CFD Study on Thermohydraulic Performance Enhancement of Solar Flat Plate Air Heaters Using Novel Turbulators

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Abstract: The performance of solar flat plate air heaters (SFPAHs) are controlled by the fundamentally poor convective heat transfer coefficient of air. To overcome this, current research recommends a novel turbulator integrated SFPAH to augment the thermohydraulic performance (THP) of an SFPAH equipped with a smooth absorber plate (SAP). Three-dimensional computational fluid dynamics (CFD) simulations were made by means of ANSYS 2025 R2 Fluent for the following mass flow rates 0.01, 0.02 and 0.03 kg/s. Key contours (velocity, temperature, pressure, and turbulent kinetic energy) were analyzed to investigate the fluid flow and heat transfer characteristics. The proposed novel turbulator increased turbulence, upheld secondary flow structures, disturbed the boundary layer, causing improved heat transfer with a tolerable pressure penalty. Also, the current research validates the practicability of the suggested passive enhancement technique for improving SFPAH performance.

Keywords: solar flat plate air heater; stepped turbulator; thermohydraulic performance; computational fluid dynamics; heat transfer enhancement

Introduction

The rising demand for renewable energy systems has fast-tracked examination on solar thermal technologies capable of dropping reliance on conventional fossil fuels. Between these equipment, SFPAHs have involved substantial consideration because of their low maintenance requirements, simple structure, environmental friendliness, and appropriateness for claims such as food processing, space heating, agricultural drying, and timber seasoning [1]. In spite of these merits, SFPAHs with SAP normally record low thermal efficiency due to relatively low heat capacity and thermal conductivity, ensuing in low convective heat transfer between the flowing air and the absorber plate [2].

Numerous passive heat transfer augmentation methods have been suggested to advance the thermal performance of SFPAHs. Roughness elements (artificial), including cylindrical protrusions, dimples, wire meshes, W-shaped ribs, V-shaped ribs, winglets, twisted tapes, and transverse ribs, have been widely examined. These strategies disturb the thermal boundary layer, enhance fluid mixing, produce separation of flow and reattachment, and thus enhances the heat transfer coefficient. However, these developments are regularly supplemented by a substantial increase in losses (frictional), which may decrease the overall THP of the SFPAH system [3].

Current studies have confirmed that the arrangement and geometry of turbulence agents play a critical role in matching pressure loss and heat transfer enhancement. Optimized fluid flow turbulences proficient of producing organized vortices can significantly advance transfer of energy while lessening penalties of hydraulic. Therefore, the growth of novel turbulator structures remains an dynamic area of study in SFPAH systems [4]. Though many research have concentrated on existing rough absorber plates, reasonably limited consideration has been dedicated to individual turbulator geometries proficient of producing sturdy secondary vortices deprived of wide surface roughening [5]. Also, complete visualization of the fluid flow field through temperature, velocity, pressure, and turbulent kinetic energy contours is important for accepting the underlying improvement mechanisms and directorial forthcoming design optimization. So, the current research suggests a novel stepped turbulator combined within the air passage of a SFPAH having a smooth absorber plate. A 3D numerical investigation was supported out using ANSYS 2025 R2 Fluent under steady-state conditions for the following mass flow rates 0.01, 0.02 and 0.03 kg/s. The effect of the suggested geometry on temperature field, pressure variation, velocity distribution, and turbulent kinetic energy was examined. The THP of the projected design was subsequently assessed to evaluate its appropriateness for practical solar thermal based heating applications.

Materials and Methods

A 3D computational model of a SFPAH integrating the proposed stepped turbulator was established using ANSYS 2025 R2 Design Modeler toolbox. The computational field consisted of an entry section, SAP, well insulated bottom plate, four side walls, exit section, and the proposed turbulator located within the fluid flow channel. The geometry of the turbulator was planned to disturb the inward airflow, produce vortices (localized), and increase air mixing near the absorber plate. The computational mesh was produced using ANSYS 2025 R2 Meshing. Local mesh modification was useful around the turbulator to exactly seizure separation of flow, formation of vortex, and thermal gradients. Layers of inflation were presented near the surfaces of the wall to determination the boundary layer exactly. A grid freedom study was directed using medium, coarse, and fine meshes to guarantee that the numerical forecasts were autonomous of mesh and its density. The medium mesh containing around 499538 elements was designated since it provided accurate predictions while maintaining reasonable computational cost.

