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Passive Cooling: Energy Analysis of a Flat Plate Photovoltaic Module with Multidirectional Tapered Fin Heat Sinks (MTFHS)

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ABSTRACT

Solar energy has been increasingly popular as a renewable energy source in recent years, displaying significant potential for power generation. However, the main limitation of photovoltaic module systems is the reduced electrical efficiency that occurs as the module temperature increases due to exposure to the sun. Utilizing heat sink fins on a photovoltaic (PV) module is feasible, particularly in passive cooling. This study aims to examine the energy analysis of a Multidirectional Tapered Fin Heat Sink (MTFHS) on a flat plate PV module. The MTFHS design is made from aluminum alloy and has a high thermal conductivity, effectively absorbing and dissipating the heat from the PV module. COMSOL Multiphysics was used to simulate and examine the energy performance of the MTFHS. The simulation was conducted with a solar irradiance of 200, 400, 600, 800, and 1000 W/m^2 with a wind speed of 0.5 to 3.0 m/s. The MTFHS was compared with a bare PV module without any fins. The findings reveal that utilization of the MTFHS contributes to lowering the PV module, thus enhancing the electrical efficiency compared to the bare PV module. Overall, the MTFHS showed a significant enhancement in electrical efficiency, with the highest efficiency recorded at 200 W/m^2 with 19.21% efficiency.

Keywords: Heat sink; fins; passive cooling; photovoltaic module; solar

INTRODUCTION

The increasing global energy demand, coupled with growing concern about climate change and the depletion of fossil fuels, has propelled the utilization of renewable energy sources to the forefront of sustainable development efforts. Renewable energy, characterized by its inherent sustainability and abundant availability, presents a significant transformational potential far beyond its direct environmental benefits (Ibrahim et al. 2011). The transition to a global energy system powered by renewable resources like solar, wind, hydro, and geothermal offers a pathway to mitigate environmental degradation and stimulate a positive feedback loop of economic expansion and ecological conservation (Ishak et al. 2023). This transition can foster new industries, create jobs, and enhance energy security while simultaneously reducing greenhouse gas emissions and preserving natural resources. Among these renewable energy sources, solar energy has emerged as a particularly prominent and promising option, possessing substantial potential for large-scale power generation and a viable solution to pressing global environmental concerns (Bassam et al. 2023). The vast and readily available solar resource, combined with advancements in photovoltaic technology, makes solar energy a key player in the global shift towards a cleaner and more sustainable energy future.

However, despite the numerous advantages of solar energy, PV technology faces a significant challenge: a decline in energy conversion efficiency as the module temperature increases. This temperature dependence stems from the fundamental physics of semiconductor materials. As a PV module absorbs sunlight and converts it into electricity, a portion of that energy is inevitably transformed into heat. Prolonged exposure to high solar irradiance, particularly in hot climates, substantially increases the module's operating temperature (Yusaidi et al. 2024; Ishak

et al. 2023). This temperature increase has a detrimental impact on the energy conversion process. The energy conversion from sunlight to useful electrical energy undergoes a discernible decrease when subjected to these conditions (Assadeg et al. 2023). The elevated temperatures hinder the smooth transmission of electrical current within the PV module, leading to a subsequent decrease in the overall energy generation (Ewe et al. 2021). The hotter the module gets, the less efficient it becomes at converting sunlight into electricity. This inverse relationship between temperature and efficiency poses a significant obstacle to maximizing solar energy systems' performance and economic viability. The efficiency of a solar module is intrinsically linked to its operating temperature, and elevated temperatures can induce various forms of losses, including increased electrical resistance and reduced voltage output, all of which ultimately diminish the module's performance (Ewe et al. 2022).

Consequently, addressing the issue of PV module temperature has become a critical area of research and development. Numerous cooling methodologies have been explored as potential solutions to this challenge, ranging from active cooling systems that utilize external power sources to passive cooling techniques that rely on natural processes (Al-Aasam et al. 2023). Among these approaches, implementing heat sink fins positioned beneath the PV module represents a particularly viable and promising strategy, especially for passive cooling applications (Kumar et al. 2022). Heat sink fins are essential components with high thermal conductivity designed to absorb and disperse heat generated by the PV module (Dey et al. 2022). Their primary function is to facilitate the efficient removal of heat from the module, thereby maintaining a lower operating temperature and improving energy conversion efficiency (Xu et al. 2021). By increasing the surface area available for heat transfer, heat sink fins promote convective cooling, allowing heat to dissipate more readily into the surrounding air.

