STM JOURNALS

International Journal of
Radio Frequency Innovations

Volume 2, Issue 2, 2024
July–December
DOI (Journal): 10.37591/IJRFI

https://journals.stmjournals.com/ijrfi

Review IJRFI

Optimizing Fin Parameters to Enhance Passive Heat Dissipation in Photovoltaic Panels

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Abstract

This study explores passive cooling techniques to enhance the thermal management of photovoltaic (PV) modules, which is crucial for maintaining efficiency. A computational fluid dynamics (CFD) model, using ANSYS Fluent, was developed to evaluate three fin shapes—rectangular, trapezoidal, and triangular—attached to the back of PV modules. The study varied parameters such as fin count, thickness, and length to determine optimal configurations for cooling. Among the designs, triangular fins demonstrated the highest cooling efficiency, achieving a temperature reduction of 5.3% for a 30 mm length and 4.85% for a 60 mm length. Trapezoidal fins also effectively reduced temperatures, with improvements up to 7.05%. The findings suggest that enhancing fin thickness and quantity can further optimize cooling, with triangular and trapezoidal designs outperforming rectangular fins. These insights indicate that carefully designed fin configurations can meaningfully improve PV performance by reducing operating temperatures, thus aiding in sustainable energy production.

Keywords: Photovoltaic module cooling, passive cooling, fin design, heat dissipation, temperature reduction, triangular fins, trapezoidal fins, simulation model, PV efficiency

INTRODUCTION

PV cells are the basic building blocks of any photovoltaic system. They are usually assembled into larger units called modules or panels, and then they are strung into arrays that power small devices as well as entire buildings. The conversion efficiency of a photovoltaic cell depends primarily on the quality of semiconductor material, how strongly sunlight hits it, and just how efficient the cell is designed. Photovoltaic technological innovations have led to recent efficiency increases making solar energy accessible and affordable for residential, commercial, and industrial use [1].

Photovoltaic technology is very important in terms of reducing the emission of greenhouse gases and weaning ourselves off fossil fuels, since it uses an abundant, inherently renewable source of energy: the sun. It also is a flexible technology that has applications in all kinds of environments-from rooftops and open fields to remote and off-grid locations [2]. The systems can be connected to the grid or run as a stand-alone system, which will be powered directly from the storage battery and so they are suitable for electricity generation in places where proper access to conventional power is not available. Continuing towards an increasing demand of global energy, photovoltaic technology has remained one of the most crucial technologies for the development of sustainable energy [3].

Heat management in a photovoltaic (PV) panel is critical so that the solar cells have their efficiency and performance maintained properly. The PV panel absorbs sunlight as it goes about its function.

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Received Date: November 18, 2024
Accepted Date: November 20, 2024
Published Date: November 25, 2024

Citation: Arya Shukla, Smita S. Palnitkar, Avdhut Ranaware, Swapnil Gurme. Wireless Solar Charging Systems for Electric Vehicles: Technology, Design, and Implementation Challenges. International Journal of Radio Frequency Innovations. 2024; 2(2): 25–35p.

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Not all this energy though gets converted to electricity, and much of it does end up generating heat [4]. Solar cells are not productive; as a PV panel increase in temperature, they become less productive in producing electricity for the same quantum in electricity with the same quantum in sunlit energy. This is because at high temperatures, the generation of electricity is significantly affected by the transfer of excited electrons across the semiconductor material in the cells. Hence, there might be a power output loss that can be quantified when there is excessive heat, especially during an enlightening climate or peak sunlight hours [5].

Proper heat management, for example, can improve the lifetime and energy output of PV modules by maintaining an ideal operating temperature. There are also passive cooling and more aggressive systems through water or air cooling that remove excessive heat from panels. These kinds of methods keep performance from degrading and maintain a low steady temperature that leads to an overall increase in energy conversion efficiency. Optimize heat management so that the return on investment for solar installations can be maximized [6]. In this way, power can thus be supplied reliably and with high efficiency over the expected lifetime of a given installation.