The results of simulations were achieved using the pressure-based solver available in ANSYS Fluent 2025 R2. Fluid was assumed as Newtonian, incompressible, and to own constant thermophysical properties. The equation of energy was actuated to interpretation for heat transfer. Effects of Turbulence were modeled using the Realizable k–ε turbulence model with enhanced wall treatment, due to its established capability in calculating internal flows (turbulent) with heat transfer augmentation devices.

A stable heat flux conforming to absorption of solar energy was realistic to the absorber plate, while the rest of the walls were considered as adiabatic. The entry boundary condition was quantified as an entry with flow rates variable from 0.01, 0.02 and 0.03 kg/s, while the exit was distinct as exit operating at atmospheric pressure. Convergence was attained when the residuals of momentum, continuity, energy and turbulence quantities decreased below 10^{-6}. The THP of the suggested configuration was assessed using pressure drop (ΔP), friction factor (f), outlet air temperature (T2), useful heat gain (Qu), and thermohydraulic performance parameter (THPP). Figure 1 presents the graphical illustration of the observed fluid domain.

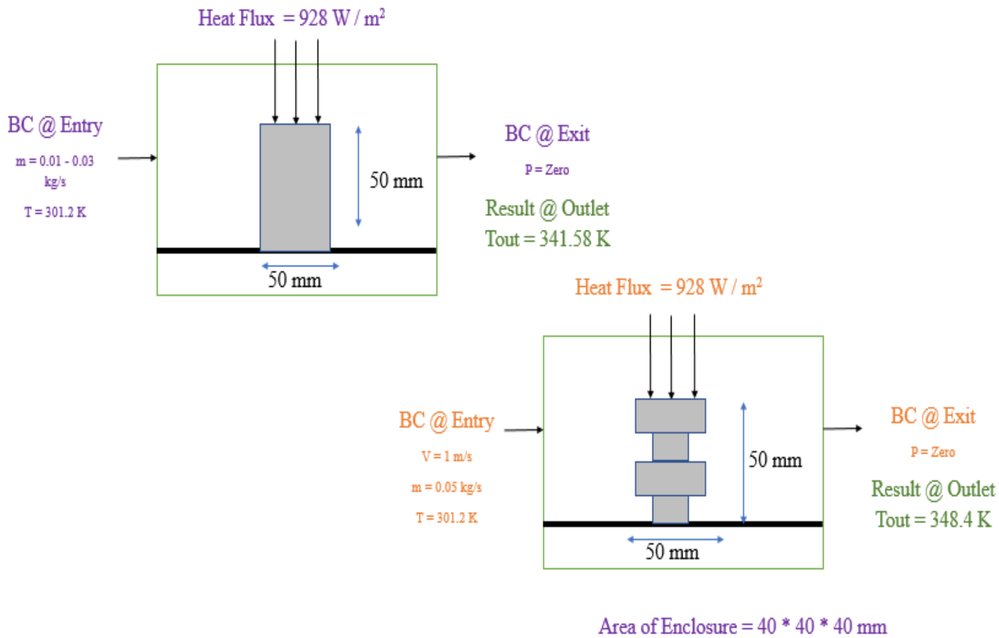

Figure 1. Graphical illustration of the flow domain.(A) solid and (B) stepped cylindrical turbulator

Results and Discussion

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3.1 Pressure contours

Figure 2 presents the pressure contours of the proposed stepped turbulator in to the SFPAH assembly. Pressure contours point out the presence of a intense region upstream of the proposed turbulator due to stagnation of flow, whereas a low-pressure wake established downstream due to flow separation. As projected, the ΔP increased with increasing mass flow rate. While the planned geometry announced supplementary hydraulic based resistance, the consistent improvement in heat transfer compensated for this penalty, subsequent in an upgraded overall THP.

