Enhancing Photovoltaic Panels Passive Heat Dissipation through Fin Parameter Optimization

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***Abstract*:** The magnitude of heat developed during the operation of photovoltaic (PV) panels greatly affects their efficiency because higher temperatures decrease their power output and lifespan. This study explains the active and passive cooling techniques for PV cells by fin parameter optimisation of heat dissipation. Computations were performed using CFD to compare the performance of three fin types: rectangular, trapezoidal, and triangular. The research considered the configuration parameters of the size of fins, thickness, and spacing to determine their effects on the enhancement in cooling with efficiency. Of these analyzed configurations, trapezoidal fins showed better cooling performance, followed by triangular and then rectangular fins. The results thus point to the tremendous potential that optimized passive cooling techniques have in enhancing the thermal management and efficiency of photovoltaic panels, thereby making solar energy a more sustainable and efficient tool in fulfilling global demands.

Keywords: Photovoltaic panels, passive cooling, fin optimization, heat dissipation, computational fluid dynamics, thermal management.

I. INTRODUCTION

One sustainable and clean energy source is solar power. Since the bulk of conventional fuels are the product of photosynthesis, it is also connected to the great majority of other renewable energy sources, either directly or indirectly. In just 1.5 hours, the Earth's annual energy needs could be met by the sun energy incident on the planet [1]. The production of renewable energy has increased during the last ten years, with solar, wind, and hydropower being the most popular and dependable renewable energy sources. The most abundant resource, solar energy, is ranked third in renewable energy sources for building heating and electricity generation. Due to its zero greenhouse gas emissions and global resource endowment qualities, solar energy is the best choice to meet the world's increasing energy demand. Photovoltaic technology, which converts sunlight directly into electricity using the photovoltaic effect of silicon cells, a semiconducting semiconductor, is the primary source of energy from solar power [2].

It is necessary to address the inherent obstacles that photovoltaic (PV) cells confront in order to use solar energy more extensively and efficiently. Even though photovoltaic solar panel technology is cost-effective, low maintenance, and has the highest power density among renewable energy sources, the percentage of incident solar energy that is transformed into electrical output is still naturally low, usually between 5% and 20%. Heat is produced by the solar panel from the majority of the solar radiation that strikes it. The heat produced causes the PV cells' temperature to rise, which lowers the cells' efficiency, power output, and lifespan. It is well known that the voltage and the operating temperature of the PV panel vary inversely. A 1 °C increase in PV cell temperature is thought to result in a 0.65–0.85% decrease in power output. The problem is exacerbated during the summer months when the temperature of the solar panel can reach 40 to 70 degrees Celsius, resulting in a sharp decline in conversion efficiency of 7.5% to 22.5% [3]. The scientific community is very interested in recently developed high-efficiency multi-junction solar cells. Compared to traditional silicon cells, the cells were designed to generate higher electrical current per unit area. Because of their higher conversion efficiency than single-junction cells and the possibility of boosting electrical generation by focusing solar energy using low-cost Fresnel lenses, MJ solar cells are generally considered to be a promising technology for sustainability. Under typical testing conditions, some studies have reported power efficiencies of up to 50% [4].

The stagnation zone close to the fin-confined areas of the rectangular heat sink is a typical issue with natural convection flow, which results in a notable decrease in heat transfer. Because of inadequate ventilation in the inner region, the traditional flat plate-fin heat sink architecture will reduce the overall convective heat transfer coefficients. By creating air turbulence between the fins and a cross-fin heat sink to permit air penetration for enhanced thermal efficiency, poor ventilation subjected to natural flow can be remedied [5]. In general, cooling techniques can be divided into two categories: active and passive. Passive cooling solutions have the advantages of free convection, radiation, no energy usage, and surface alterations to enhance heat transfer, whereas active cooling systems depend on an external source. Although active techniques like spray cooling, forced convection, thermoelectric cooling, and employing liquids as coolants improve heat transfer, they are also more complex and costly than passive alternatives. However, it makes more sense to combine the aforementioned techniques because of the substantial surface heat density, which is the amount of heat multiplied by the heat sink's surface area. One of the most adaptable and dependable cooling techniques is air-based. Researchers are attempting to make up for the air's poor thermal properties, such as low thermal conductivity and heat capacity, because it is the least expensive coolant on the market and because it is simple to control pressure and leakage [6].