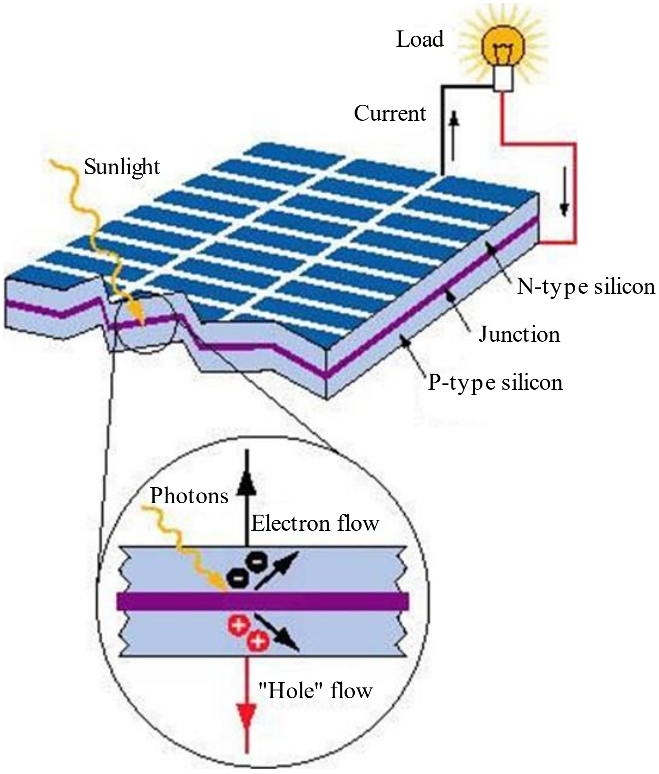

Figure 1. The Photovoltaic Effect on a Solar Cell [7].

In Figure 1, it is depicted as how a solar PV cell converts sunlight into electrical form. When photons of sunlight fall upon the PV cell, they excite the free electrons in the semiconductor material that is mainly made of silicon. The layers in the cell are an n-type or negative layer and a p-type or positive layer, which forms a junction between them. At this stage, the photons produce energy to excite the electrons, which move in a general direction toward the n-type layer, and "holes" move in the direction of the p-type layer. This movement of electrons and holes produces an electric field that contributes to the flow of current. Solar energy is converted to electrical energy with the help of an external circuit that allows current to flow through it in order to power a load, such as a light bulb.

Application of Photovoltaic

PV technology has numerous applications within various sectors because it can produce clean, renewable energy directly from sunlight. In today's residential systems, PV panels installed on rooftops can generate electricity for individual homes and serve as one of the biggest applications. Such systems enable consumers to offset electricity supplied through the grid, decrease utility costs, and decrease their carbon footprint. Residential PV systems, however, use battery backup more often for power supply during utility grid blackouts, thus furnishing a more reliable source of energy [8]. Additionally, the surplus energy that may be generated at peak sunlight hours can be fed back to the grid; the process is called net metering, thus further promoting solar power in place, aligning for energy distribution within the local community.

PV technology is greatly applied in commercial and industrial processes through scalable energy solutions that reduce the operation costs and improve the environmental performance. Companies apply solar panels on rooftops of their buildings, facades, and even in parking structures to decrease dependency on traditional forms of energy [9]. The solar farms in the form of large arrays of photovoltaic panels are deployed at the utility scale to supply renewable energy, significantly reducing the greenhouse gas emissions associated with fossil fuels. Photovoltaic technologies thus have been crucial investments not only for the "bottom line" but also for the fulfillment of corporate sustainability goals, becoming today more and more vital elements for investors, customers, and regulatory bodies.

PV technology also offers a vital source of energy to power remote and off-grid locations, covering entire rural communities, islands, and even space missions. In locations without access to a power grid, photovoltaic systems maintain running power for lighting, water pumping, and communication systems, enhancing the overall quality of life of the residents and their potential for economic progress. For instance, in remote areas where infrastructure development is limited, PV-powered water pumps and solar lanterns are priceless [10]. PV panels harness solar energy to power satellites and space stations-a source that is very much needed, as this is actually the best source or resource found in space exploration that is indeed viable and sustainable. These serve as examples of the versatility of PV technology in different applications, and these may help greatly vary global energy requirements.

Environmental Parameters Affecting Module Efficiency

Other environmental parameters are important to determine how the solar panels will perform. These depend on their efficiency as well as output power. Most important among them are solar irradiance, or sunlight; ambient and module surface temperatures; wind speed; humidity; shading; dust; and installation height. Of these parameters, solar irradiance and temperature are the most dominant. Solar irradiance impacts the Isc because light of greater intensity directly translates to a greater number of photons absorbed by the semiconductor [11]. Even though the power output is almost proportional to irradiance, increased cell temperature reduces efficiency. Moreover, ambient temperature impacts PV performance. With rising temperature beyond 25°C, VOC drops significantly but increases only slightly with Isc. Hence, this kind of temperature dependency is known as the temperature coefficient, implying that cooling techniques are needed to reduce the adverse thermal effects on PV cells.

