findings across heat transfer & friction in rectangular ducts textured using a novel arrangement of "separate V-down ribs" along a single wall are presented in this work. A solar air heater's thermohydraulic efficiency gets a major boost when the proportional gap is at 0.65. This position also leads to the greatest gains in both the Nusselt number and friction factor. Muluwork et al. [8] The present research shows an optimal thermal efficiency factor value of 1.93 after numerically analysing the conveyance of heat and fluids characteristics using the solar air heater duct with staggered V-shaped ridges over the surface of the absorber plate. Singh, I., & Singh, S [9] Circular, square, and triangular metal rib sections with a sixty-degree slope to air flow were used to test the lower side of an absorber plate. Grit rib components were staggered onto the bottom and analysis was done using CFD. Mittal, M. K. [10], the artificial roughness elements positioned beneath a solar air heater's absorber surface significantly enhance thermal efficiency. This modification works by promoting increased turbulence and facilitating enhanced thermal exchange between the heated surface and the airflow. When V-shaped ribs are integrated with staggered gaps, the heat transfer capability is significantly improved compared to a plain duct. This configuration increases the Nusselt number, ranging from 1.77 to 3.18, indicating higher convective heat transfer. Deo et al. [11] Integrating V-shaped ribs with staggered gaps leads to a significantly improved heat transfer over a smooth duct. This setup leads to the Nusselt number increasing by a factor of 1.77 to 3.18, which shows a proportional rise in convective heat transfer. The configuration achieved a maximum improvement of 3.34 times in the Nusselt number and 2.45 times in thermo-hydraulic efficiency relative to a conventional smooth surface. Maithani & Saini [12] this study aimed to enhance the heat transfer coefficient in a solar air heater by incorporating V-shaped ribs with symmetrical gaps along the air duct, which promoted greater turbulence in the airflow. Compared to a smooth duct, the heat transfer effectiveness, as indicated by the Nusselt number, was boosted by as much as 3.6 times. This enhanced performance, however, was accompanied by an approximate 3.67-fold increase in the resistance to flow (friction factor) under identical operating parameters. The optimal rib parameters resulting in peak improvements in both heat transfer and frictional characteristics were determined as: number of gaps (N_g) = 3, gap-to-height ratio (g/e) = 4, pitch-to-height ratio (P/e) = 10, and rib inclination angle (α) = 60°. Kumar et al. [13] conducted an experimental study to understand how the design of staggered V-shaped ribs with gaps, affixed to the bottom of a heated rectangular duct, affects heat transfer and fluid flow. Their findings indicated substantial improvements in both areas, with the Nusselt number increasing by approximately 6.32 times and the friction factor by around 6.12 times compared to a smooth duct. Optimal thermohydraulic efficiency was achieved when the relative gap distance and width were maintained at 0.69 and 1.0, respectively, indicating the importance of these geometric variables. Kumar Sahu et al. [14] this research evaluates the exergetic performance of a solar air heater enhanced with arc-shaped wire ribs, aiming to understand their influence on energy conversion efficiency. The addition of arc-shaped roughness elements led to a 56% increase in exergetic efficiency over a smooth absorber plate, particularly when the relative roughness height (e/D) was maintained at 0.0422. Alfarawi et al. [15] conducted an investigation into heat transfer enhancement within rectangular ducts by implementing hybrid rib geometries, including semi-circular, rectangular, and combined shapes. These roughness elements were designed to promote fully developed turbulence, thereby improving thermal and frictional performance. The test section comprised ducts measuring 320 mm in length and 120 mm in height, with experiments carried out over a broad Reynolds number range (12,500–86,500) and varying relative pitch-to-height

ratios (6.6–53.3). The study reported heat transfer (Nu/Nus) and friction factor (fr/frs) enhancements between 1.3 and 2.14 in comparison to a smooth duct. Andallib Tariq et al. [16] evaluated the influence of slit-type ribs applied to a test surface under downstream flow conditions. The experimental work assessed how slit rib configurations affected thermal performance, with the results indicating a rise in heat transfer efficiency by approximately 10% to 50%, contingent on the coverage area and design of the ribs. Patil and Babu [17] reviewed the use of square-shaped channels embedded in circular tubes for solar air heating purposes. The review analyzed thermal and hydrodynamic behaviour based on earlier research, emphasizing the structural modification's effect on system performance. Ganesh Kumar et al. [18] developed a dual-mode solar thermal system capable of heating both air and water. The system used a nanofluid blend of solar glycol and multi-walled carbon nanotubes (MWCNTs) within a rectangular flow channel. At a nanoparticle concentration of 0.2% and a mass flow rate of 0.01%, the system achieved a maximum thermal efficiency of 51.03%. Surendhar et al. [19] explored solar air heaters fitted with arc-shaped ribbed fins, comparing fixed and variable rib configurations. They observed that performance improved significantly with variations in rib spacing ($P/e = 10$ mm) and height-to-hydraulic diameter ratios. These results highlighted that adjustable arc rib geometry contributes more effectively to heat transfer enhancement than fixed designs. Pashchenko [20] carried out a simulation using ANSYS Fluent to determine the behaviour of a SAH [22 – 24] at different solar tilt angles. The study identified 60° as the optimal inclination for maximizing energy capture, particularly during peak sunlight hours from 1:00 PM to 2:00 PM, and this design gives good thermal performance.

Although previous studies have demonstrated the effectiveness of arc-shaped ribs, variable roughness parameters, and optimized tilt angles in enhancing the thermal performance of solar air heaters, limited attention has been given to the combined influence of semi-circular roughness elements on internal heat transfer characteristics under turbulent flow conditions. The present study introduces a novel roughness configuration employing combined semi-circular elements on the absorber surface and systematically evaluates their effect on convective heat transfer and frictional losses in comparison with a smooth duct. Unlike earlier investigations that primarily focused on fixed or single-type rib geometries, this work provides a comprehensive analysis over a wide Reynolds number range (3,000–24,000) using key non-dimensional performance parameters (Nu , fr , and Nu/Nus). The results offer new insights into the thermal–hydraulic trade-off associated with combined roughness geometries, thereby contributing to the development of more efficient and thermally optimized solar air heater designs.

