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Enhancing Flat-Plate Solar Collector Efficiency: A Numerical Study

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Abstract

This study explores the improvement in performance of flat-plate solar collectors by integrating hybrid Photo-Voltaic (PV)-thermal systems. Numerical simulations were performed using ANSYS software, incorporating Computational Fluid Dynamics (CFD) and steady-state thermal modeling. The research focused on a circular-section PV/T collector exposed to solar irradiation of 1000 W/m^2, with ambient and inlet water temperatures set at 288 K. Three different flow rates (0.02, 0.025, and 0.03 kg/s) were examined to determine their effects on collector efficiency and water outlet temperature. Two configurations were analyzed: one without a glass cover (steady-state analysis) and another with water cooling (CFD). The findings revealed that increasing the flow rate from 0.02 to 0.03 kg/s significantly lowered the panel's heating rate, enhancing efficiency but reducing water output. Future research aims to develop PV cells with improved photon absorption to maximize both electrical and thermal energy production. Furthermore, adding extra layers within the panel could optimize heat transfer and boost overall performance. These hybrid systems' capability to generate electricity and thermal energy under diverse atmospheric conditions, such as dust, clouds, and snow, sets them apart from conventional collectors and highlights their potential for sustainable energy solutions.

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Major Findings: *Increasing the water flow rate from 0.02 to 0.03 kg/s reduced panel heating, improving system efficiency (up to 95 %) but decreasing water output. Optimal performance was achieved at 0.03 kg/s, maintaining the lowest panel temperature (312.50 K) and ensuring efficient heat dissipation. Hybrid PV-thermal systems demonstrated superior energy generation under diverse conditions, highlighting their potential for sustainable energy solutions*

Keywords: ANSYS, CFD, Flat-Plate Solar Collector, Hybrid PV-Thermal System, Numerical Simulation

1.0 Introduction

In the face of growing energy demands and the urgent need to transition away from fossil fuels, renewable energy sources have gained significant prominence. Solar energy, with its abundant and readily available nature, presents a viable and sustainable alternative. Flat-plate solar collectors, owing to their simplicity and cost-effectiveness, have been widely employed for thermal energy harvesting. However, conventional flat-plate collectors often exhibit limitations in terms of efficiency and versatility. To overcome these limitations, hybrid Photo-Voltaic (PV)-thermal systems have emerged as a promising technology. These systems integrate photovoltaic cells with thermal collectors, enabling simultaneous generation of electricity and utilization of waste heat. This synergistic approach enhances energy efficiency and expands the range of applications, making them attractive for both residential and commercial sectors. This research investigates the performance enhancement of flat-plate solar collectors through the integration of hybrid PV-thermal systems. Numerical simulations, employing ANSYS software, were conducted, encompassing Computational Fluid Dynamics (CFD) and steady-state thermal modeling. The study evaluated a circular-section PV/T collector under controlled conditions, analysing the impact of varying flow rates on collector efficiency and water outlet temperature. The findings of this research provide valuable insights into the design and optimization of hybrid PV-thermal systems. Future research directions include developing PV cells with enhanced photon absorption capabilities to maximize both electrical and thermal energy generation. Additionally, incorporating innovative materials and advanced heat transfer mechanisms within the panel can further optimize performance. The ability of these hybrid systems to generate both electricity and thermal energy under diverse atmospheric conditions, including dust, clouds, and snow, distinguishes them from traditional collectors and underscores their potential for widespread adoption and a sustainable energy future. Enhancing the efficiency of flat-plate solar collectors involves various innovative approaches, as demonstrated by recent studies. One effective strategy is the integration of Phase Change Materials (PCMs) and rotating tubes, which significantly reduces radiative and convective heat losses, thereby improving thermal absorption rates by 30 % and achieving an exergy efficiency of 90 %[1]. Another approach involves optimizing the design of fins within the collector. Computational Fluid Dynamics (CFD) analysis reveals that wavy fin patterns at specific mass flow rates can maximize the outlet temperature, while V-shaped fins achieve the highest thermal efficiency of 34.7% under certain conditions[2]. The use of nanofluids, particularly hybrid nanofluids containing Al_2O_3, Cu, MWCNT, and SiO_2, has also been shown to enhance thermal performance, achieving a peak thermal efficiency of 70.4 % and significantly higher heat gains compared to traditional fluids[3]. Finally, employing nanofluids like CuO and Al_2O_3 in a corrugated flat plate solar collector with triangular tubes can further improve heat collection performance, with CuO-EG nanofluids outperforming others under varying radiation intensities[4]. Overall, the integration of nanofluids significantly improves the thermal performance of flat plate solar collectors, making them a promising solution for renewable energy applications[5,6]. Hybrid Photo-Voltaic-Thermal (PVT) systems enhance the efficiency of flat-plate solar collectors by simultaneously generating electrical and thermal energy, addressing the common issue of reduced electrical efficiency due to elevated temperatures in photovoltaic cells. Numerical studies indicate that configurations such as the Verre-PV-Verre collector achieve an average electrical efficiency of 15.34%, outperforming alternatives like the Verre-PV-Tedlar, which has an efficiency of 13.85%[7]. Optimization techniques, including various meta-heuristic algorithms, have shown that design parameters significantly influence performance, with maximum electrical efficiencies ranging from 13.85% to 14.28% and thermal efficiencies