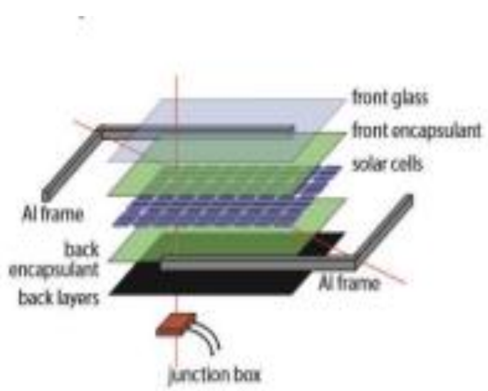


Figure 1 Components of a PV panel [7]

Figure 1 gives the structure of a photovoltaic panel, built with several layers to serve as protection and enhancement in its performance. The glass at the top is considered the front glass, covering the panel from the external surroundings, followed by the encapsulant layer on the front side that keeps the solar cells in place while keeping water and dirt away. The solar cells, which convert sunlight into electricity, are encapsulated between the encapsulant layers for added protection. The back layers add extra support and durability. The assembly is surrounded by an aluminium frame to ensure stability, and the junction box at the back collects and transmits the electrical energy generated by the cells [7].

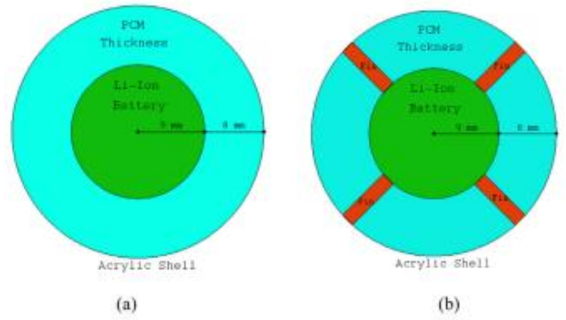


Figure 2 Structure of PCM module (a) Without Fin (b) With Fin [8]

The above image Figure 2 represents cross-sectional views of two designs, which involve an acrylic shell that encases a lithium-ion battery with a phase change material (PCM) layer for thermal management. In the first design, a PCM layer completely surrounds the battery uniformly and offers thermal regulation by absorbing and releasing heat during phase transitions. In the second design, fins are added within the PCM layer to enhance heat transfer. These fins probably improve the efficiency of heat dissipation, making the system more effective at maintaining the battery's temperature within safe operational limits. Both designs aim to improve the battery's thermal performance.

II. LITERATURE REVIEW

Elbreki, A. M., et al. (2020) [9] combining a planar reflector with an extended backplate surface is the goal of the current study in order to optimize the efficiency of the PV module. A parametric study was conducted using CFD, ANSYS, and FLUENT to investigate the performance of PV modules by looking at a number of characteristics, including wind speed, solar irradiation, fin spacing, number of fins, and lapping fin height. To carry out the numerical computations, ANSYS and FLUENT were used to solve the energy equations of 3-D Navier-Stokes. EES software was utilized to determine the temperature of the bare PV module in the meantime. The results show that when the fin pitch increases from 20 to 60 mm, the number of fins decreases from 20 to 10, increasing the PV module's temperature between 44.13-54.01 °C. With 18 lapping fins and a fin pitch of 27.7 mm, the PV module's temperature dropped to 39.73 °C from 64.3 °C without cooling. This increased electrical efficiency to 11.2% compared to 9.81% for bare PV, and the temperature differential at 1000 W/m2 was 24.57 °C. The lapping fins are more effective at lowering the PV modules' temperature, they concluded. The thickness of the aluminium of the suggested fins was also found to have no discernible effect on PV power and efficiency beyond 2 mm.

PraveenKumar, S., et al. (2021) [10] the module's performance and the PV material itself may be impacted by the photovoltaic cells' linear temperature change. This study suggested a passive cooling system that uses specially made aluminium sheets that are affixed to the PV module's back side in order to solve this significant problem. The average temperature for the cooled panel over the course of the experiment was 41.09 °C, whereas the reference panel's temperature was 51.08 °C, according to the data. This indicates a 10 °C drop in temperature. The PV module's efficiency increased by 4% as a result of the temperature drop. The referenced module's average output power is 11.14 W, but the cooled module's is 12.19 W. This resulted in a 9.43% increase in the cooled module's power output. The referenced module's average energy efficiency is 5.55%, while the cooled module's is 7.55%. Additionally, the results showed that the cooled panel, which required an additional expenditure because of the heat sink's integration, recorded a comparatively lower cost of 0.42 $/kWh compared to 0.45 $/kWh for the comparable panel. Due to the significant amount of electricity it produced during that time, the suggested mechanism actually worked well and did not result in additional costs for power generation. Instead, it marginally decreased the power plant's energy costs.