2. Methodology

This section outlines the methodology used for designing the SAH, which incorporates a rectangular channel. The aim is to enhance heat transfer by integrating combination of semi-circular components that contribute to the absorption plate's smoothness. Compared to a smooth channel, this design improves thermal performance. Numerical analysis including grid generation, transition modelling, and turbulence models is employed. So, we designed a new rectangular channel with combination of Semi-circular roughness with same dimensions. In this section, model of combination of semi-circular roughness on rectangular smooth SAH is design in ANSYS workbench after that is simulated by CFD. The geometry was designed based on validated from a 1200 mm long duct with a height of 25 mm and width of 280 mm. The inlet section, 130 mm used for the working fluid without separation, and it helps to promote that the flow entering the test portion, 850 mm is fully developed and, the air, after striking the roughness, will pass from the exit section OF 220 mm. The exit portion has been used long enough, like the entry part, to permit the flow to completely recover from the distortions in the test section. Various roughness configurations, types of combination of semi-circular features (inner and outer diameters are 2.8 and 3.3 mm respectively) with constant gap ($g = 1.2$ mm) with height of roughness, $e = 2.2$ mm, were introduced to study thermal performance improvements. Initially, the results for the smooth channel were validated by comparing them with theoretical equations until acceptable agreement was achieved, as illustrated in Figure 2. For the combination of semi-circular, additional variations were implemented by incorporating gaps within the rib structure, as detailed in the parameter range section. The model design relies on several critical parameters, particularly the geometry of a rectangular solar duct incorporating various combined semi-circular roughness patterns with a fixed gap. A consistent heat flux of 1000 W/m^2 is introduced, chosen to optimize heat transfer within the channel. This heat input is treated as a constant, reflecting consistent solar radiation. Key design inputs include dimensionless parameters such as the relative pitch-to-height ratio ($P/e = 7, 8, 9, 10$, and 11) along with Reynolds numbers ranging from 3000 to 24,000 in increments (3000, 6000, 9000, 12,000, 15,000, 18,000, 21,000, and 24,000). The geometry of the rectangular solar duct featuring combination of semi-circular roughness was developed to address solar energy enhancement. The primary aim of incorporating combination of semi-circular ribs in a smooth rectangular duct, as shown in Figure 1, was to optimize thermal performance.

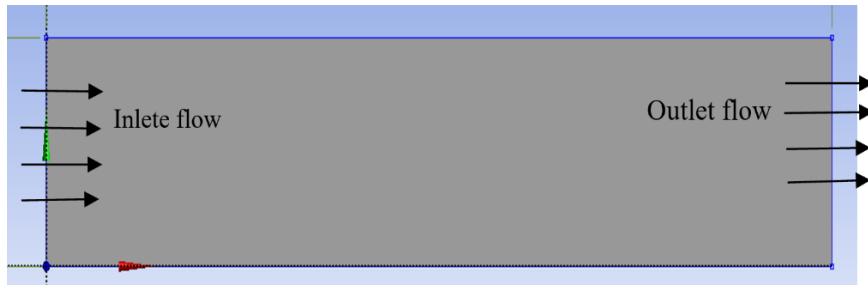


Fig. 1. A rectangular, smooth channel design.

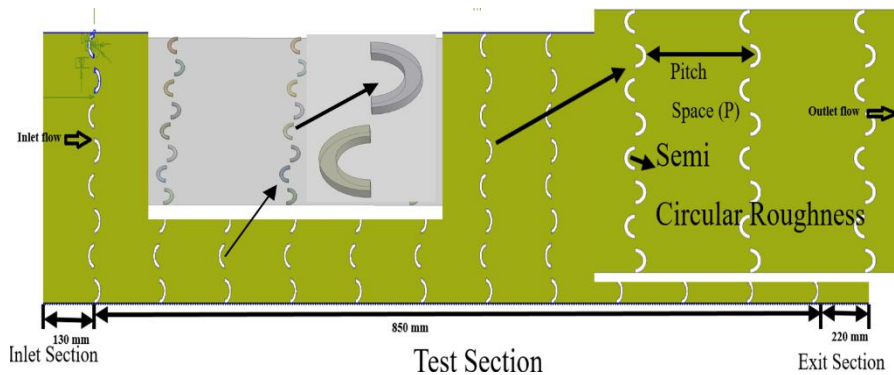


Fig. 2. Design of combination of Semi-circular solar air heater.

2.1 Mesh generation for combination of semi-circular SAH

Mesh generation was carried out using mapped face meshing and refinement tools in ANSYS. Triangle, pyramid, and tetrahedral cells were used to enhance grid quality. A grid independence test was conducted, and 1161025 elements were found optimal for reliable results. The mesh generation method is used after the design of the model, and this method produces the most appropriate mesh for an accurate performance solution. In the model, the grid generation uses triangle, pyramid, and tetrahedron cells, and this mesh method improves the mesh quality of the rectangular duct. In figure 3, Meshing is an effective method for generating accurate and necessary results. For best results, we have to find a grid test that contains several elements as shown in table 1. The grid test helps determine the independence of results from the meshing elements. We conducted this test on the meshing elements themselves to establish this independence. We found several elements 1161025 at an element size of 0.001 m, mapped size, and refinement.

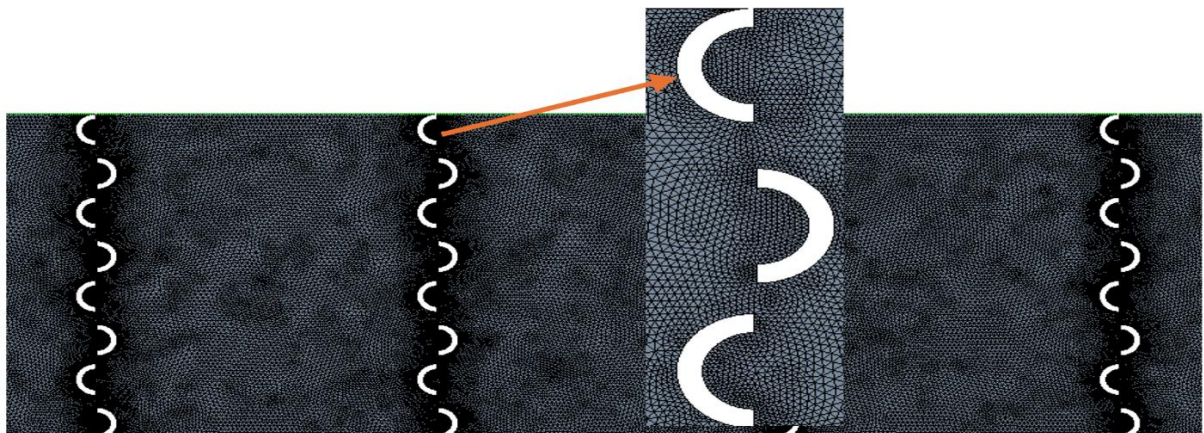


Fig. 3. Meshing of staggered-shaped SAH.