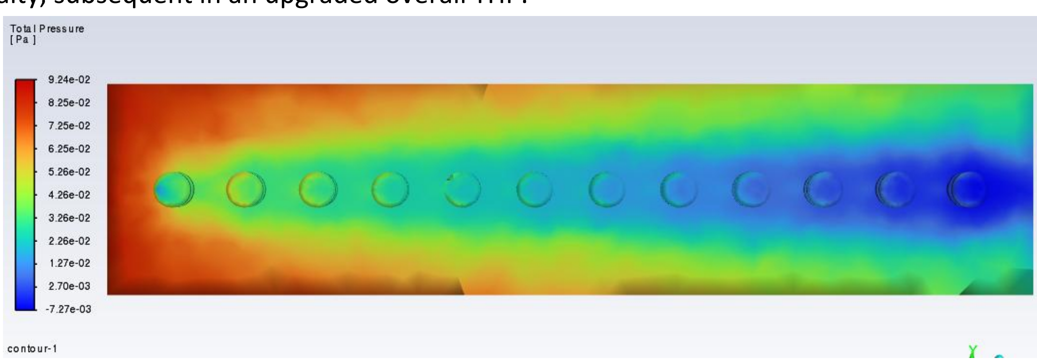

Figure 2. Graphical illustration of the pressure contour.

3.2 Velocity profile

Figure 3 presents the velocity contours of the proposed stepped turbulator in to the SFPAH assembly. It is clearly revealed that the addition of this novel geometry considerably changed the fluid flow configuration within the duct. As the inward air faced the turbulator, limited acceleration occurred nearby the turbulator, followed by separation of flow and downstream recirculation. These structures of secondary flow augmented mixing of fluid and supported repeated communication between the flowing air and the heated absorber plate. The strength of these whirlwinds became more noticeable with growing fluid flow rate due to the analogous increase in Reynolds number.

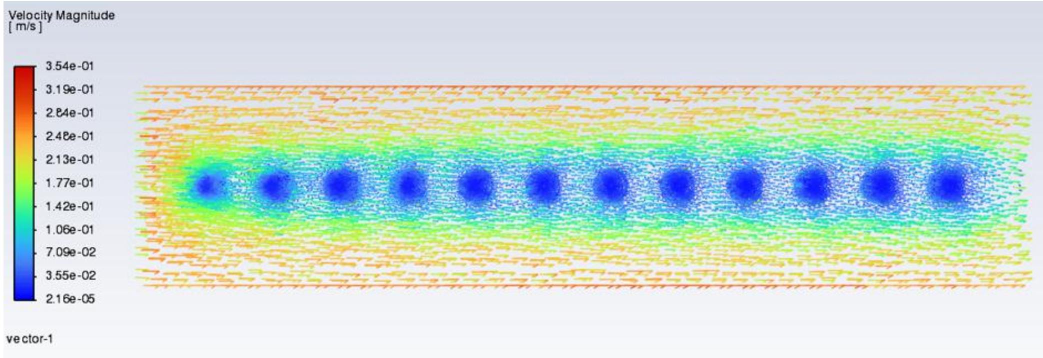

Figure 3. Graphical illustration of the velocity contour.

3.3 Temperature profile

Figure 4 presents the temperature contours of the proposed stepped turbulator in to the SFPAH assembly. It is clearly revealed that the addition of this novel geometry revealed improved thermal transport through the fluid flow channel. Related with the SAP configuration, the suggested turbulator efficiently disturbed the layer of thermal boundary adjacent to the absorber plate, allowing cooler air from the core region to continuously replace the heated air near the wall. Accordingly, a more unvarying distribution of temperature was experiential across the exit section, representing developed extraction of heat from the absorber plate.