Wongwuttanasatian, T., et al. (2020) [11] A finned container heat sink was suggested as a way to improve the passive cooling of a solar module. Because palm wax was far less expensive than other commercial phase transition materials, it was used in this study. Three distinct PCM containers were first designed and tested: grooved, tubed, and finned containers. The container with fins was found to provide the best cooling effect. To produce the most electrical output, the PV module's temperature has to drop significantly. After that, the finned box passive cooling system and the cooling-free module were examined and contrasted. With the finned box, the module's temperature might drop from 57.9 to 51.8 degrees Celsius, a drop of 6.1 degrees. Module efficiency thus rose from 9.33% to 9.82%, a 5.3% improvement. In addition, the averaged performance ratio (PR) increased from 0.63 to 0.66, a 4.8% increase. One significant PCM that was thought to be able to cool the PV module was palm wax. Crucially, depending on the irradiance, PCM cooling of the PV module was not always advantageous. The findings demonstrated that when solar irradiation surpassed 500 W/m2, PV performance significantly increased with cooling. However, cooling is not necessary if there is normally less irradiation.

Agyekum, E. B., et al. (2021) [12] the electrical efficiency of a photovoltaic (PV) module is determined by the cooling temperature of the cell. This technology's drawback is that electrical efficiency declines with increasing PV module temperature. The reason for this is that when a PV module's temperature coefficient is negative, its voltage drops significantly but its current just slightly increases. In this study, active and passive cooling methods are used to increase the electrical output of a PV module. An aluminium fin heat sink and an ultrasonic humidifier were used to cool the display. A humidifier with an ultrasonic function was used to generate a humid environment behind the PV module. The average panel temperature was reduced by 14.61 ◦C thanks to the cooling process used in the study. This lowering resulted in a 6.8% increase in the electrical efficiency of the module. The average power of the cooled panel was 12.23 W, while that of the referenced module was 10.87 W. Over the course of the trial, evaporation resulted in an approximate total water use of 1.5 L. In fact, the efficiency of the recommended cooling approach was demonstrated.

Beldjani, C., et al. (2022) [13] Heat is produced during photovoltaic conversion, which lowers the efficiency of the cell since it heats up. This process happens as a result of the cells heating up since they are unable to absorb all of the solar light. Numerical investigation of improving photovoltaic (PV) panel cooling by the use of an air-cooled heat dissipator was part of the current project. The suggested heat dissipator, which was made of a copper plate with cylindrical ribs, was positioned beneath the PV panel. The ANSYS-Fluent software was used to numerically simulate forced convection and turbulent flow on the 3D model. Three distinct mass flow speeds-0.03, 0.045, and 0.061 kg/s-were used in the simulations, which were run at 35°C and 500 W/m2 of solar radiation. According to the results, a higher flow velocity improved convectional heat transfer, which lowered panel temperature and raised electrical efficiency.

Table 1 Comparison of Cooling Mechanisms and Efficiency Improvements in Photovoltaic Studies

Study Name	Cooling Mechanism	Temperature Reduction	Efficiency Improvement
Elbreki, A. M., et al. (2020)	Lapping fins and extended surfaces with parametric study (CFD analysis)	From 64.3Â°C to 39.73Â°C with lapping fins	Electrical efficiency improved from 9.81% to 11.2%
PraveenKumar, S., et al. (2021)	Aluminium sheets as a heat sink for passive cooling	Average reduction by 10Â°C	4% improvement in electrical efficiency
Wongwuttanasatian, T., et al. (2020)	PCM (palm wax) with finned containers for passive cooling	Reduction from 57.9Â°C to 51.8Â°C (6.1Â°C drop)	Efficiency improved from 9.33% to 9.82% (5.3%)
Agyekum, E. B., et al. (2021)	Combination of aluminium fins and ultrasonic humidifier	Average reduction by 14.61Â°C	6.8% improvement in electrical efficiency
Beldjani, C., et al. (2022)	Copper plate with cylindrical ribs (air-cooled heat dissipator)	Temperature reduced based on flow velocity (forced convection)	Efficiency improved with increased flow velocity

III. OBJECTIVES

- To study the thermal performance of fins and slits.
- To study the temperature distribution of the fins and slits with different configurations of fin.
- To compare different configurations of fin for enhance performance of fins.
- To suggest best configuration of fins.