Other environmental factors that impact PV efficiency include dust, shading, moisture, and wind. Dust and shading could potentially causing hot spots on a panel, thereby resulting in serious power loss, up to 70% for partial shading. Accumulation of dust, especially for desert climate, can reach as high as almost 40%. Humidity affects PV performance both through scattered sunlight by the particles of water vapor and the moisture that can penetrate closed modules. Changes vary proportionally to temperature. Wind plays a critical role in the cooling of the outer surface of the panel, thus increasing efficiency indirectly because of module temperature reduction [12]. For every 1°C drop resulting from wind cooling, the solar PV efficiency can rise by 0.05%. Hence, it is quite essential to know about and control these environmental parameters so that the output from solar panels is maximized and stable.

This Figure 2 presents some of the environmental factors that affect the performance of PV modules. Major elements include solar radiation, operating temperature, dust, shading, soiling, humidity, and wind. Solar radiation is the foundation of power generation while operating temperature affects module efficiency because high temperatures weaken it. Dust and soiling at the module's surface prevent the absorption of light, leading to power loss. Partial shading, and complete shading as well, will lead to hot spots, and efficiency is reduced even further. Humidity affects both the materials of the PV module and the overall performance; any wind makes the module a bit cooler, which helps improve efficiency by lowering the operating temperature. All these need to be managed together in order to maintain optimal performance in PV.

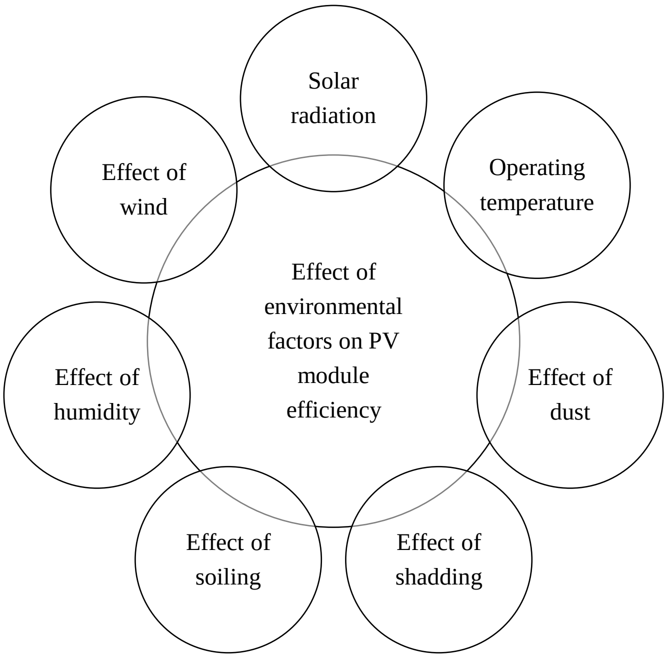

Figure 2. Parameters affecting module efficiency [11].

LITERATURE REVIEW

Koohestani, S. S. et al. (2023) [13] Photovoltaic systems have a reliable method to generate electrical power from direct solar irradiance. Their efficiency is only up to 20% in real operating circumstances and is affected adversely by the inevitable temperature rise in their surface. Passive, active or combined cooling methods are applied to reduce operating temperature to a suitable level, depending on specific application. A Great body of literature has been investigating different PV cooling methods and techniques to reach optimized system efficiency and cooling effect. It is critical for both researchers and practitioners to have a thorough understanding and awareness of the most recent advances and existing gaps. Although there are certain review papers in this field, it is necessary to have up-to-date reviews of the most recent progress and research since the previous ones. In the present work, the main focus was to provide a review of the most recent studies and to compare their outcomes to provide a reference for practitioners and researchers. The holistic classification and evaluation of all the possible cooling technologies were provided in order to draw a comparison between various cooling approaches. Based on the analysis obtained, cooling techniques can ensure improvement in electrical efficiency in a range from 1% to 53% with expected decrease in the photovoltaic panel's surface operating temperature from 1.8 °C to 46 °C. It was also found that spectrum filtering and jet impingement indicated highly remarkable enhancements. The other factors, such as the size of the examined photovoltaic panel, photovoltaic technology, as well as climate circumstances have a strong impact on the cooling performance besides the selection of the specific coolant. The necessity for integral evaluation (performance, economic and environmental) of cooling techniques was also identified as key issue.