Table 1: Grid Independence test

Number of Grid elements	Nusselt Number (Nu)
421332	38.64411
624266	82.16161
1161025	39.35411
1284891	40.05655
1526961	48.45448

2.2 Boundary Condition

Boundary condition is an important part of the designed model, which is applied after meshing, and it's also given before the results setup method. Boundary condition is given to the rectangular duct as name selection and limited conditions for the entrance of the rectangular ducts, shown as inlet, exit side of the ducts shown as outlet, when the roughness is used in the smooth channel as nominated combination of semi-circular. The roughness is attached on both sides of the solar rectangular duct, which is effective characteristics and the f_r coefficients. No slip condition is taken by the ANSYS workbench for the velocity of the flowing air, which is specified as a zero stress wall boundary condition on the whole surface of the solar duct. If the turbulent flow is used, then the turbulent intensity taken by ANSYS Fluent at 5% is taken by ANSYS Fluent automatically.

2.3 Equations of Governing for SAH

In this section, the ANSYS workbench uses the governing equation automatically, but this governing equation performs accurately in the case of an accurate design of the model. The governing equation method is used after the meshing section of the solar duct. The governing equation consists of the types of models as the standard k-e model. We used the standard k-e model under which the Standard k-e method is used.

2.3.1 Turbulent Flow

Turbulent flow is used when the working fluid comes into contact with the roughness of multiple V-shaped roughness elements, causing the fluid to circulate the roughness. The turbulent flow converts the circulated energy into a heat transfer rate. But some equations are solved for transferring the energy automatically by the computational fluid dynamics system.

The model classifies energy equations of the model to resolve the smartly transformations, problem in laminar flow, turbulent flow and transition flow and conversion equation.

2.3.1.1 Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

2.3.1.2 Momentum Equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{du_1}{dx_1} \right) + \frac{\partial(-\rho u_i' u_j')}{\partial x_j} \right] \quad (2)$$

2.3.1.3 Energy Equation

$$C_p \left(u_i \frac{\partial T}{\partial x} + u_j \frac{\partial T}{\partial y} \right) = \frac{k}{\rho} \nabla^2 T \quad (3)$$

Where C_p represents the specific heat capacity of the fluid, while (u_i, u_j) depicts the velocity component of fluid in the xy-direction. The symbols ρ , T , p , and δ_{ij} are the density of the fluid, temperature, pressure, and Kronecker's constant consecutively in eqs. (1, 2 and 3) [21].

Numerical method: The governing continuity, momentum, and energy equations were solved using the finite volume method (FVM) in ANSYS Fluent under steady-state, incompressible turbulent flow assumptions. **Convergence Criteria:** The solution was considered converged when the following criteria were simultaneously satisfied. Residuals: Continuity, momentum, k, and ϵ : 10^{-5} , Energy equation: 10^{-6} , Monitored parameters: Stabilization of average Nusselt number, Stabilization of friction factor, Constant outlet air temperature.

Discretization schemes: Pressure-velocity coupling was achieved using the SIMPLE algorithm. Momentum and energy equations were discretized using second-order upwind schemes to reduce numerical diffusion and accurately capture flow separation, reattachment, and heat transfer enhancement caused by the semi-circular roughness elements. Turbulence kinetic energy (k) and dissipation rate (ϵ) equations were discretized using a first-order upwind scheme initially and later switched to second-order upwind for improved accuracy.

3. Results and Discussion

3.1 Performance Analysis Based on Dittus-Boelter Correlation and Smooth Rectangular Duct Flow

Figure 4 illustrates a comparative analysis between the smooth rectangular duct and the theoretical prediction based on the Dittus-Boelter correlation. This comparison serves to validate the accuracy of the heat transfer coefficient in a duct without any combination of semi-circular roughness elements, providing a reference baseline for evaluating enhancements introduced by surface modifications. The comparison between theoretical and numerical analysis findings (CFD) demonstrates the outcomes of the heat transmission. Figure 4 compares the impact of the smooth channel and the Dittus-Boelter equations ($Nu = 0.023 Re^{0.8} Pr^{0.4}$). In figure 5, For all turbulence models, the CFD findings for a smooth rectangular channel demonstrate a regular rise in Nusselt number with Reynolds number. In contrast to the $k-\omega$ model, which produces comparatively lower values, the RNG $k-\epsilon$ model predicts higher heat transfer rates and standard $k-\epsilon$ model has better agreement with experimental correlation [25]. The standard $k-\epsilon$ model was therefore chosen for the analysis.

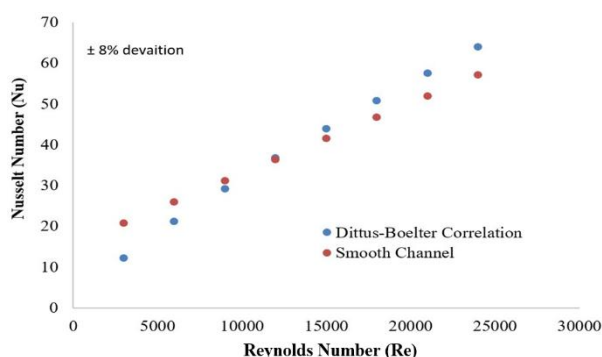


Fig. 4. Expressed the heat transfer rate.