IV. Methodology

Zero-energy buildings (ZEBs) are a focus of recent regulatory initiatives to lower CO2 emissions, which also emphasize renewable energy sources like photovoltaic systems to fulfil growing energy demands. Although the efficiency of Si-based flexible solar cells is promising, a major obstacle still exists in striking a balance between their performance and durability.

A. Physical Model

In order to model passive cooling of the PV modules and simulate airflow effects under regulated settings in a three-dimensional domain, fins of three different sizes positioned on the rear of the module are taken into consideration. For an accurate steady state analysis of the airflow surrounding the module, a polyhedral mesher is used.

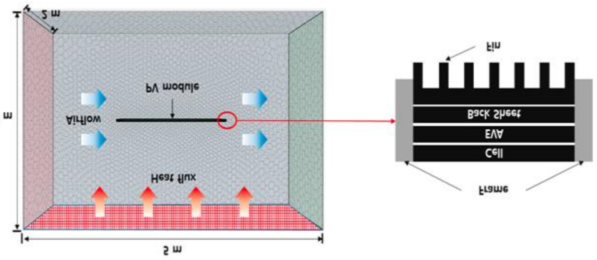


Figure 3: Simulation model schematic diagram [14].

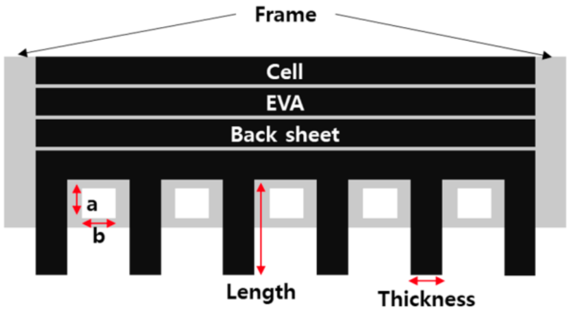


Figure 4: Fin and slit configuration [14].

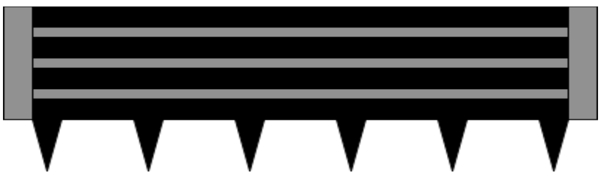


Figure 5: Triangular fin arrangement

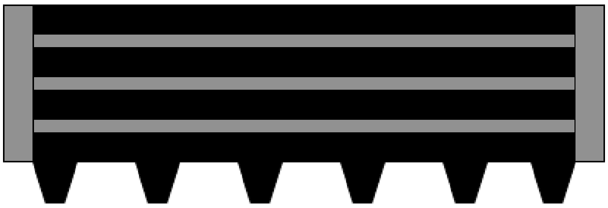


Figure 6: Trapezoidal fin configuration

B. Computational Fluid Dynamics Analysis

Computational fluid dynamics, which is founded on advances in numerical techniques and computing capacity, may provide sophisticated simulations of heat, mass transport, and fluid flow in both industrial and non-industrial settings. CFD with ANSYS Fluent is used in this study to evaluate solar stills by introducing phase-shifting materials and mathematical methods like momentum conservation. The three primary parts of CFD are the post-processor, solver, and pre-processor. The flow problem, grid parameters, fluid properties, and boundary conditions are all defined at the pre-processing stage. The solver converts fluid flow equations into algebraic structures that can be solved iteratively using suitable mathematical approaches such as finite differences, finite elements, or spectral methods. Results can be visualized using a variety of plot types, including 2D/3D surface, vector, or contour plots, with animation frequently incorporated to create dynamic displays, thanks to the post-processor.