The utilization of a MTFHS represents a novel and innovative approach to heat sink fin design. This design aims to effectively facilitate the circulation of air around the PV module, thereby enhancing the heat transfer process and promoting more effective cooling. Unlike conventional heat sink designs, which often focus on a specific fin geometry, such as rectangular fins, the MTFHS incorporates a tapered fin structure that allows for multidirectional airflow. In contrast to prior investigations that primarily examined the geometry of rectangular fins design, this study presents a heat sink design that can be used multidirectional, allowing wind to enter from any four junctions of the fins. This design allows wind to enter from any direction, maximizing the cooling potential regardless of prevailing wind patterns. This multidirectional capability is a significant advantage, particularly in environments where wind direction can be variable. This study contributes to a new design of a heat sink fin which allows the heat sink to receive passive air cooling in multiple directions. This novel design best suits flat photovoltaic modules utilizing passive air cooling.

This paper is structured into several sections to comprehensively analyze the MTFHS and its impact on PV module performance. The first section, the introduction, lays the foundation for the study by explaining the fundamental concepts related to PV cooling, discussing the challenges associated with high module temperatures, and reviewing prior research in the field. At the end of the introduction section, the specific novelty and contribution of this study, namely the development and evaluation of the MTFHS, is highlighted. The second section details the CFD simulation methodology employed in this research, discussing the geometrical modelling of the MTFHS against a bare PV module (without any cooling mechanism), focusing on key metrics such as PV module temperature and electrical efficiency. Finally, the conclusion section summarizes the study's key findings and offers concluding remarks about the effectiveness of the MTFHS in improving the energy performance of PV modules.

CFD SIMULATION

GEOMETRICAL MODELLING

COMSOL Multiphysics software was employed to analyze the energy performance of a flat plate photovoltaic (PV) module with Multidirectional Tapered Fins Heat Sinks (MTFHS). The MTFHS was compared to a PV module without the MTFHS (bare) with the same PV module size of 1 m x 2 m to compare the energy performance of the PV module with and without the MTFHS (bare) as a benchmark. The MTFHS fins were designed in a four-junction array to allow the fins to function in any case of wind from any four directions (multidirectional). Each junction consists of five tapered fins acting as heat sinks. The height of the fins varies from the lowest to the highest fins in the middle to allow an aerodynamic flow of the wind. The fins are made from aluminum alloy to allow better heat convection and are attached to the back of the PV module. The fins provide a larger surface area, allowing better heat absorption and dispersing the heat, resulting in the PV module temperature cooling down (Imad et al. 2023). Fig 1 and Fig 2 illustrate the MTFHS design from different points of view. The CFD simulation was performed with a solar irradiance of 200, 400, 600, 800, and 1000 W/m^2 with a wind speed of 0.5, 1.0, 1.5, 2.0, 2.5,

and 3.0 m/s. The CFD simulation will analyze the PV module temperature and electrical efficiency.

MESH INDEPENDENT ANALYSIS

Within the realm of CFD modeling, mesh Independence pertains to a favorable property of the simulation in which the results exhibit less sensitivity to alteration. The mesh characteristic may impact the precision of the simulation outcomes. When the mesh has a coarse resolution characterized by big elements, the obtained results may exhibit a lack of precision. Conversely, in the event that the mesh is too refined and characterized by smaller elements, the simulation time increases significantly. To allow a precise simulation result, mesh independence was conducted on eight different mesh configurations, as shown in Figure 3.

The mesh independent analysis procedure was conducted similarly using a method based on a previous study by comparing the average element quality with the number of element quality (Ishak et al. 2023). Based on the mesh independence analysis on eight different mesh configurations, the mesh configuration with finer showed the highest average element quality, as presented in Figure 4. It was observed that the average element quality started to decrease by using extra fine. Therefore, the simulation was performed using a finer mesh configuration.