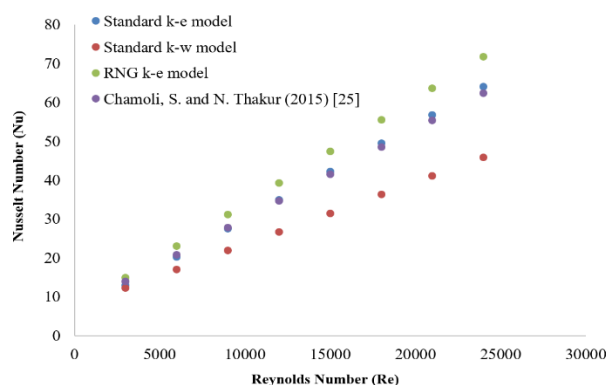


Fig. 5. Comparison of turbulence model with variations in Nusselt number.

3.2 Findings and explanation of the solar rectangular duct's variants using combination of semi-circular roughness

This section presents the results obtained from ANSYS Fluent simulations. There are many results investigated under the following conditions, like variations in the Reynolds number, pitch space between combination of semi-circular roughness, and variations in the pitch space, $P = 15.4, 17.6, 19.8, 22,$ and 24.2 mm of roughness. This study examines the performance differences between systems incorporating surface roughness and those with smooth surfaces under identical operational conditions. The analysis particularly focuses on how variations in the geometry of roughness—specifically the height of the ribs, $e = 2.2$ mm and outer diameter is 3.3 mm. In the case of the solar rectangular duct, different rib heights were introduced to The circulation of fluid depends upon the turbulent flow and constant surface area. In this system, a solar air heater is utilized for solar energy absorption and subsequent heat transfer to the flowing air. The introduction of combination of semi-circular roughness elements is instrumental in enhancing this energy delivery. The study's parameters consist of Reynolds number range from 3000 to $24,000$, selected to investigate reductions in fluid viscous effects.

3.2.1 Variations of fluids as contour

The motive of the model is to boost the efficiency of solar air heaters with the use of combination of semi-circular roughness because roughness mounted on a smooth tube is more efficient than a single smooth tube, and mass flow rate also enhance the thermal performance. The velocity contour is presented to see the maximum mass flow rate condition at different parameters. Utilizing the speed contour, the overall mean speed, discharge, and mass flow rate are calculated throughout the entire solar duct. The contour depicts a graph of constant air property values at a given moment. In the Figure 6, can see that the combined semi-circular roughness blocks the fluid and remains constant but near and around the roughness reattachment zone is formed which illustrates the variations in the velocity contour during the change in the fluid velocity from 0 m/s to 17.9 m/s at the Reynolds number $Re = 3000 - 24,000$, relative roughness pitch $p/e = 10$, height of combination of semi-circular roughness $e = 2.2$ mm, and constant in the gap $g = 1.2$ mm and $d_{out} = 3.3$ mm. The velocity of fluid affects the solar air heater. This velocity magnitude is more effective for maximum heat transfer rate because after striking the air to the combination of semi-circular roughness, gets deflected around the near The interaction between the heated surface of the solar air heater and the airflow generates circulation and a reattachment zone, facilitating. In the roughness can achieve more energy without loss because no more separation from roughness.

Figure 6, displays variations the speed of fled in the harsh areas and found increment of velocity as compared to fig. 7. This increment of velocity is the main reason of pitch space between roughness's. The pitch space creates a free or windward zone for air flow and at windward zone air start to increase at upward form and leeward zone is also found when the separation of fluid after striking on the roughness. The velocity is minimum after striking to roughness and maximum in red color zone. The back of roughness, pressure drop is maximum because of low velocity of fluid. At $P/e = 10$, the spacing between ribs allows flow to reattach, resulting in strong recirculation zones and jet-like acceleration, enhancing core flow velocity and resulting in higher average velocity magnitudes. At $P/e = 10$, pressure losses are minimal, and combination of semi-circular, promoting smoother acceleration and higher overall velocity levels as compared to $P/e = 7, 8, 9,$ and 11 as shown in figures 7, 8, 9, and 10 respectively. In figure 11 (a, b, c, d, and e), can see that variations in the temperature contour at an angle of combination of semi-circular roughness with respect to the $Re = 24,000$ at fig. 11 {(a) $P/e = 7$, (b) $P/e = 8$, (c) $P/e = 9$, (d) $P/e = 10$ and (e) $P/e = 11$ }, we are taking these values because Nusselt numbers are maximum at given various fixed values. In figure 12, at a constant pitch-to-height ratio (P/e) of 10 in a solar air heater duct with multi combination of semi-circular roughness, the width (w) of the ribs has a directly influence on the distribution of turbulent kinetic energy (TKE) and turbulence intensity Among the widths tested, TKE reaches its highest value when $d_{out} = 3.3$ mm, this behavior is due to how the rib width changes the flow separation and reattachment characteristics in the duct. At $d_{out} = 3.3$ mm, the flow separates effectively from the rib surface and reattaches downstream, forming strong vortices that actively interact with the airflow, increasing velocity fluctuations and enhancing turbulence. The presence of wide ribs interferes with the natural flow, impeding effective energy exchange between flow layers. This makes the flow more stable in undesirable regions and results in low turbulence energy. Overall, it is clear that $d_{out} = 3.3$ mm provides a balanced geometry that allows proper flow disruption, strong vortex activity, and high interaction between the air and the heated surface.