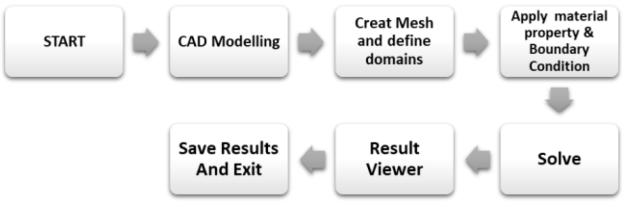
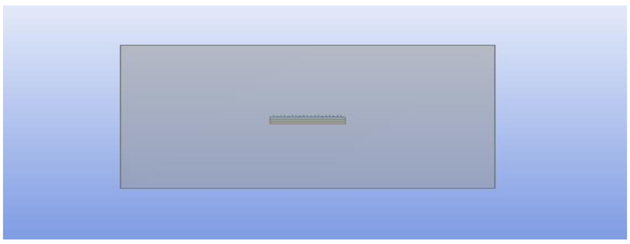


Figure 7: CFD analysis algorithm

C. Boundary Conditions

The pressure-velocity coupling was numerically analyzed in this study using FLUENT 6.3 and the SIMPLE algorithm. The finite-element model was meshed in Gambit using an unstructured tetrahedral grid. A parameter research examines a PV module's slitted fins' cooling capabilities and fin shape. By allowing the continuity, momentum, and energy residuals to drop below \(10^{-6}\), convergence is accomplished.



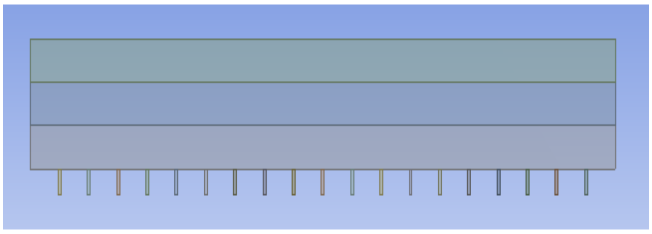


Figure 8. CFD model

D. Choosing The Physical Properties

Setting up the model requires defining the physical characteristics of fluids and solids, such as density, viscosity, specific heat, and thermal conductivity. EVA (ethylene vinyl acetate), cells, a back sheet, and fins-aside from glass-made up the PV module that was simulated. To put it another way, the impact of transmission bodies like glass and EVA on the solar irradiance's transmissivity was disregarded. The airflow's velocity entrance and pressure exit were placed on either side of the domain.
The boundary condition on the upper surface was the heat flux (Table 3). The velocity and heat flux were set at 0.5 m/s and 600 W/m2, respectively, which fell within the NOCT condition's effective range. Furthermore, the contact resistance was adjusted to 0 m2K/W and it was believed that each layer's interface was in complete contact. The thermal characteristics of every component used in the PV module simulation are displayed in Table 2.

Table 2 Simulation conditions

Heat flux, W/m^2	Velocity inlet (m/s)	Ambient temperature, °C	Initial temperature, °C	Contact Resistance, m^{2}K/W
600	0.5	26.84	26.84	0

Table 3 Thermo physical properties

Components	Density (Kg/m^3)	Thickness, mm	Specific heat (J/Kg°C)	Thermal conductivity, (W/mk)
Cell (Si)	2330	10	677	148
EVA	960	10	2090	0.35
Frame (Al)	2702	60	903	237
Back sheet	1200	1	1250	0.2
Fin (Cu)	8900	3	385	400

E. Control Parameters

It should be noted that only proper modeling and numerical control methods will expedite stability and convergence in calculation. FLUENT converts the governing equations to algebraic forms that are amenable to numerical solutions through a control volume-based approach. In the control volume technique, by integrating the governing equations over each control volume, it yields discrete equations that preserve each quantity on a control-volume basis. The user must select the best numerical schemes that will make it possible to discretize equations. Using the first order upwind numerical scheme simulates the difficulties.

V. RESULTS AND DISCUSSION

A. Model Validation

A computational fluid dynamics (CFD) simulation model was created for the current study in order to analyze a passive cooling technique that uses fins that are affixed to the rear of the photovoltaic module. As seen in Figure 9, the heat transport findings from this investigation were initially confirmed using Kim and Nam (2019). The figure clearly shows that the average temperature is within a reasonable range of ±5%.