reaching up to 52.08%[8]. Overall, these advancements highlight the importance of optimizing both thermal and electrical components in PVT systems to maximize solar energy utilization[9,10]. Additionally, innovative designs like high vacuum PVT collectors can achieve electrical efficiencies of 12.2% while maintaining high thermal conversion rates, demonstrating the potential for substantial energy savings compared to traditional systems[11]. The collaborators have extensively investigated advanced thermal management techniques for electronic devices, as evidenced by their research. Key studies include analysing the impact of substrate board thermal conductivity on electronic component temperature control, computational evaluation of PCM cooling for smartphone circuits, CFD-based thermal management of IC chips using phase change materials and enhancing IC chip reliability through CFD approaches. These works emphasize their commitment to improving electronic performance and reliability using innovative thermal solutions and computational methods[12-15]. Researchers have made significant contributions across various fields through innovative studies. Their work includes predictive IC chip placement for thermal cooling using ANN-GA techniques, water-saving and hygienic faucet designs for public spaces, and experimental analysis of heat transfer enhancement in tubular heat exchangers using minijet impingement and twisted tape inserts with circular holes. Additionally, they have conducted comprehensive studies on the performance and emissions of *Calophyllum inophyllum* biodiesel blended with dimethyl carbonate in diesel engines and explored the use of recycled aluminum cans in solar collectors for drying applications. These studies reflect a multidisciplinary approach to addressing challenges in thermal sciences, energy, and sustainability[16-21]. This compilation of research explores innovative solutions in thermal management, nanofluid applications, and aerodynamic optimization, tackling challenges in electronic cooling, heat transfer, and mechanical behaviour. It highlights advancements in PCM cooling, fuzzy logic-based heat transfer enhancement, and aerofoil design using CFD and experimental methods[22-29]. The collection of studies showcases progress in thermal management, mechanical design, and green technologies. Key contributions include numerical and experimental analyses of heat transfer enhancement using nanofluids and twisted tape inserts, PCM integration for electronic cooling, and energy-efficient HVACR system designs. Additionally, investigations into curved plate welding, substrate material effects on electronics, and biocarbon adsorbents for heavy metal removal demonstrate a multidisciplinary approach to solving engineering challenges[30-41]. The research highlights advancements in heat transfer augmentation using corrugated twisted tape inserts, the impact of steel plate thickness on laser-welded joint strength, and temperature variation techniques for wind turbines. Reviews on hybrid composites and jet impingement further underscore progress in thermal and material sciences[42-48].

Based on the extensive review of existing research, this study focuses on hybrid Photo-Voltaic Thermal (PV/T) collectors as a promising technology for solar energy harvesting. The research aims to compare the performance of two different types of PV/T collectors under varying flow rate conditions.

2.0 Computational Methodology

The initial design and development of the system were undertaken using SolidWorks CAD software. This phase involved the creation of a 3D computational model encompassing several critical components:

- Photoelectric Cells: These are the fundamental elements responsible for converting solar energy into electrical energy.
- Glass Panel: This transparent panel serves as a protective cover for the photoelectric cells, safeguarding them from environmental influences while simultaneously allowing sunlight to penetrate.
- Curved Risers: These components facilitate the efficient circulation of the heat transfer fluid (likely water or a suitable coolant) within the system.