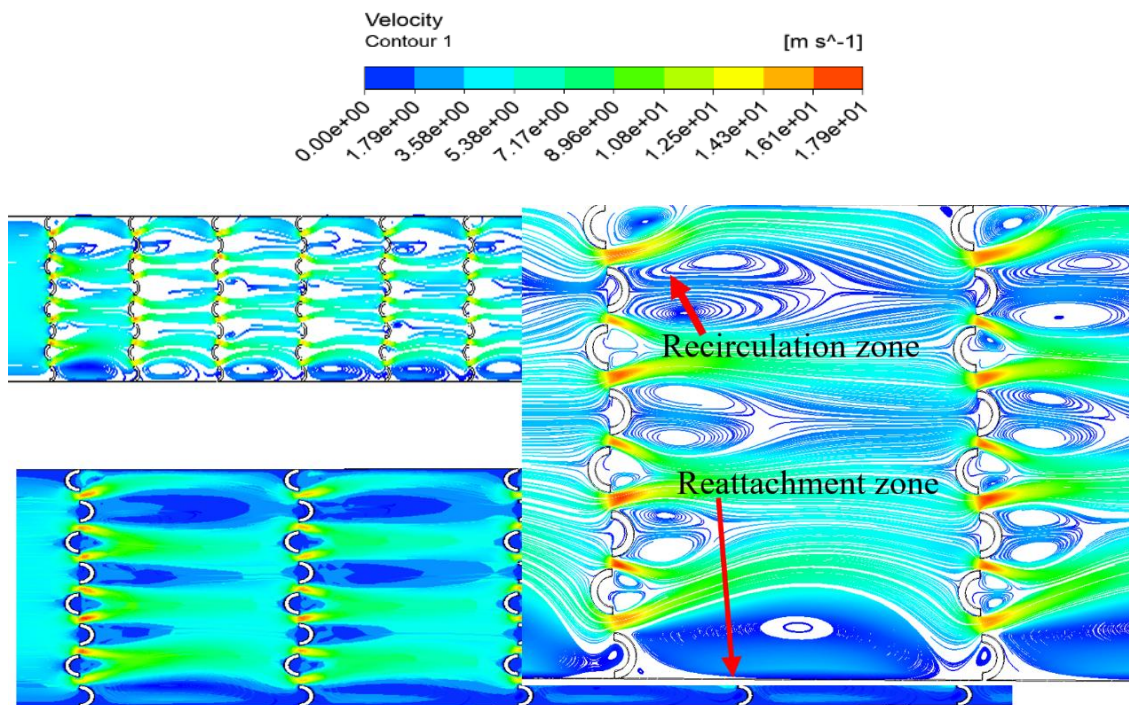


Fig. 6. Velocity contour at $P/e = 10$.

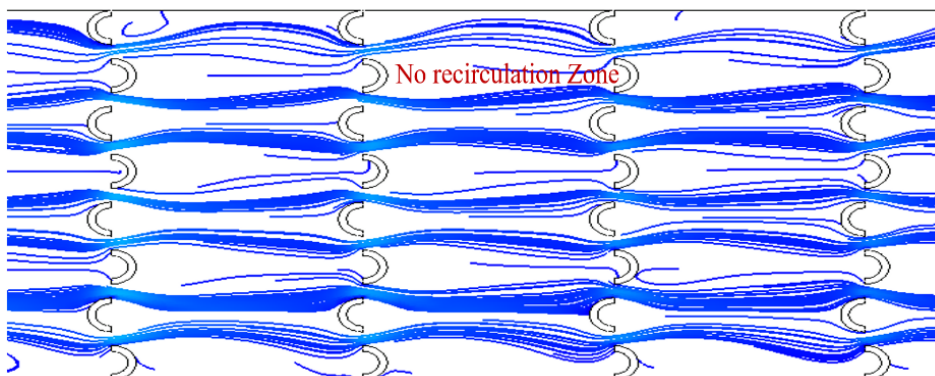


Fig. 7. Velocity increment of fluid at $P/e = 7$.

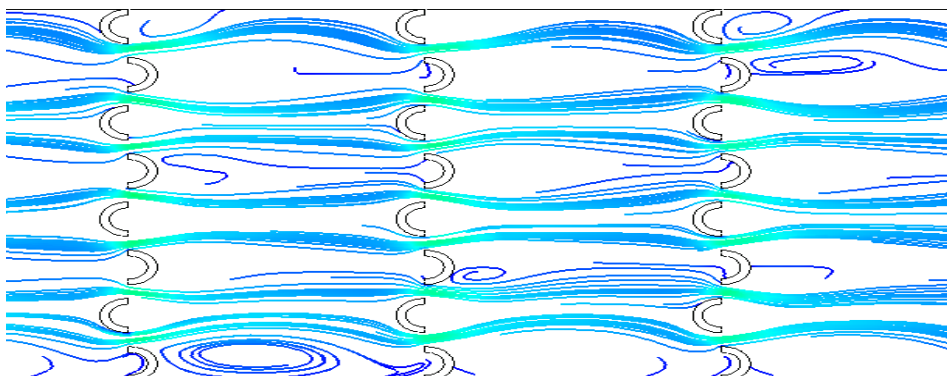


Fig. 8. Change in velocity of fluid at $P/e = 8$.

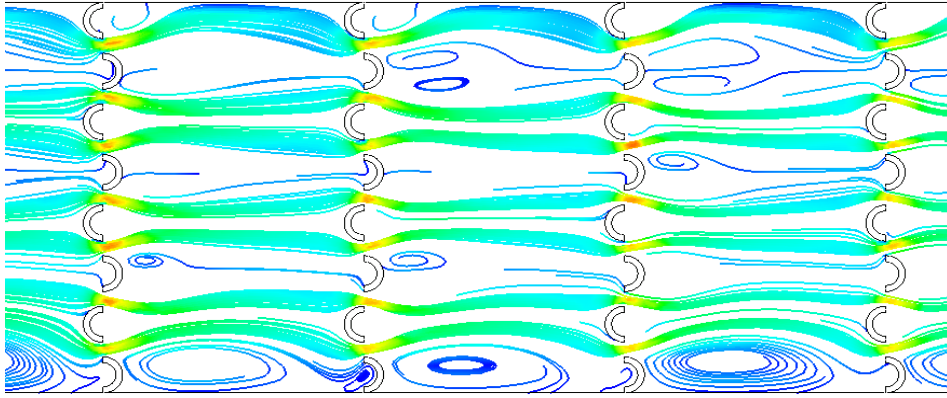


Fig. 9. Change in velocity of fluid at $P/e = 9$.