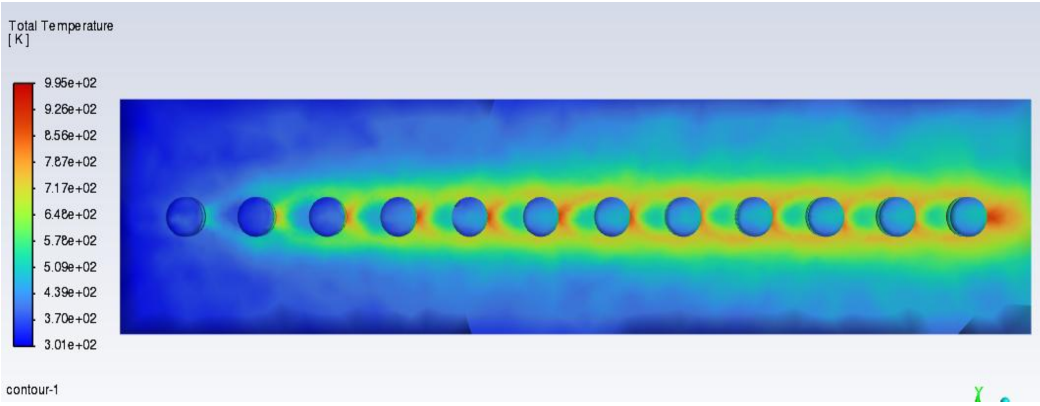

Figure 4. Graphical illustration of the temperature contour.

3.4 Turbulent kinetic energy profile:

Figure 5 presents the turbulent kinetic energy (TKE) contours of the proposed stepped turbulator in to the SFPAH assembly. The TKE contours further established the effectiveness of the recommended design. Higher TKE values were witnessed around the two edges (leading and trailing) of the turbulator, signifying enhanced momentum exchange and vigorous turbulence generation. These regions accorded with strengthened thermal mixing, thus authenticating the role of turbulence in refining convective heat transfer.

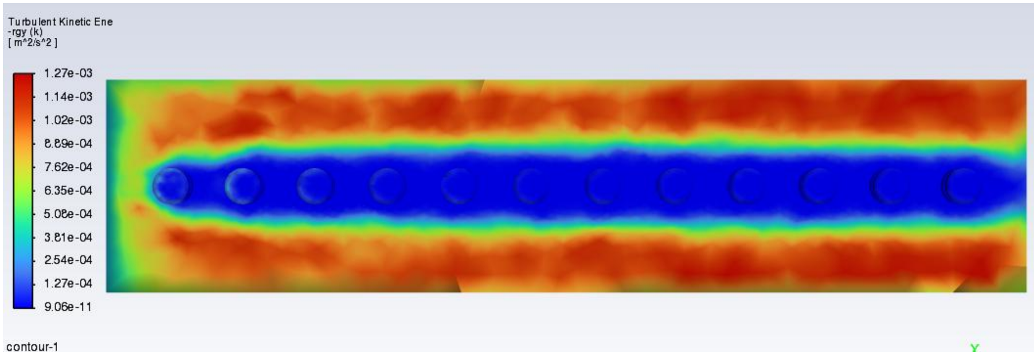

Figure 5. Graphical illustration of the turbulent kinetic energy contour.

Based on the witnessed flow appearances and thermohydraulic performance, the proposed stepped turbulator displays substantial possibilities for improving the thermal performance of SFPAHs.

Conclusions

A novel stepped turbulator was numerically examined to increase the THP of a SFPAH with a SAP. The 3D CFD simulations showed in ANSYS Fluent 2025 R2 validated that the proposed geometry successfully enhanced turbulent mixing, produced secondary vortices, and disturbed the layers of thermal boundary. Velocity, pressure, temperature, and TKE contours confirmed enhanced convective mode of heat transfer associated with SAP based flow conditions. Though losses of pressure augmented because of flow block, the overall THP improved. The proposed stepped turbulator design signifies a favorable passive augmentation technique for high-efficiency SAH applications and deserves future investigational validation.

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