He, B., Lu, H. (2023) [14] Carbon neutrality has become a global consensus for green development, and solar photovoltaic power generation has increasingly become one of the key technologies for carbon reduction. Large-scale photovoltaic power plants are often built in arid and sandy areas, which carry a large number of dust particles in the air. Dust deposition on photovoltaic modules has a significant impact on the transmittance, temperature, and roughness of photovoltaic modules, reducing their power generation efficiency and service life. The paper has the following structure: i) relevant research all over the world; ii) the mechanism of dust deposition and the influencing factors on photovoltaic modules; and iii) some current methods of cleaning are summarized, and the mechanism of self-cleaning coatings for dust deposition prevention. It is found that the process of dust deposition is accomplished dynamically and repeatedly under the joint action of several forces. And the diameter of the particle, the installation angle of photovoltaic modules and wind speed have a great influence on the behavior of dust deposition. Self-cleaning coatings have an obvious effect on the prevention of dust deposition. The paper also looks forward to future research methods of particle deposition and cleaning on photovoltaic modules.

Chaichan, M. T. et al. (2023) [15] Airborne dust and dust storms are natural disasters that transport dust over long distances from the source basin, sometimes reaching hundreds of kilometers. Today, Iraq is a basin that produces dust storms that strike all neighboring countries such as Iran, Kuwait and Saudi Arabia. These storms affect the productivity and capacity of the photovoltaic modules and reduce the amount of electricity that is generated clearly. Airborne dust reduces the intensity of solar radiation by scattering and absorbing it. In addition, the dust accumulated on the photovoltaic modules causes a deterioration in their productivity. In this study, an extensive review of wind movement and its sources, especially those that hit the city of Baghdad, the capital of Iraq, was conducted. Practical experiments were also carried out during a storm to measure important variables that had not been measured practically before at this site. The experimental tests were carried out starting from 1 April 2022 and continued until 12 April. Within this period, a dust storm occurred that lasted for three consecutive days that was considered one of the most severe storms that the city of Baghdad had experienced in the last few years. Practical measurements showed a deterioration in the solar radiation intensity by up to 54.5% compared to previous days. The air temperature during the storm decreased by 21.09% compared to the days before the storm. From the measurements of ultrafine aerosol particles PM1 and PM2.5, there was a significant increase of 569.9% and 441% compared to the days before the storm, respectively. Additionally, the measurements showed an increase of 217.22% and 319.21% in PM10 and total suspended particles, respectively. Indoor performance experiments showed a deterioration of current, voltage, power and electrical efficiency by 32.28%, 14.45%, 38.52% and 65.58%, respectively, due to dust accumulated during the storm days compared to the previous days. In the outdoor experiments, the rates of deterioration of current, voltage, power and electrical efficiency were greater, reaching 60.24%, 30.7%, 62.3% and 82.93%, respectively, during the storm days compared to the days before it. During a storm, cleaning the panels is futile due to the high concentration of dust in the air, especially by water. However, the photovoltaic modules can be dry cleaned with bristle brushes after the storm has subsided.

Kazem, H. A. et al. (2023) [16] Solar tracking systems (TS) improve the efficiency of photovoltaic modules by dynamically adjusting their orientation to follow the path of the sun. The target of this paper is, therefore, to give an extensive review of the technical and economic aspects of the solar TS, covering the design aspects, difficulties, and prospects. The paper presented a comprehensive review of the TSs, which are single axis, dual axis, and others with contrasting results, efficiency, cost and useful for which type of applications. During the literature review carried out in the current study, several of the highlights presented the most progressive technological developments, such as AI and sophisticated sensors. Further, the investigation was carried out to consider feasibility by the cost-benefit analysis, return on investment, and incentive points of view. Concerning the identifiable environmental effects of the systems and sustainability, the paper also addresses the merits. The article shows that single-axis tracking systems (SATS) are expected to be somewhat less efficient than their two-axis counterparts (DATS). Hybrid and innovative tracking systems offer the best of both worlds in terms of performance and cost. Investment returns and benefits from higher energy production and potential subsidies can offset the high capital investment. The study also showed that advanced tracking system design and optimization techniques using advanced AI and machine learning techniques are critical to the accuracy and reliability of solar tracking systems. They are suitable for predictive maintenance and real-time monitoring, which improves system performance and reduces operating costs.