The panel dimensions were established as 2.14 meters in length and 0.014 meters in width, resulting in a total panel area of 0.03 square meters. The hydraulic diameter, a crucial parameter for characterizing fluid flow within the system, was set at 0.03 meters. Subsequently, the modeling and simulation of the system were executed using Ansys software, specifically version 15. To streamline the computational model, only the surface of the PV cells was incorporated into the model. This simplification was deemed acceptable due to the relatively

Table 1. Panel design specifications under review

Material	Thermal Conductivity [W/m·K]	Dimensions [cm]	Number	Density [Kg/m³]
RISER	389	4	22	8730
PV	152	0.5	667	2230



Figure 1. Panel parts.

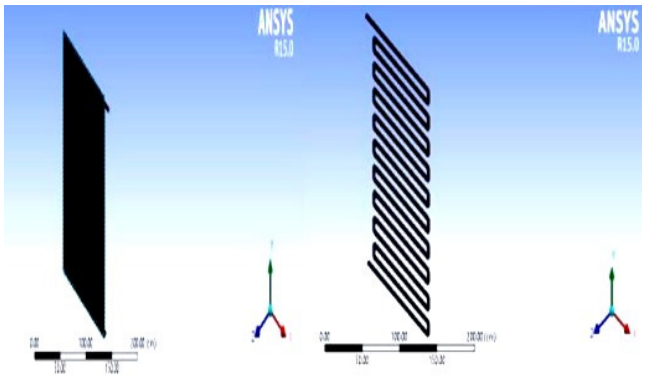


Figure 2. Panel and riser mesh configuration.

consistent heat transfer characteristics observed across the layers of the PV cells. This approach facilitated a more efficient and manageable simulation process while concurrently capturing the essential aspects of the system's behaviour.

Design panel specifications, including their dimensions, are outlined in Table 1. Figure 1 and 2 provides a visual representation of the model's mesh grid.

Following the design phase in SolidWorks, the model was imported into the ANSYS software for in-depth analysis. Finite Element Methods were employed to ensure the highest level of accuracy in the simulation results, utilizing a computational grid comprising 512,430 nodes and 1,542,980 elements. Water was designated as the working fluid, with the outlet pressure set to atmospheric conditions. The specific boundary conditions considered in this study are outlined in Table 2. A mathematical model was subsequently formulated to investigate fluid flow and heat transfer characteristics within natural ventilation systems incorporating solar chimneys and evaporative cooling mechanisms. This model development was underpinned by a set of key assumptions.

1. Conservation Equations: The equations for fluid flow and heat transfer were developed in three dimensions.
2. Incompressible Steady-State Flow: The fluid flow was assumed to be incompressible and in a steady state.
3. Three-Dimensional Heat Transfer: Heat transfer through the glass cover and absorber plate was modelled as conduction in three dimensions.
4. Turbulent Air Flow: The airflow within the channel was assumed to be turbulent, considering realistic flow conditions.
5. Boussinesq Approximation: For density variations, the Boussinesq approximation was employed to account for the effects of buoyancy.
6. Property Evaluation: All thermophysical properties were evaluated at a standard reference temperature to ensure consistency in calculations.

This framework provides a comprehensive approach to analysing the interaction of heat transfer and fluid dynamics in systems designed for enhanced natural ventilation and cooling efficiency.

Table 2. Boundary conditions

Parameter	Value
Environmental Temperature	293 [K]
Input Temperature	293 [K]
Specific Heat of Water	4200 [J/Kg·K]
Solar Irradiance	1100 [W/m^2]
Heat Transfer Coefficient	12 [W/m^2·K]
Water Flow Rate 1	0.02 [Kg/s]
Water Flow Rate 2	0.025 [Kg/s]
Water Flow Rate 3	0.03 [Kg/s]

2.1 (CFD) Model Configuration and Parameters

A second-order upwind scheme was used for both momentum and energy equations, while the SIMPLE algorithm handled pressure-velocity coupling. Under-relaxation factors were adjusted accordingly. Convergence was achieved when residuals for the energy and continuity equations were reduced to specific ranges, requiring approximately 1300-1500 iterations (Figure 3).