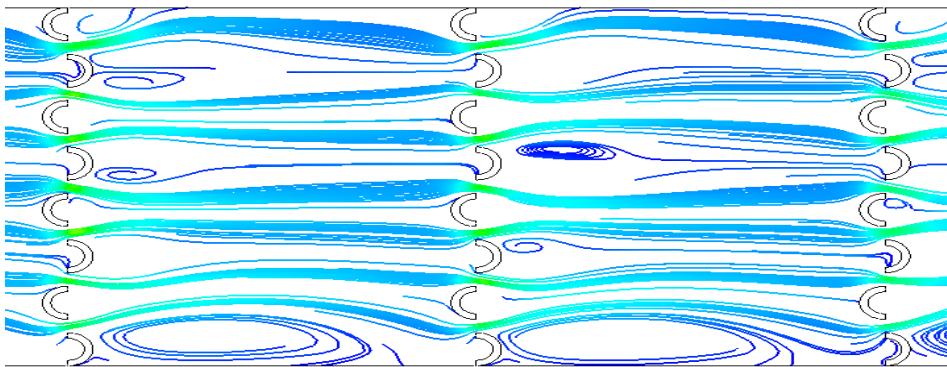
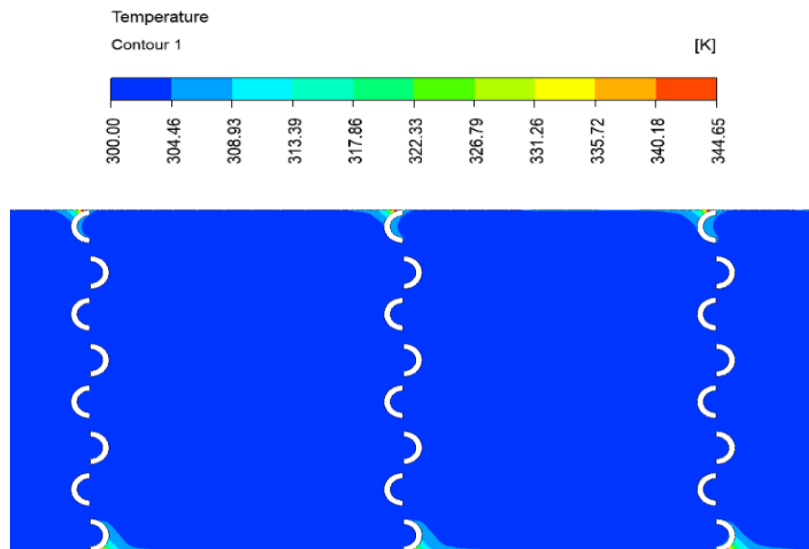
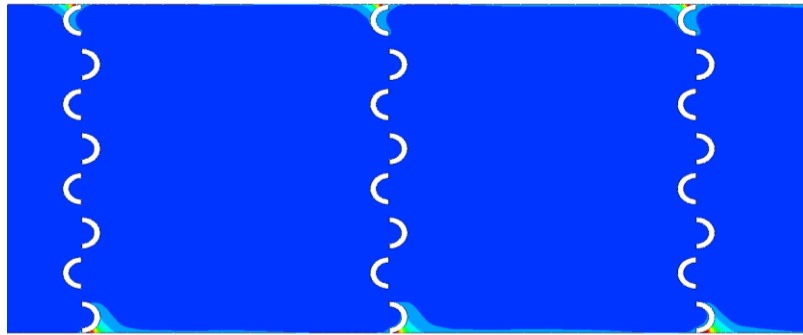


Fig. 10. Change in velocity of fluid at $P/e = 11$.

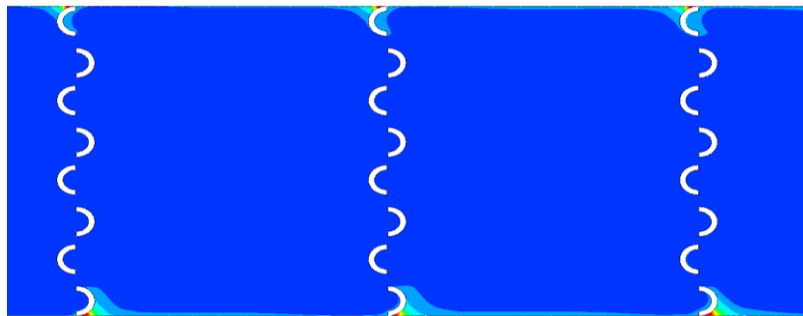


(a) $P/e = 7$

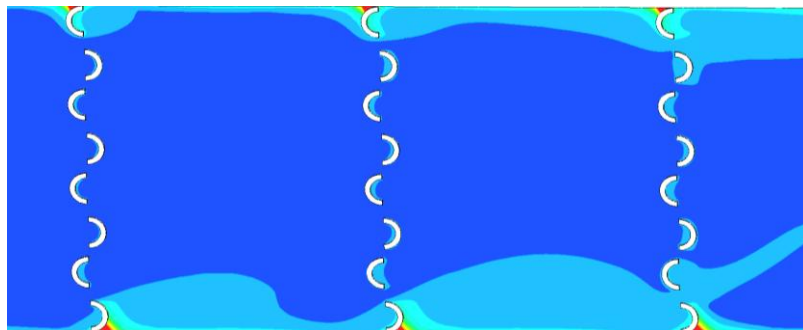
Fig. 11. Variations in temperature contour at (a) $P/e = 7$, (b) $P/e = 8$, (c) $P/e = 9$, (d) $P/e = 10$ and (e) $P/e = 11$ at $Re = 24,000$.



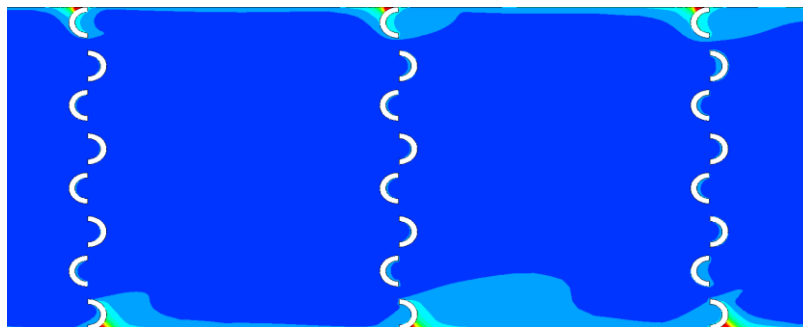
(b) $P/e = 8$



(c) $P/e = 9$



(d) $P/e = 10$



(e) $P/e = 11$

Fig. 11. Variations in temperature contour at (a) $P/e = 7$, (b) $P/e = 8$, (c) $P/e = 9$, (d) $P/e = 10$ and (e) $P/e = 11$ at $Re = 24,000$.