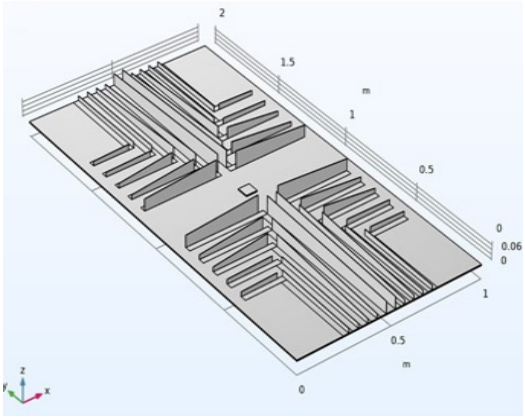


FIGURE 1. Bottom view of MTFHS

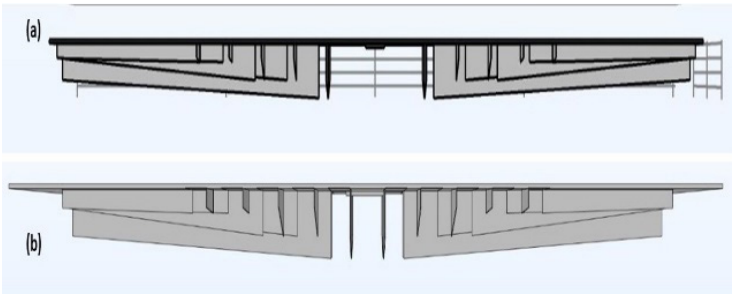


FIGURE 2. (a) Front view of MTFHS and (b) Side view of MTFHS

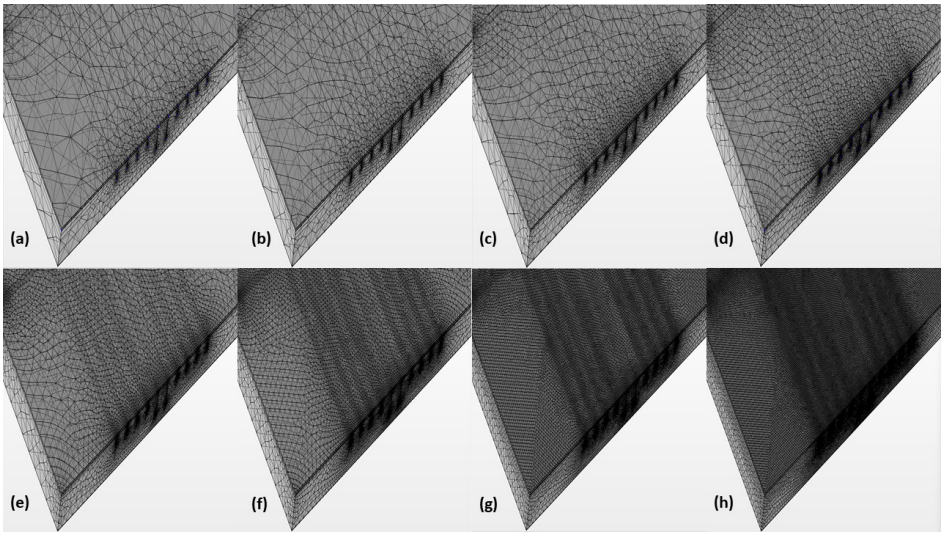


FIGURE 3. Mesh configurations from (a) extremely coarse, (b) extra coarse, (c) coarser, (d) coarse, (e) fine, (f) finer, (g) extra fine, (h) extremely fine.

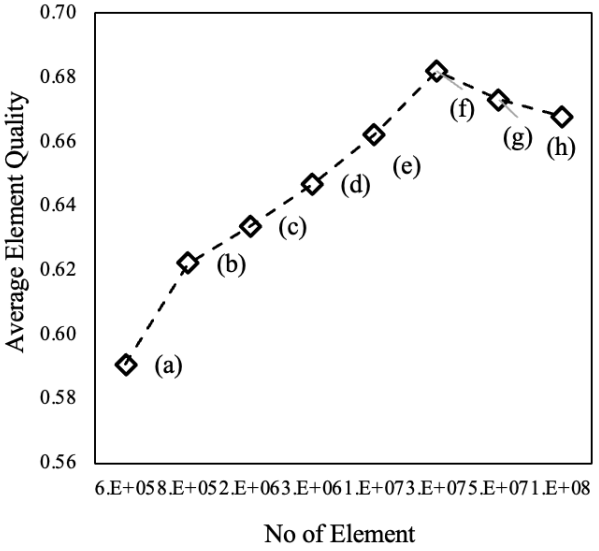


FIGURE 4. Mesh configurations correlation between average element quality and number of elements.

MODEL VALIDATION ANALYSIS

Before running the full simulation, model validation was conducted to validate the boundary settings developed from this study by comparing the numerical results achieved with the previous study. Simulation results from Ahmad et al. (2021) and experiment results from Ahmad et al. (2022) were mimicked using the boundary settings developed in this study. The established results from both studies are compared with the results achieved from current simulation settings developed as presented in Figure 5.