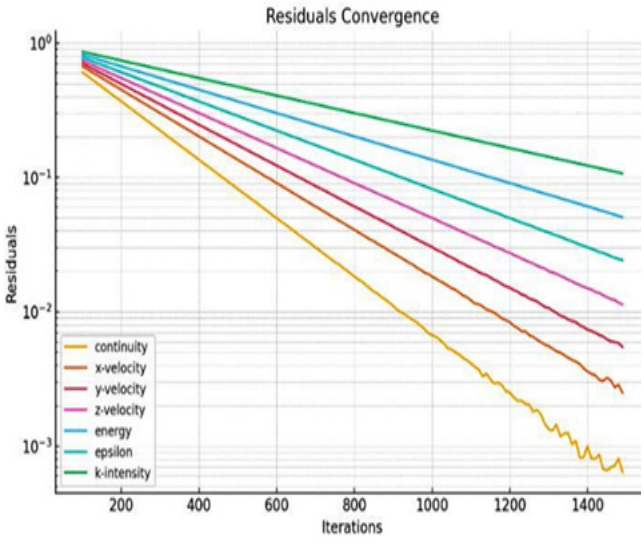


Figure 3. ANSYS FLUENT iteration.

2.2 Grid Independence Test

A comprehensive grid independence study was conducted to identify the optimal mesh configuration for accurate numerical simulations. The objective of this test was to assess the impact of varying mesh densities on the velocity distribution along the chimney. The investigation included eight different grid configurations with the following number of elements: 200,000, 400,000, 650,000, 850,000, 1,000,000, 1,200,000, 1,400,000, and 1,500,000. The results showed that the variation in velocity along the chimney between grid no. 7 (1,400,000 elements) and grid no. 8 (1,500,000 elements) was minimal, with differences of less than 3 % for the most critical velocity values. This indicates that the numerical solution is converging and approaching grid independence. Grid no. 7 was chosen as the optimal configuration, as it provided a balance between computational efficiency and solution accuracy. The grid independence test highlights that beyond Grid no. 7, further refinement in the mesh resulted in negligible improvements in accuracy while significantly increasing computational cost. Figure 4 presents the velocity profiles for the various grids, clearly demonstrating convergence as the grid density increases. By selecting Grid no. 7, the study ensures that the mesh is sufficiently refined to deliver reliable results without unnecessary computational expenses. This step is crucial for validating the accuracy of the simulation while maintaining efficiency in solving complex fluid dynamics problems. The insights gained

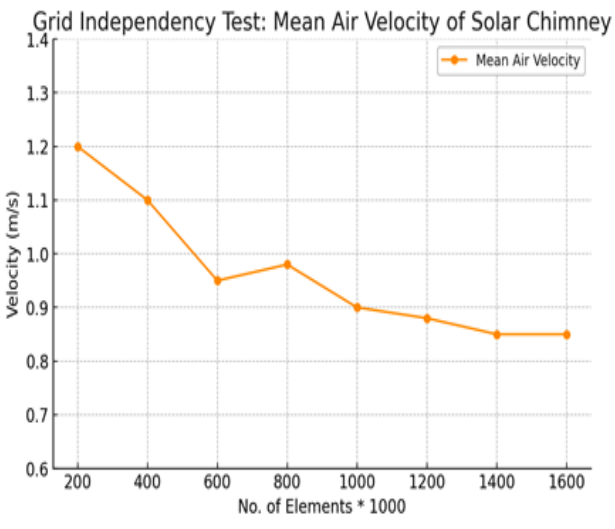


Figure 4. Grid independency test.

from this test provide confidence in the robustness of the chosen numerical approach.

3.0 Results and Discussion

The experiment evaluated the impact of a coolant on a board. In the initial phase, the board's temperature was measured under solar radiation without any cooling. As depicted in Figure 5, the PV panel's temperature reached 314.6 K. Subsequently, water was introduced as a coolant, and various flow rates were tested. Figures 6-7 show that a flow rate of 0.02 decreased the panel's temperature to 311 K. Similarly, flow rates of 0.025 and 0.03 lowered the panel's temperature to 306 K and 302 K, respectively, as illustrated in Figures 8-9 and Figures 10-11.