Table 4. CFD validation results

No. of fins	Average temperature from Kim and Nam (2019) (°C)	Average temperature from Present study (°C)
10	48.71	47.65
20	48.11	47.23

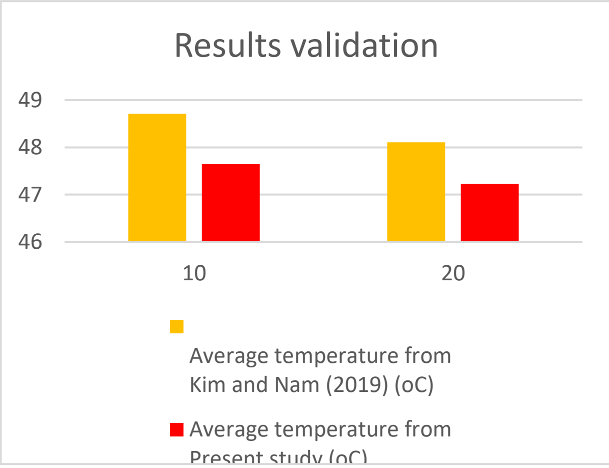


Figure 9. CFD validation results and comparison

B. Analysis of Average Temperature

One unresolved issue in the PV business is the decline in efficiency with increasing temperature. Although a number of active and passive methods have been proposed, not many quantitative studies have been conducted to estimate the cooling effect. A simulation model was created for this study in order to analyze a passive cooling technique that uses fins that are affixed to the rear of the PV module. Three simulation models were created by altering the fins' attachment to the PV. Three fin types-rectangular, trapezoidal, and triangular-were taken into consideration in this investigation. Additionally, a parametric analysis was conducted for every fin by altering the number, thickness, and length of fins.

Analysis of Average Temperature in Fins

After a simulation, Table 4 reports the average temperature. The findings demonstrated that trapezoidal fins outperform triangular and rectangular fins.

Table 4. Average Temperature in Fins

Type of fins	Average temperature from Kim and Nam (2019) (°C)	Average temperature from Present study (°C)	Percentage improvement, %
Rectangular	48.71	47.56	2.36
Trapezoidal	-	46.34	2.16
Triangular	-	45.18	2.35

With a little higher average temperature noted in the current study, this comparison implies that the rectangular fins performed similarly in cooling in the two investigations. Variations in experimental parameters, such as airflow velocity, ambient temperature, or fin dimensions, may have affected the heat transfer properties and caused the discrepancy. Comparing the current study to Kim and Nam's, there was a slight improvement in percentage for rectangular fins of roughly 2.16 to 2.36%.

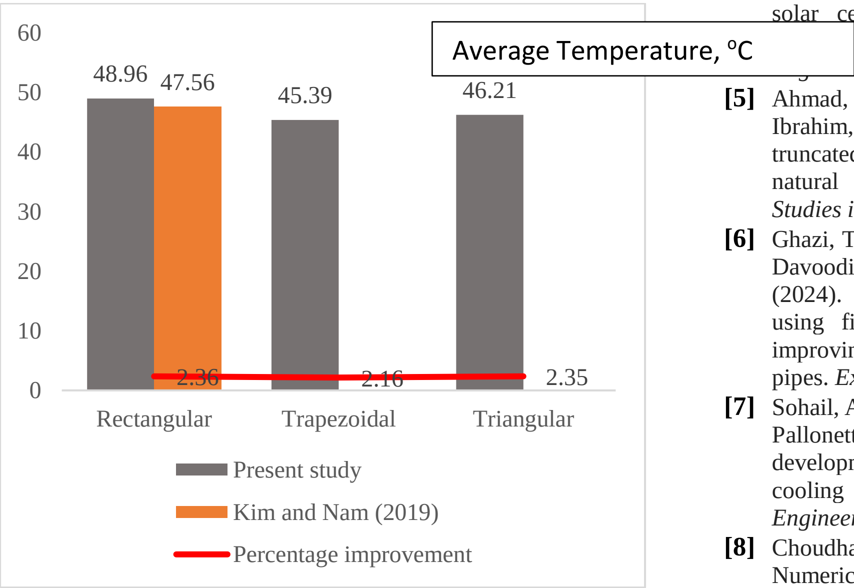


Figure 10. Comparison of average temperature

VI. CONCLUSION

This study demonstrates that passive cooling techniques, particularly those involving optimized fin configurations, significantly improve the thermal performance of PV panels. CFD simulations confirmed that trapezoidal fins are the most effective in reducing the average panel temperature, thereby enhancing electrical efficiency. The investigation validates that proper fin design and placement can address the stagnation zones in natural convection, enabling better airflow and heat dissipation. The results suggest that integrating optimized fin configurations into PV systems can mitigate the efficiency losses associated with elevated temperatures, offering a cost-effective and sustainable solution for the renewable energy sector. These findings pave the way for further research into combining passive and active cooling methods for even greater efficiency improvements.

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