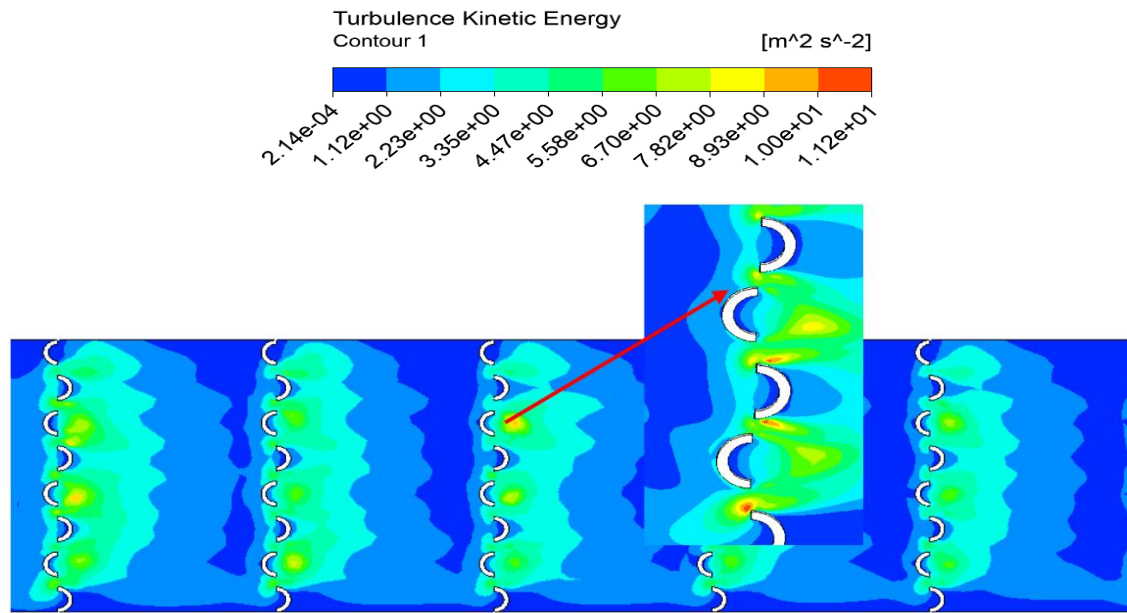


Fig. 12. Turbulent Kinetic energy for $P/e = 10$.

3.3 Impact of Re , P/e , P , and Combination of semicircular roughness on Performance Analysis

The simulations addressed various flow related challenges, such as the presence of energy-carrying turbulent eddies, using advanced computational tools. Turbulent eddy with low frequency, experimental damage due to cavitation's which is developed by block or trapped circulation air behind or near the roughness as obstacle due to this trapped air around the obstacle temperature increased continuously and turbulent eddies formed. So to reduce the turbulent eddies in the solar rectangular variation in the combination of semi-circular roughness used. In figure 13, Specifically, the highest Nusselt number obtained was Nu . By producing several counter-rotating vortices & forced flow reattachment zones, the staggered combination of semi-circular ribs improve local heat transfer for $d_{out} = 3.3$ mm at $P/e = 10$, Pitch space (P) = 22 mm, and $Re = 3000 - 24,000$. It observed 2.4 times increment in the heat transfer arte with compare to the results of smooth rectangular channel at $Re = 24,000$, $P = 22$ mm, and $p/e = 10$. The vortices communicate throughout the duct when their width is ideal, producing excellent thermal performance. Sudden merger of vortices that are too large or too small disrupts the center flow.

In figure 14, This section presents the friction factor analysis for a solar air heater incorporating combination of semi-circular roughness elements on the absorber plate. The friction factor is impacted by variations in roughness spacing and geometry. Turbulent flow, driven by irregular fluid fluctuations within the rectangular duct, leads to both enhanced heat transfers and an increase in frictional resistance. The primary aim of this roughened duct design is to regulate and optimize the friction factor. Its behavior is analyzed across a Reynolds number varying from 3,000 to 24,000, with relative roughness pitches (P/e) varying from $P/e = 7 - 11$, and a rib height of 2.2 mm.

The figure 14, shows the friction factor validated at Reynolds number $Re = 3000 - 24,000$ and variations in the relative roughness pitch $P/e = 10$ and height of the roughness $e = 2.2$ mm and $d_{out} = 3.3$ mm. In the figure we also compare with smooth channel friction factor because it is necessary to check the friction factor with combination of semi-circular and without roughness.

4. Performance of SAH with combination of semi-circular roughness

The fluctuating turbulent behavior of the working fluid contributes significantly to enhancing both hydrodynamic and thermal efficiency. Analyzing the thermal performance curve offers valuable insights into determining the required heat transfer rate for converting natural energy into usable thermal output. Additionally, this performance is strongly influenced by the airflow circulation within the solar air heater, particularly when provided with combination of semi-circular roughness, which improves the overall effectiveness of the system.

The thermal hydraulic performance theoretically is examined by the Webb and Eckert Researcher.

$$\eta_{\max} = (\text{Nu}/\text{Nus})/(\text{fr}/\text{frs})^{1/3}$$

Based on figure 15, analysis, the thermal-hydraulic performance was evaluated for the configuration with $P/e = 7 - 11$, constant gap $g = 1.2$ mm, Reynolds number (Re) = 3000 - 24,000, rib height $e = 2.2$, and pitch $P = 15.4 - 24.2$ mm using combination of semi-circular roughness elements. The findings indicate that increasing the pitch spacing between roughness elements leads to a higher Nusselt number. This configuration and its parameters have proven to be effective in achieving the peak thermal performance, with $\eta_{\max}$ reaching approximately 1.61 at $d_{\text{out}} = 3.3$ mm, $P/e = 10$, $P = 22$ mm and $\text{Re} = 24,000$ as illustrated in Fig. 15.