Shi, W. et al. (2023) [17] Global warming caused by the emission of fossil fuel consumption has become critical, leading to the inevitable trend of clean energy development. Of the power generation systems using solar energy, the floating photovoltaic (FPV) system is a new type, attracting wide attention because of its many merits. The latest progress in the research and applications of FPVs from multiple aspects is summarized in this paper. Schematic diagram of the simulation model shown in Figure 3. First, the development of FPVs is briefly described with a summary of typically installed FPV systems. Innovative photovoltaic design concepts and hybrid usage with other renewable energies are emphasized for offshore applications. The configuration of fins and slits shown in Figure 4. Furthermore, critical structural design considerations are discussed, particularly emphasizing critical aspects such as load estimations, wave-structure interaction analysis, floating structure types, and mooring system design. The configuration of triangular fins is shown in Figure 5. Finally, several significant future challenges to the development and applications of marine FPV systems are identified, including survivability in the open sea, long-term reliability, and environmental impact. The configuration of trapezoidal fins is shown in figure 6. It aims to provide a broad overview of the development status, offering limited insights into the trends and challenges for marine FPV systems.

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

METHODOLOGY

Recent policy efforts to reduce CO_2 emissions highlight zero-energy buildings (ZEBs), emphasizing renewable energy sources like PV systems to meet rising energy demands. While Si-based flexible solar cells offer promising efficiency, balancing their durability and performance remains a key challenge.

Physical Model

Three different sizes of fins mounted on the back of the module are considered in modeling passive cooling of the PV modules to simulate airflow effects under controlled conditions in a 3D domain. A polyhedral Mesher is applied for precise steady state analysis of airflow around the module.

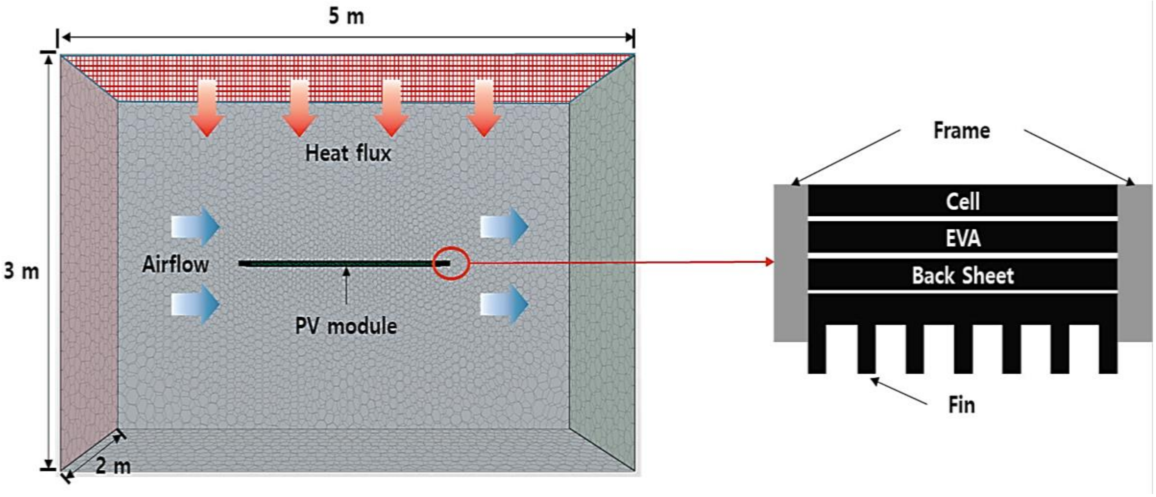

Figure 3. Schematic diagram of the simulation model (Kim and Nam, 2019).

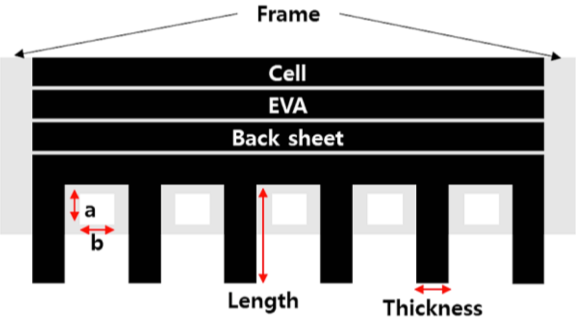

Figure 4. The configuration of fins and slits (Kim and Nam, 2019**).**

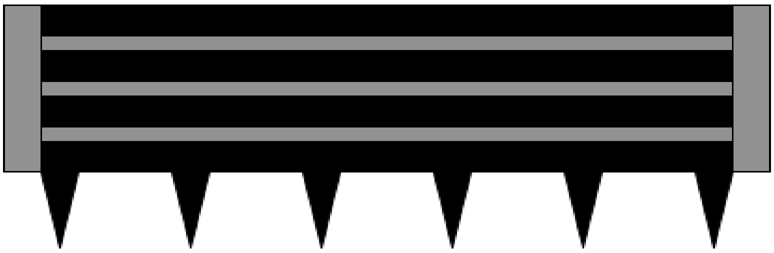

Figure 5. The configuration of triangular fins .