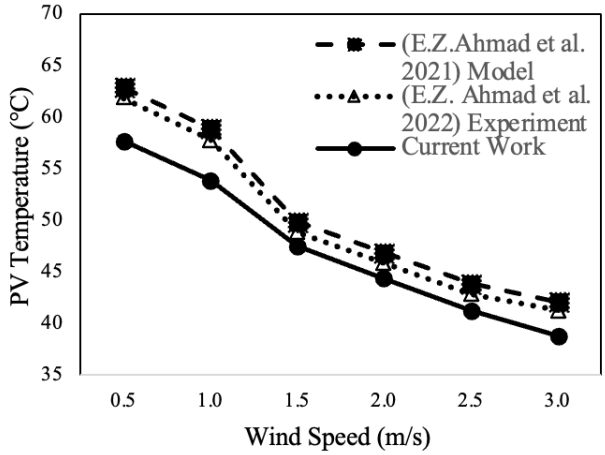


FIGURE 5. Validation of CFD modeling with prior studies (Ahmad et al. 2021, 2022).

Based on the findings, the average percentage accuracy of the current work compared to the prior established CFD results was 93.23% and 95.06% accuracy when compared to the prior established experiment results. Overall, the boundary conditions and simulation settings developed in this study show a good agreement exceeding 90% accuracy in the model validation analysis.

BOUNDARY CONDITIONS AND PHYSICS SETTINGS

The CFD simulations consist of two domains which are the fluid domain and the solid domain. The MTFHS is assigned as aluminum, which allows acting as the solid domain. At the same time, a rectangular geometry is drawn around the MTFHS to assign it as a fluid domain replicating the wind. Since the wind speed is relatively low, from 0.5 to 3.0 m/s, laminar flow settings were used in the simulation. The heat transfer in solid features was selected to analyze the heat transfer of the photovoltaic module. The reference temperature was set to T_{ref} = 30ºC as it is the common reference temperature used by previous research in SERI, University Kebangsaan Malaysia (Ishak et al. 2023). Convective heat flux with a heat transfer coefficient, h of 9 W/m^2.K, was added in the physics settings. Non-isothermal features were also included to allow the analysis of heat transfer between the fluid and solid domain and allow the simulation to detect any temperature changes from point to point. Extra fine mesh settings were used as they were the best mesh settings for the study, as presented in the mesh-independent analysis. A stationary time step was selected to allow the simulation to predict a steady-state condition wherein the behavior has no significant temperature changes over time.

The PV module temperature and Tpv of the two modules, bare and MTFHS, were analyzed to examine the electrical efficiency. The electrical efficiency of the PV module is mathematically expressed as:

$$\eta_{electrical} = n_{ref}\left[1 - \beta\ (T_{PV} - T_{ref})\ \right] \quad (1)$$

Where the module efficiency at STC, n_{ref}, is 0.2013, the relative temperature coefficient is 0.004 K^{-1}, and the reference temperature, T_{ref}, is 30 ºC.

RESULT AND DISCUSSION

PV TEMPERATURE

A detailed analysis of the PV module's temperature was conducted for both the bare module (without the MTFHS) and the module equipped with the MTFHS across a range of solar irradiance levels. This analysis aimed to quantify the temperature reduction achieved by the MTFHS under varying solar conditions. Figure 6 visually represents the temperature distribution across the PV modules, displaying temperature contours for both the MTFHS-equipped and bare configurations. These temperature contours offer a clear visual comparison of the thermal behavior of the two module types.

Referring to Figure 7, a clear trend emerges: the PV module equipped with the MTFHS temperature is consistently lower than the bare PV module across all irradiance levels. This temperature reduction directly results from the MTFHS's ability to dissipate heat from the PV module effectively. Furthermore, the data reveals a significant relationship between the MTFHS PV module temperature and wind speed. The MTFHS PV module temperature markedly decreases with increasing wind speed. This is because higher wind speeds enhance the convective heat transfer process, effectively carrying away more heat from the fins and, consequently, from the PV module. This enhanced cooling effect is not observed to the same extent in the bare PV module, which exhibits a less pronounced reduction in temperature with increasing wind speed. The bare module's temperature reduction, while present, is solely due to natural convection and is less influenced by wind speed compared to the actively cooled MTFHS module.

The lower operating temperature achieved with the MTFHS is crucial because lower PV module temperatures directly translate to enhanced electrical efficiency. PV modules, like many semiconductor devices, operate more efficiently at lower temperatures. Elevated temperatures can negatively impact the module's performance, reducing its ability to convert sunlight into electricity. Therefore, by maintaining a lower operating temperature, the MTFHS contributes to a significant improvement in the module's overall performance.