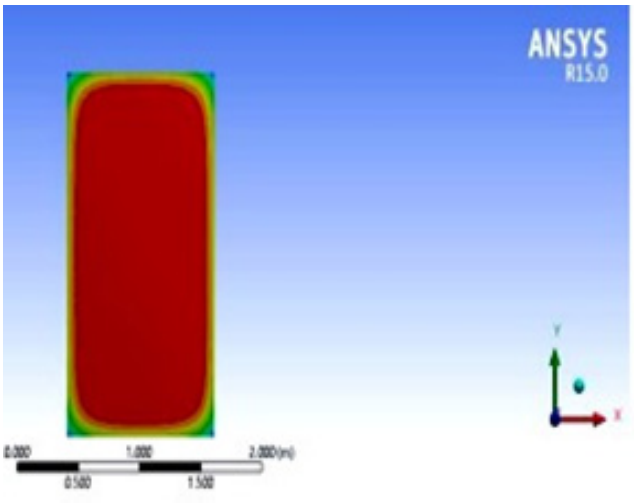


Figure 5. Temperature variation in PV panels without water cooling.

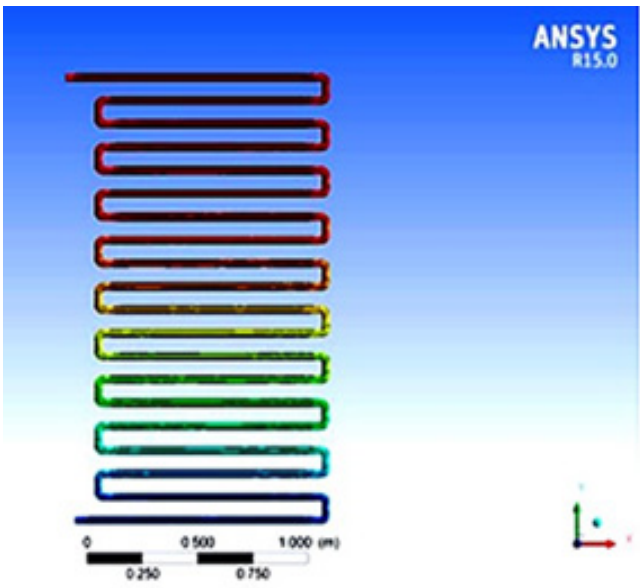


Figure 6. Water temperature variation for a flow rate of 0.02.

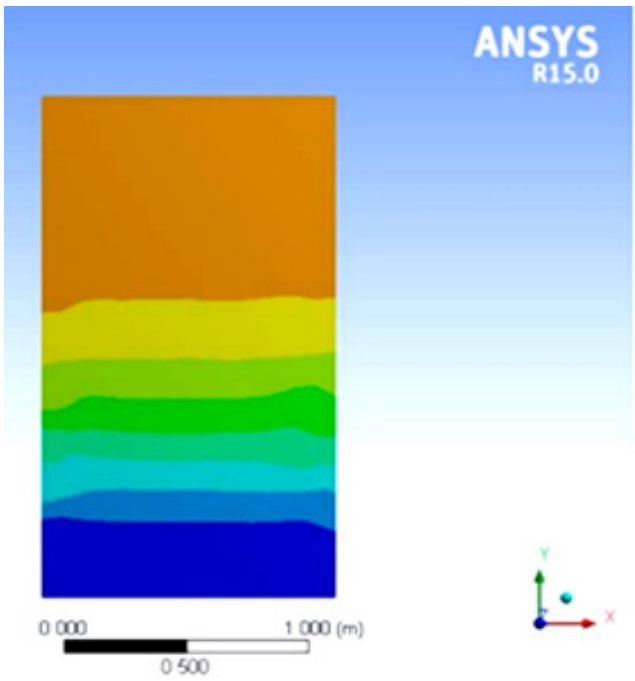


Figure 7. Temperature variation across the panel.

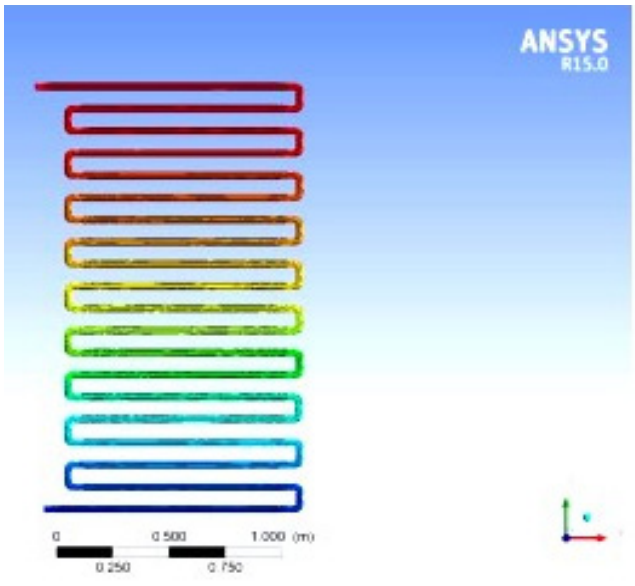


Figure 8. Water temperature variation for a flow rate of 0.025.