Figure 6. The configuration of trapezoidal fins.

Computational Fluid Dynamics Analysis

Computational Fluid Dynamics, based on improvements in computational power and numerical methods, has the ability to offer advanced simulations of fluid flow, heat, and mass transfer in industrial and non-industrial applications. For this research, CFD using ANSYS Fluent is employed in the evaluation of solar stills through the introduction of phase-shifting substances and mathematical models such as momentum conservation. Algorithm used for CFD analysis shown in Figure 7. CFD comprises three main components: the pre-processor, solver, and post-processor. The pre-processing phase defines the flow problem, grid parameters, fluid properties, and boundary conditions. The solver uses appropriate mathematical techniques that include finite differences, finite elements, or spectral methods to transform fluid flow equations into algebraic structures to be solved iteratively. The post-processor enables the visualization of results with several kinds of plots such as 2D/3D surface, vector, or contour plots with animation often added to make dynamic displays.

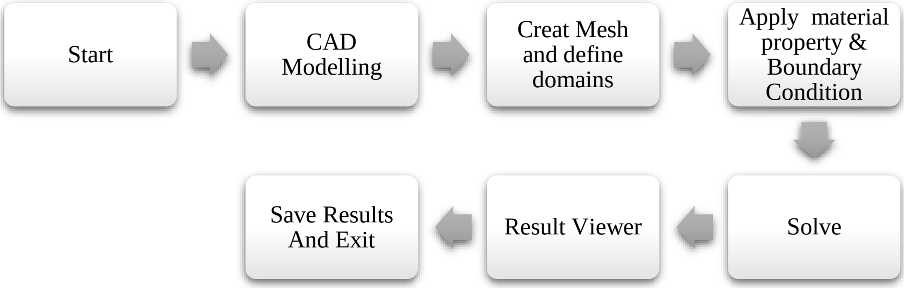

Figure 7. Algorithm used for CFD analysis.

Boundary Conditions

This study used FLUENT 6.3 with the SIMPLE algorithm for numerical analysis of pressure-velocity coupling, with the finite-element model meshed in Gambit using an unstructured tetrahedral grid. CFD model.

Shown in Figure 8. A parameter study checks fin shape and the cooling performance of slitted fins on a PV module. Convergence is achieved by letting residuals for continuity, momentum, and energy fall to less than \ (10^{-6}\)).

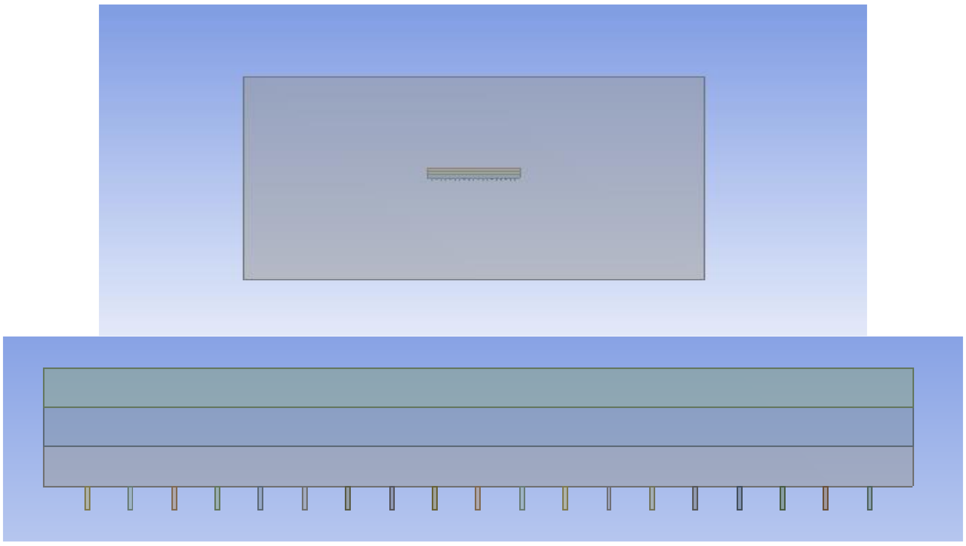

Figure 8. CFD model.