Specifically, the lowest PV module temperature observed in this study was under 200 W/m^2 solar irradiance. Under these conditions, the MTFHS-equipped module achieved a temperature ranging from 36.44-39.39 ºC. In stark contrawst, the bare PV module, under the same 200 W/m^2 irradiance, reached a significantly higher temperature range of 45.57 to 46.12 ºC. This difference of approximately 9 ºC highlights the substantial cooling capacity of the MTFHS even under relatively low irradiance conditions. When operating at the highest solar irradiance of 1000 W/m^2, the PV module temperature naturally increases for both configurations. However, the MTFHS continues to provide significant cooling benefits. At 1000 W/m^2, the PV module temperature for the MTFHS ranged from 47.51-54.69 ºC. While higher than the temperatures at 200 W/m^2, this range is still considerably lower than expected for a bare module at such high irradiance. These results indicate that the fins, functioning as a heat sink, substantially and positively influence the PV module's temperature, even under the most demanding solar conditions.

The significant improvement in temperature regulation achieved with the MTFHS illustrates its beneficial impact on the entire solar system. By reducing the operating temperature of the PV module, the MTFHS not only enhances electrical efficiency but also contributes to increased system longevity and reliability. The MTFHS improves the heat transfer rate by augmenting the surface area available for heat exchange. This increased surface area allows the MTFHS to effectively absorb heat from the PV module and dissipate that heat to the surrounding environment through convection and radiation. As a result of this enhanced heat transfer, the temperature of the solar module is significantly decreased, leading to the observed improvements in performance.

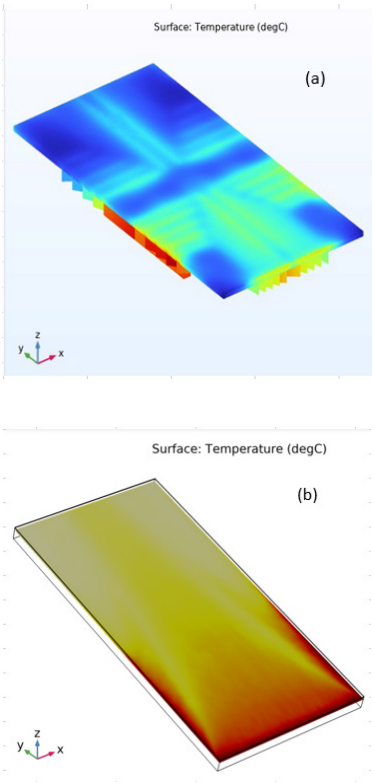


FIGURE 6. PV temperature contour of a photovoltaic module with (a) MTFHS and (b) Bare at 1000 W/m^2 irradiance.