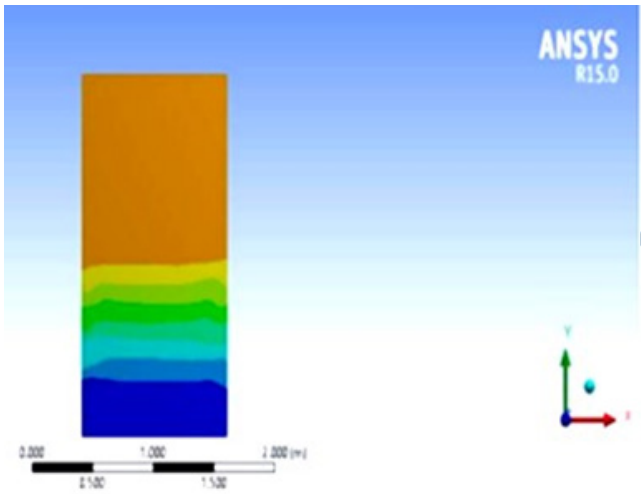


Figure 9. Panel temperature variation for a flow rate of 0.025.

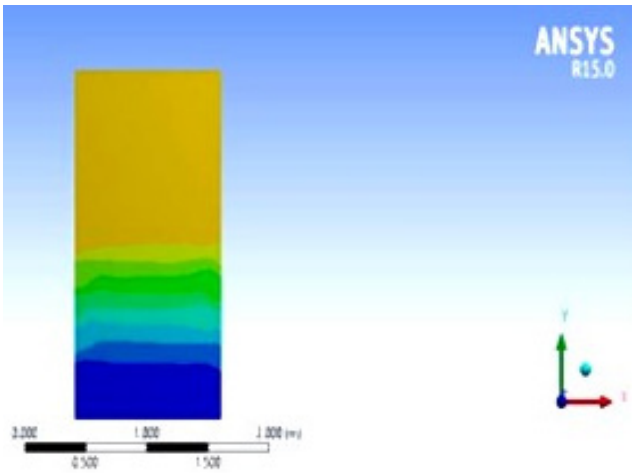


Figure 11. Panel temperature variation for a flow rate of 0.03.

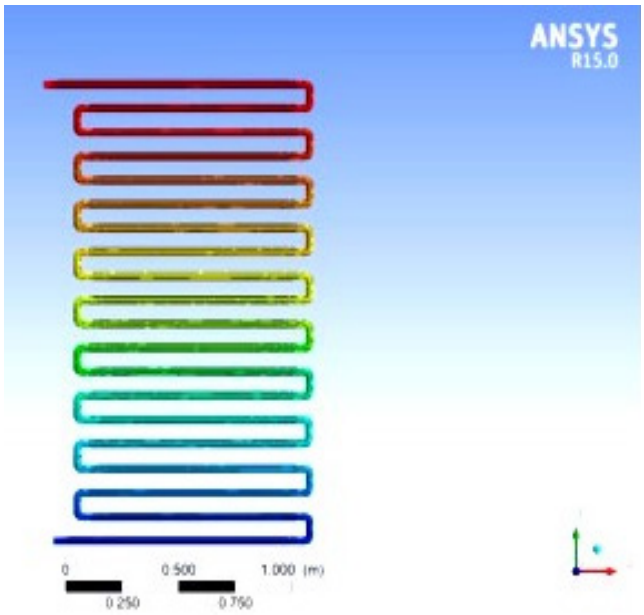


Figure 10. Water temperature variation for a flow rate of 0.03.