Choosing The Physical Properties

The definition of physical properties (thermal conductivity, density, viscosity, specific heat) of fluids and solids is a necessary factor for setting up the model. Simulation conditions shown in Table 1. The PV module implemented through simulation consisted of cells, EVA (ethylene vinyl acetate), a back sheet, and fins, except glass. In other words, the effects of transmission bodies, such as glass and EVA, on the transmissivity of solar irradiance were ignored. The two sides of the domain were set as the velocity inlet and pressure outlet for the airflow. On the top surface, the heat flux was set as the boundary condition. The values of the heat flux and velocity were set to 600 W/m^2 and 0.5 m/s, which were in the effective range under the NOCT condition. In addition, the interface of each layer was assumed to be in full contact, and the contact resistance was set to 0 m^{2}K/W. Table 2. shows the thermal properties of each component entered into the simulation of the PV module.

Table 1. Simulation conditions.

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

Table 2. Thermophysical properties.

Components	**Density (Kg/m^3)**	**Thickness, mm**	**Specific heat (J/KgºC)**	**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

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Control Parameters

It is noteworthy that proper numerical control and modelling techniques are necessary for to speed up convergence and stability of the calculation. With a control volume- based technique, FLUENT converts the governing equations to algebraic forms that can be solved numerically. This control volume technique consists of integrating the governing equations inside each control volume, yielding discrete equations that conserve each quantity on a control-volume basis [11]. For discretization of equations, the user needs to select the respective numerical schemes. The first order upwind numerical scheme is selected to simulate the problems.

RESULTS AND DISCUSSION

Model Validation

In the present study, a CFD (computational fluid dynamics) simulation model was developed to analyses a passive cooling technology using fins attached to the back of the PV module. CFD validation results (Table 3) and comparison shown in Figure 9. The heat transfer results obtained from the present study were first validated with Kim and Nam (2019), as shown in Figure 3. It is evident from the figure that the average temperature is reasonably well within the range of ±5%.

Table 3. CFD validation results.

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

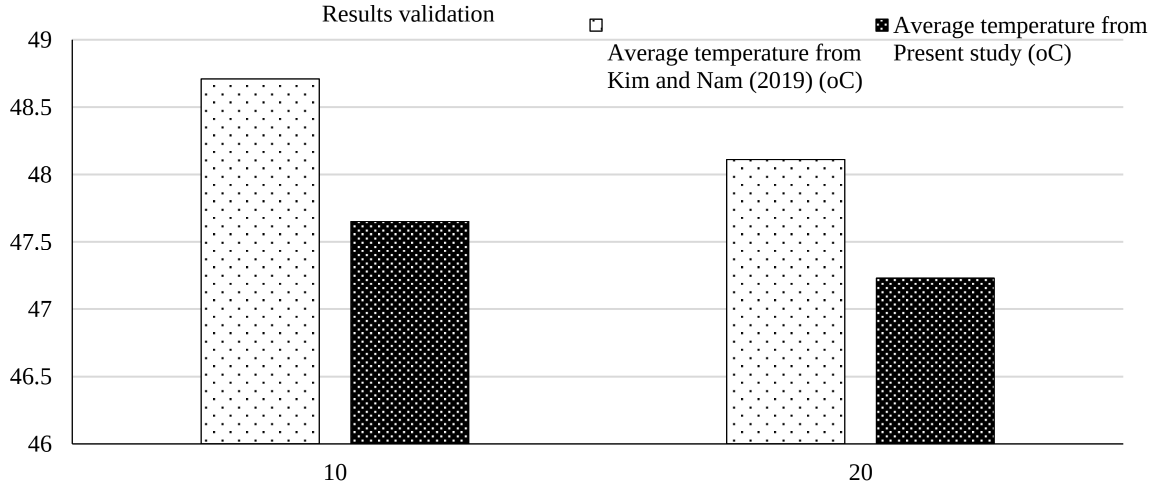

Figure 9. CFD validation results and comparison.

Analysis of Average Temperature

The issue of efficiency decrease according to temperature increase is a pending problem in the PV market. Several active and passive technologies have been suggested but few quantitative studies on the estimation of the cooling effect have been carried out. In this study, a simulation model was developed to analyze 0a passive cooling technology using fins attached to the back of the PV module. Three simulation models were developed by changing the shape of fins attach to PV. In this study, three types of fins were considered viz. rectangular, trapezoidal and triangular. Further, a parametric study was performed for each fin by varying no. of fins, fins thickness and fins length.