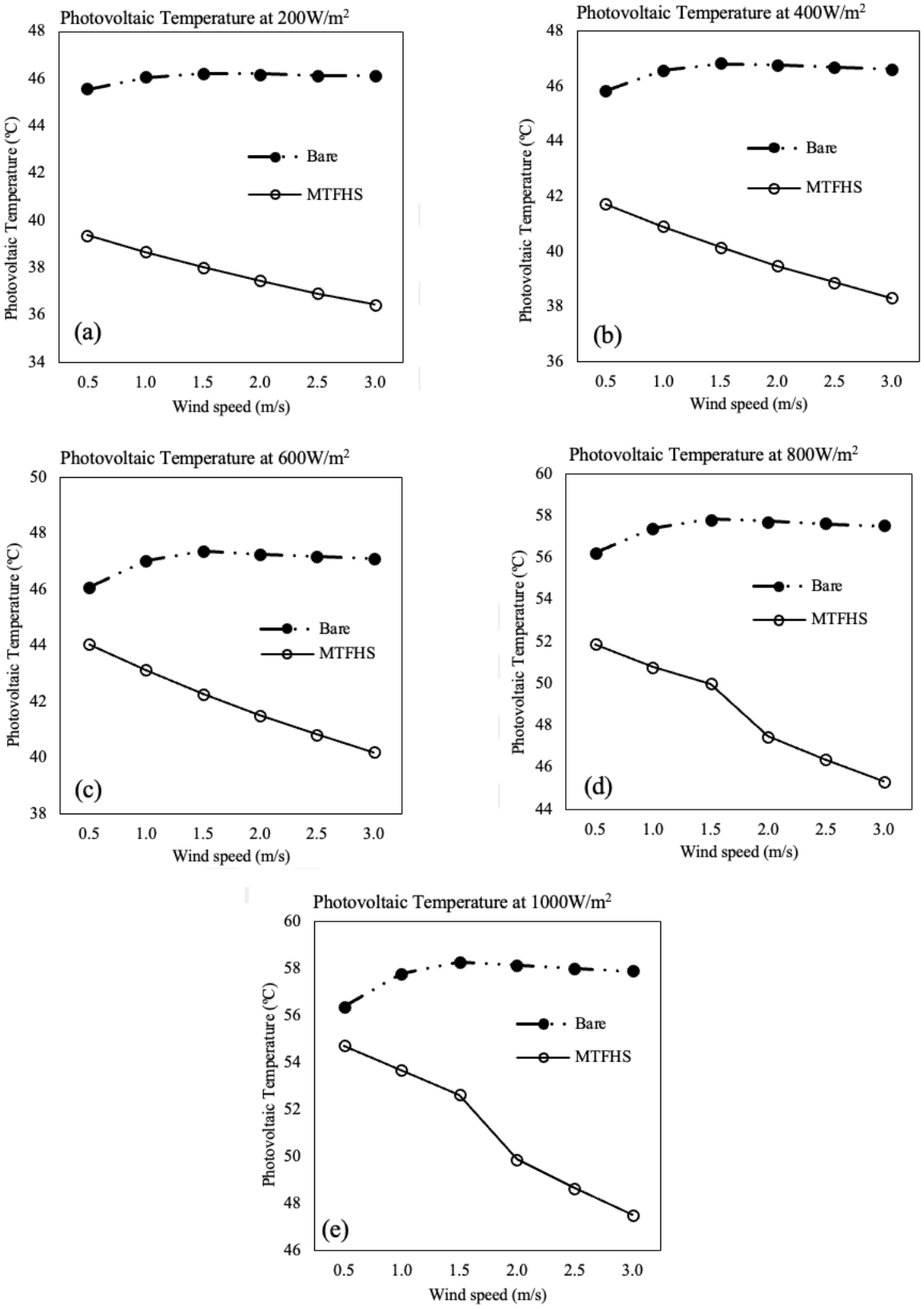


FIGURE 7. PV temperature comparison of a photovoltaic module with MTFHS and Bare under different solar irradiance

ELECTRICAL EFFICIENCY

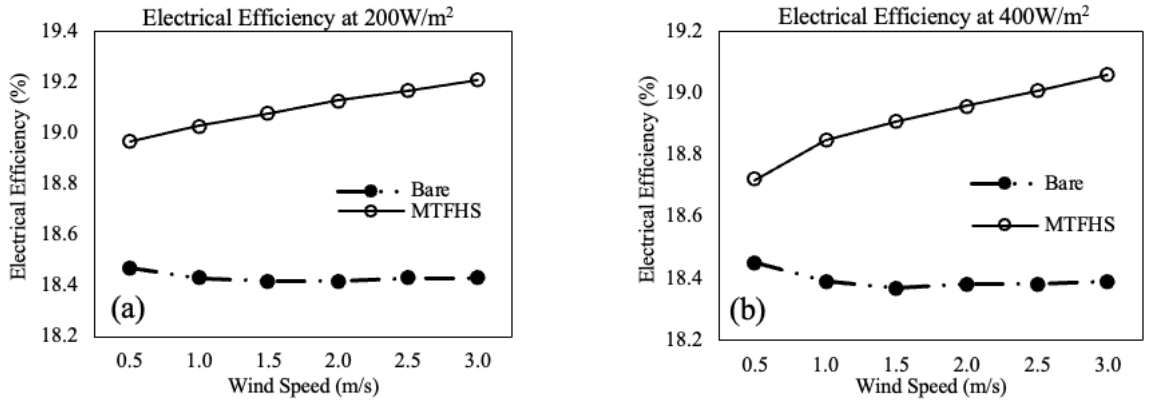
The result depicted in Figure 8 demonstrates the positive impact of the MTFHS on the electrical efficiency of the PV module. Across all solar irradiation levels evaluated in this study, the MTFHS-equipped PV modules consistently improved electrical efficiency compared to the bare PV modules, which lacked the heat sink. This consistent performance enhancement underscores the effectiveness of the MTFHS in mitigating the detrimental effects of elevated temperatures on PV module performance.

A key observation from the data is the correlation between wind speed and electrical efficiency. The electrical efficiency of the MTFHS-equipped PV module demonstrably increases with an increase in wind speed. This phenomenon can be attributed to the enhanced heat transfer facilitated by higher wind speeds. As wind speed increases, the convective heat transfer from the MTFHS photovoltaic module is significantly enhanced. The increased airflow effectively carries away heat from the fins, leading to a substantial reduction in the operating temperature of the PV module. This reduction in temperature, as discussed previously, directly translates to an improvement in the module's electrical efficiency. The cooler the PV module operates, the more efficiently it converts sunlight into electricity.