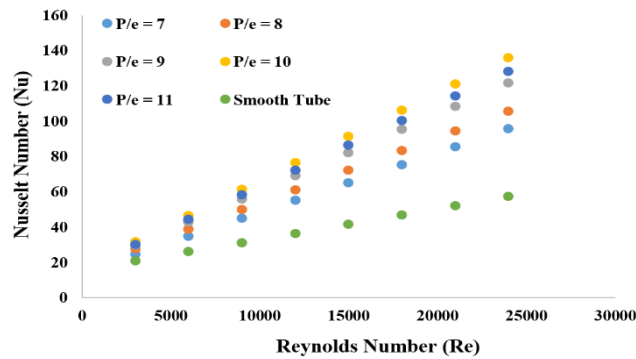


Fig. 13. Expressed the Nusselt number at $e = 2.2$.

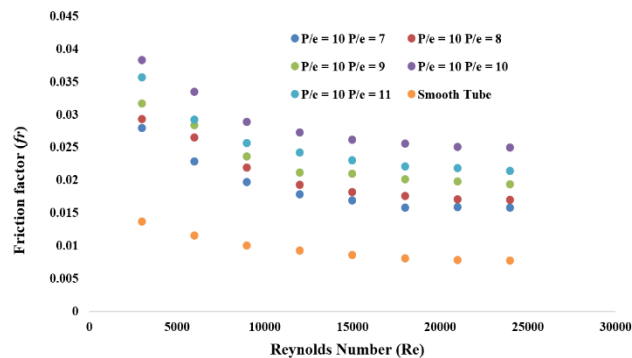


Fig. 14. Presented a relation between friction factors and Reynolds number.

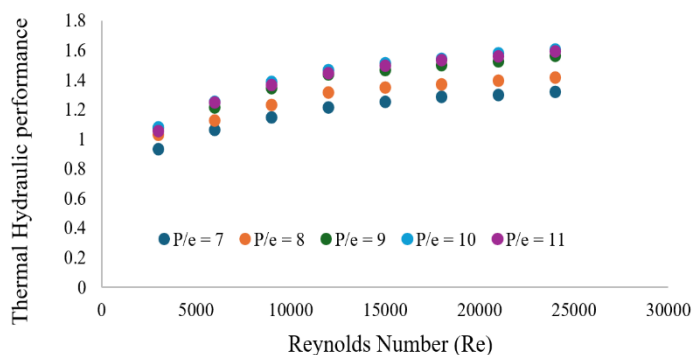


Fig. 15. Presents maximum thermal hydraulic performance of combined SAH.

The THPP of the present semi-circular roughness is compared with previously published geometries and depicted in Table 2. It is clearly seen that the semi-circular roughness shows its superiority in terms THPP over many geometries. Thus, it is favorable to use the semi-circular roughness to improve the overall performance of SAH.

Table 2: THPP comparison of the present proposed semi-circular roughness with other previously explored geometries.

Type of roughness geometry	Reference	THPP
Multi v-shaped rib with gap roughness	Kumar, A., Saini, R. P., & Saini, J. S. (2012). Experimental investigation on heat transfer and fluid flow characteristics of air flow in a rectangular duct with Multi v-shaped rib with gap roughness on the heated plate. <i>Solar Energy</i> , 86(6), 1733-1749.	1
V down perforated baffle	Chamoli, S. and N. Thakur (2015). "Effect of roughness height ratio in V down perforated baffle roughness on thermohydraulic performance of solar air heater: an experimental study." <i>International Journal of Ambient Energy</i> 36(5): 242-247.	1.52
Semi-circular roughness	Present study	1.61

5. Conclusions

The study discusses the design and analysis of a solar rectangular duct featuring semi-circular roughness elements, using Computational Fluid Dynamics (CFD) in ANSYS Fluent. Key findings indicate that thermal performance is significantly affected by the geometric configuration and spacing of the roughness elements (constant gaps of 1.2 mm) and their height ($e = 2.2$ mm) at Reynolds numbers ranging from 3000 to 24,000. The presence of roughness enhances temperature distribution and improves thermal hydraulic performance compared to a smooth channel.

- The SAH model using the standard $k-\epsilon$ turbulence model provided reliable boundary layer predictions.
- The study found that heat transfers enhanced by up to 262% compared to a smooth duct, especially at constant dimensions, $g = 1.2$ mm, $P = 22$ mm, $P/e = 10$, and $Re = 24,000$. The optimal Nusselt number of 135.53 was observed for $g = 1.2$ mm, $P/e = 10$, $e = 2.2$ mm, at $Re = 24,000$ and minimum Nusselt observed of 95.51 at $Re = 24,000$, $P/e = 7$.
- The Nusselt number observed the maximum increment of 2.3 times with relation to smooth channel at $P/e = 10$, $P = 22$ mm and $Re = 24,000$. The minimum friction factor obtained 1.93 times as compared to smooth channel at $Re = 12,000$, and $P/e = 7$.
- The maximum thermal performance, with η_{max} reaching approximately 1.61 at $P/e = 10$, $P = 22$ mm and $Re = 24,000$.

Nomenclature

L	Total length of Rectangular Channel, mm
W	Width of the rectangular Channel, mm
H	Height of the rectangular Channel, mm
D_h	Equivalent hydraulic diameter of duct, mm
e	roughness's Height, mm
Nu	Nusselt number
Re	Reynolds number
d_{in}	Inner diameter
d_{out}	Outer diameter
$f_{r,f}$	Friction factor
t	Thickness of roughness, mm
I	Heat flux, w/m^2
P	Pitch shape, mm
D_h	Hydraulic diameter, m
P/D_h	Pitch to hydraulic diameter ratio
v	Velocity of fluid, m/s
T	Air temperature, K

W/H	Channel Aspect Ratio
Pr	Prandtl Number
e/D_h	Relative Roughness Height
p/e	Relative Roughness Pitch
Pr	Pressure, Pa
x, y	Rectangular Channel coordinate
CFD	Computational Fluid Dynamics
SAH	Solar air Heater
THP	Thermal Hydraulic Performance

Greek symbol

α	Angle of attack, (θ°)
Γ	Gamma function
ρ	Density, kg/m^3
μ	viscosity, kg/m s
γ	Euler's constant
λ	Thermal conductivity, W/m-K
η	Thermal hydraulic performance

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