Analysis of Average Temperature in Fins

Simulation was conducted and average temperature was reported in Table 4. The results showed that trapezoidal fins perform better as compared to rectangular and triangular fin.

Table 4. Average Temperature in Fins.

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

This comparison suggests that the rectangular fins had a similar cooling performance in both studies, with a slightly higher average temperature recorded in the present study. The difference could be attributed to variations in experimental conditions, such as airflow velocity, ambient temperature, or fin dimensions, which may have influenced the heat transfer characteristics. For rectangular fins, there was a marginal percentage improvement of approximately 2.16 to 2.36% in the present study compared to Kim and Nam's study. Comparison of average temperature shown in Figure 10.

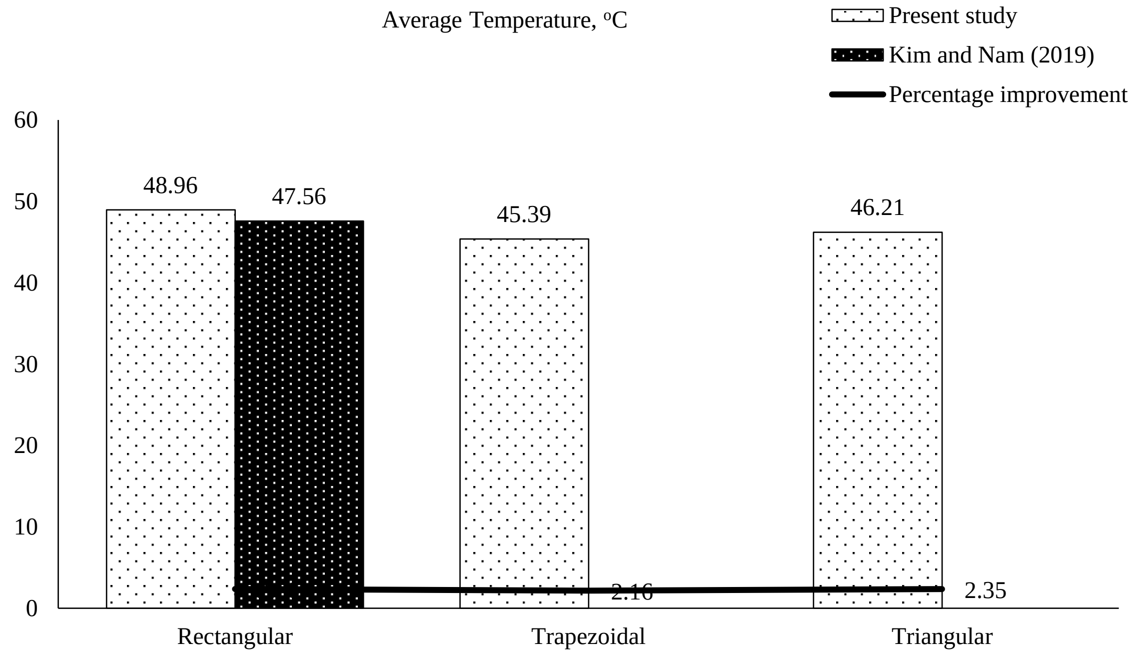

Figure 10. Comparison of average temperature.

CONCLUSION

This study points out the possibility of enhancing passive cooling of PV modules with optimized fin designs improving their thermal regulation by reducing conduction heat on the surface, which may eventually maintain efficiency at higher temperatures. Using comprehensive simulations, many fin shapes including rectangular, trapezoidal, and triangular, have been considered for their performance in cooling of a PV module applied to its back side. It shows that triangular and trapezoidal fins provide superior heat dissipation while triangular fins provide the nearest temperature reductions. Such designs of fins thus can reduce the operating temperature of PV modules and avoid efficiency losses generally resulting from thermal buildup. Additionally, it also studied the effect due to applying slits to the fins, which improved the forced airflow around the module, which further increased the cooling capability. This active airflow distribution demonstrates the effective potential of small changes in design to yield enormous increases in thermal management. Ultimately, the analysis shows how a passive cooling strategy in the form of optimized fin and slit configuration can actually be an efficient, sustainable alternative for energy-intensive active cooling techniques. Such insights also benefit the enhancement prospects of passive cooling systems to raise PV efficiency and contribute towards more sustainable solutions in solar energy production.

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