The MTFHS demonstrated a notable and quantifiable improvement in electrical efficiency relative to the bare PV modules. This improvement highlights the practical benefits of integrating the MTFHS into PV systems. Specifically, the peak electrical efficiency of 19.21 % was recorded under the conditions of 200 W/m^2 solar irradiance and a wind velocity of 3 m/s. This peak performance underscores the combined positive effects of lower irradiance (which inherently leads to lower temperatures) and higher wind speed (which enhances cooling). Conversely, under the same operating conditions (200 W/m^2 and 3 m/s), the bare PV module exhibited a lower electrical efficiency of 18.43 %. This difference of approximately 0.78 % represents a significant gain in energy output due to implementing the MTFHS.

At the other end of the spectrum, the lowest electrical efficiency was observed when the PV modules operated under the highest irradiance level of 1000 W/m^2. As expected, higher irradiance leads to increased module temperatures, reducing efficiency. Even under these challenging conditions, the MTFHS-equipped modules maintained a higher efficiency than the bare modules. Specifically, the electrical efficiency of the MTFHS modules ranged from 17.74 % to 18.32 % at 1000 W/m^2, while the bare PV modules only achieved efficiencies ranging from 17.48 % to 17.6 %. Again, the MTFHS demonstrates its value even in high-irradiance scenarios, providing a noticeable boost in performance.

Overall, the solar module utilizing the MTFHS exhibited a substantial improvement in temperature regulation and electrical efficiency compared to the bare photovoltaic module across all evaluated irradiation levels and wind speeds. This consistent performance enhancement underscores the effectiveness of the MTFHS. Integrating the MTFHS into PV systems offers a notable and practical advantage in cooling the PV modules, thereby directly improving the module's electrical efficiency and overall energy output. The results suggest that the MTFHS has the potential to significantly enhance the performance and economic viability of solar energy systems, particularly in regions with high solar irradiance and variable wind conditions.



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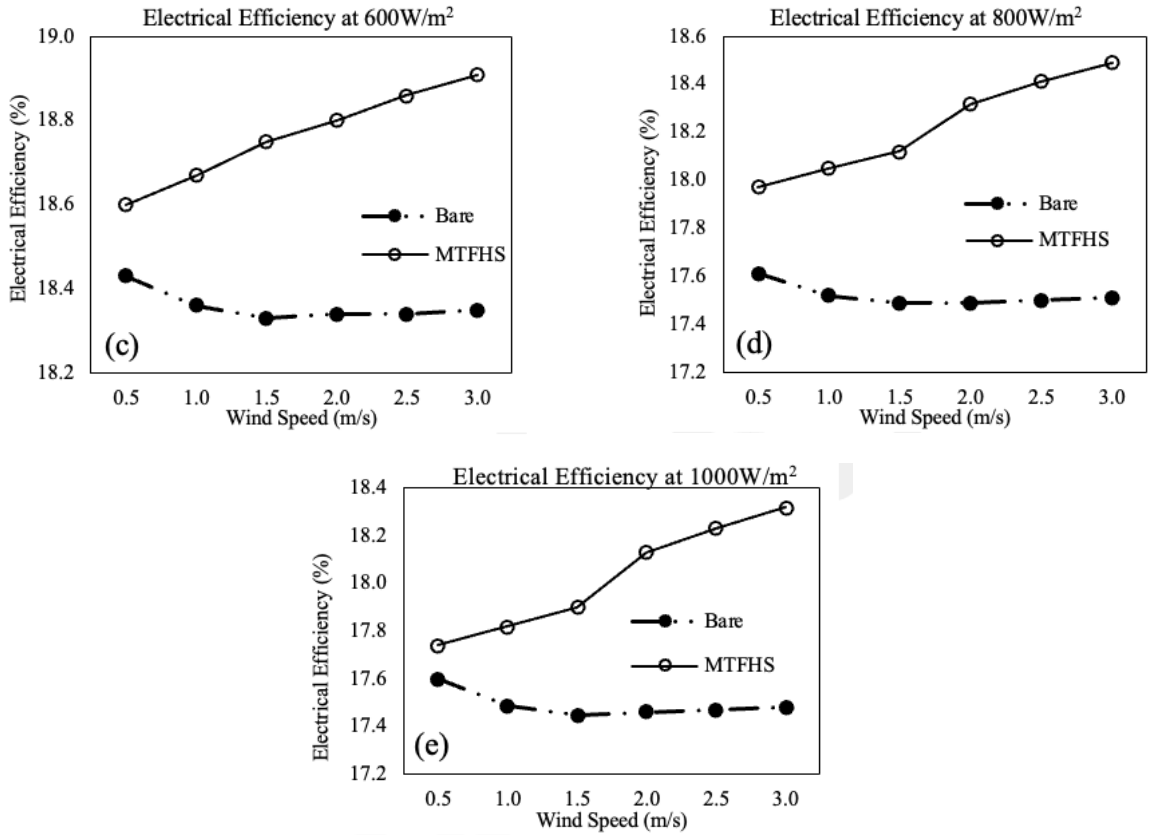


FIGURE 8. Electrical efficiency comparison of a photovoltaic module with MTFHS and Bare under different solar irradiance.