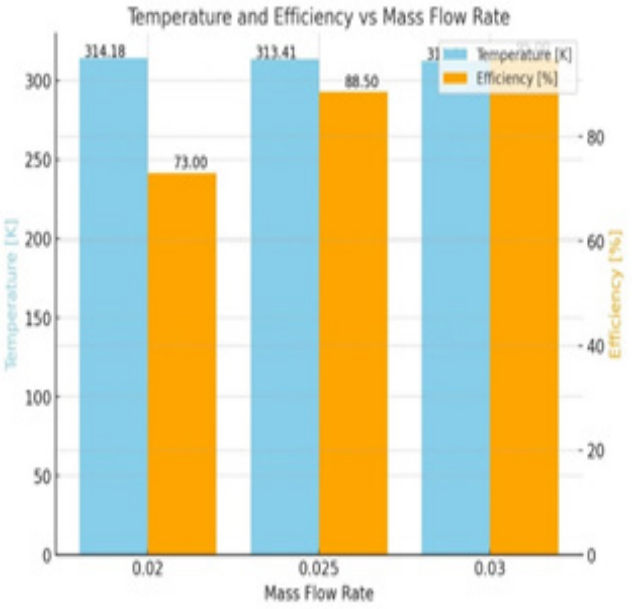


Figure 12. Flow rates, water temperatures, and efficiency values comparison.

Efficiency was determined based on temperature readings across varying mass flow rates, with the results summarized in Table 3. and shown in Figure 12.

Figures 13, 14, and 15 illustrate various comparisons: Figure 13 depicts the relationship between flow rate values and water temperature, Figure 14 shows the correlation between flow rate values and panel efficiency, and Figure 15 highlights the comparison of flow rate values with panel temperature.

The absence of a heat exchanger in the initial phase led to a significant temperature rise in the panel, reaching 314.6 K due to the accumulation of heat from solar radiation. However, the introduction of water as a coolant significantly mitigated this temperature increase.

Table 3. Efficiency values based on temperature and flow rate

Mass flow rate	Temperature[K]	ηth
0.02	314.18	73 %
0.025	313.41	88.50 %
0.03	316.5	96 %

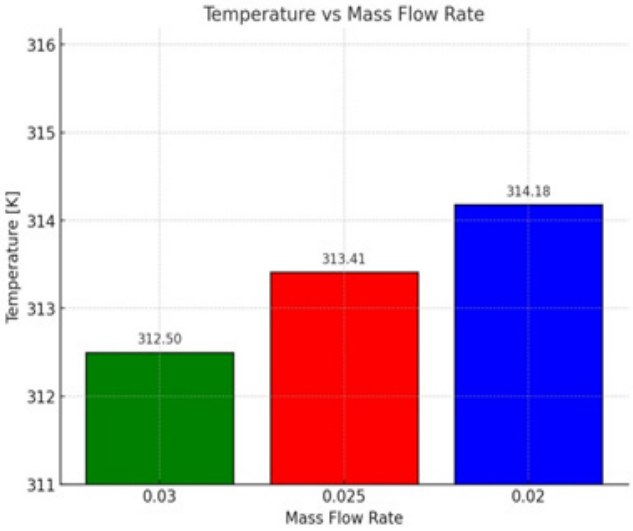


Figure 13. Flow rate values and water temperature comparison.

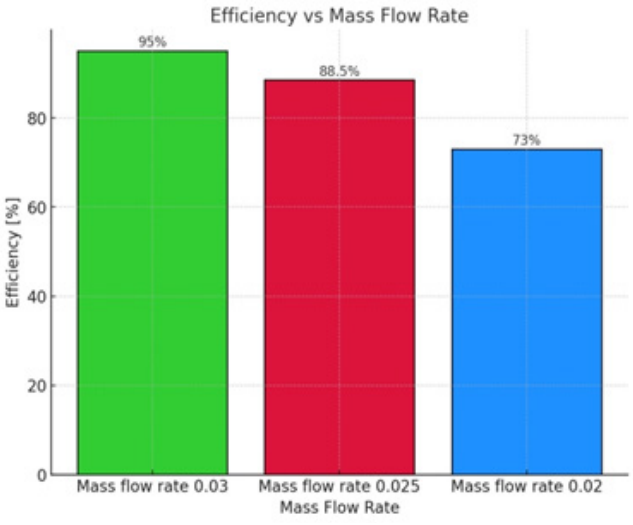


Figure 14. Flow rate values and panel efficiency comparison.

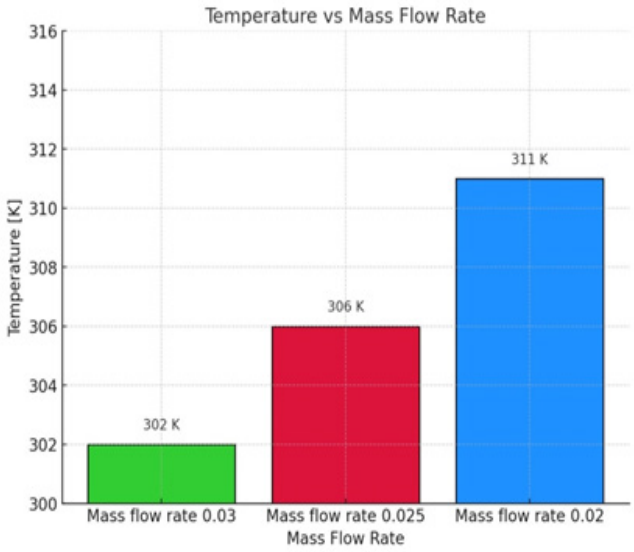


Figure 15. Flow rate values and panel efficiency comparison.

Under controlled experimental conditions, with constant solar radiation (1000 W/m²) and a fixed convection heat transfer coefficient (10 W/m²), the results consistently demonstrated a decrease in panel temperature, an increase in panel efficiency, and a rise in water temperature. The analysis revealed a direct correlation between usable heat, efficiency, and flow rate. Higher flow rates resulted in increased usable heat and consequently, higher efficiency. This trend was further validated by the observed efficiency values, where higher flow rates (e.g., 0.03 kg/s) exhibited higher efficiency compared to lower flow rates (e.g., 0.02 kg/s). The optimal performance was achieved at a mass flow rate of 0.03 kg/s, delivering the highest efficiency (95 %) while maintaining the lowest panel temperature (312.50 K), ensuring optimal heat dissipation and efficient energy utilization.

4.0 Conclusion

This study investigated the performance of a circular-section PV/T collector using numerical simulations in ANSYS. The analysis focused on the impact of varying water flow rates on key parameters such as panel temperature and system efficiency. The key findings are,

- Simulation Parameters: The simulations were conducted with a heat flux of 1000 W/m², an

ambient temperature of 288 K, and water flow rates ranging from 0.02 to 0.03 kg/s.

- Comparison of Scenarios: Two scenarios were analysed: an ANSYS Steady-State simulation without a glass layer and a CFD simulation incorporating water cooling.
- Flow Rate Impact:
  1. Increasing the water flow rate from 0.02 to 0.03 kg/s resulted in a significant reduction in the heating rate of the panel surface.
  2. This led to improved system efficiency.
  3. However, higher flow rates also resulted in decreased water production.
- Optimal Performance:
  1. The optimal performance was observed at a mass flow rate of 0.03 kg/s.
  2. This condition delivered the highest efficiency of 95 %.
  3. It also maintained the lowest panel temperature (312.50 K), ensuring efficient heat dissipation and effective energy utilization.

5.0 Future Research Directions

- Enhance PV Cell Performance: Focus on developing photovoltaic cells with improved photon absorption capabilities to enhance overall energy generation.
- Improve Heat Transfer: Incorporate additional layers within the panel to optimize heat transfer and retention.
- Expand Operational Range: Investigate the performance of these systems under various challenging atmospheric conditions such as dust, clouds, and snow.

6.0 Author's Contribution

Anant Sidhappa Kurhade: Conceptualization, Project administration, Supervision, Methodology development, Writing – original draft, and Review & Editing. E. Amruth: CFD simulation support, Numerical validation, and Manuscript editing. Pratik Shamrao Joshi: SolidWorks modeling, Panel design development, and Data visualization. Ganesh E. Kondhalkar: Grid independence analysis, Mesh optimization, and Software implementation. Pallavi Abhinandan Jadhav: Data curation, Figure preparation, and Draft formatting. Govindarajan Murali: Thermal performance analysis, Discussion framing, and Proofreading. Rupesh Gangadhar Mahajan: Literature review, Referencing, and technical verification. Shital Yashwant Waware: Experimental insight, Result interpretation, and Manuscript revision.

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