CONCLUSION

A passive cooling method using the heat sink fins technique to cool down the photovoltaic module temperature while enhancing its electrical efficiency was presented in this study. The Multidirectional Tapered Fin Heat Sinks (MTFHS) were attached to the rear side of a photovoltaic module to analyze the enhancement in energy efficiency of a photovoltaic module. A CFD simulation was carried out by comparing the MTFHS with a bare photovoltaic module without the MTFHS. The CFD simulation was conducted with a solar irradiance level of 200 W/m^2 to 1000 W/m^2 and a wind speed ranging from 0.5 m/s to 3.0 m/s. It was observed that the photovoltaic module employing the MTFHS showed a significant improvement in lowering the PV module temperature compared to the bare photovoltaic module. The MTFHS functions to provide a larger surface area to absorb heat while dispersing the heat to the surroundings. Thus enhancing the heat transfer rate of the photovoltaic module. It was also observed that the PV module temperature employing the MTFHS decreases as the wind speed increases.

The lowest PV module temperature attained by the MTFHS was 36.44 ºC under 200 W/m^2 at 3 m/s wind speed. Meanwhile, the bare PV module temperature was 46.12 ºC under the same operating conditions. A higher PV module was observed at higher solar irradiance, and 1000W/m^2 was the highest module temperature recorded. In addition, the MTFHS showed an enhancement trend in electrical efficiency compared to the bare PV module. As the PV module temperature decreases, the electrical efficiency improves. Overall, the highest electrical efficiency was observed under 200 W/m^2, with an efficiency of 19.21% at 3 m/s. While under the same operating conditions, the bare PV module's electrical efficiency was 18.43%. In a nutshell, the efficacy of the heat sink fins was validated by the significant decrease in temperature seen across different solar irradiance. In addition, the enhanced surface area for heat transfer offered by the MTFHS plays a significant role in enhancing photovoltaic and electrical efficiency. This attribute renders it a viable option for enhancing the energy performance of a photovoltaic module.

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DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Ahmad, E.Z., Fazlizan, A., Jarimi, H., Sopian, K. & Ibrahim, A. 2021. Enhanced heat dissipation of truncated multi-level fin heat sink (MLFHS) in case of natural convection for photovoltaic cooling. *Case Studies in Thermal Engineering* 28: 101578. https://doi.org/10.1016/j.csite.2021.101578

Ahmad, E.Z., Sopian, K., Fazlizan, A., Jarimi, H. & Ibrahim, A. 2022. Outdoor performance evaluation of a novel photovoltaic heat sinks to enhance power conversion efficiency and temperature uniformity. *Case Studies in Thermal Engineering* 31: 101811. https://doi.org/10.1016/j.csite.2022.101811

Al-Aasam, A.B., Ibrahim, A., Sopian, K., Bassam, A.M. & Dayer, M. 2023. Nanofluid-based photovoltaic thermal solar collector with nanoparticle-enhanced phase change material (Nano-PCM) and twisted absorber tubes. *Case Studies in Thermal Engineering* 49: 103299. https://doi.org/10.1016/j.csite.2023.103299

Assadeg, J., Sopian, K., Ibrahim, A., Fudholi, A., Al-Waeli, A.H.A. & Hamid, A.S.A. 2023. Thermal and thermo-hydraulic performance of finned double-pass solar air collector utilizing cylindrical capsules nano-enhanced PCM. *International Journal of Renewable Energy Research* 13(1): 126–135. https://doi.org/10.20508/ijrer.v13i1.13880.g8668

Bassam, A.M., Sopian, K., Ibrahim, A., Al-Aasam, A.B. & Dayer, M. 2023. Experimental analysis of photovoltaic thermal collector (PVT) with nano PCM and micro-fins tube counterclockwise twisted tape nanofluid. *Case Studies in Thermal Engineering* 45: 102883. https://doi.org/10.1016/j.csite.2023.102883

Dey, A., Ahmed, Z.U. & Alam, M.R. 2022. Thermal and exergy analysis of pin-finned heatsinks for nanofluid cooled high concentrated photovoltaic thermal (HCPV/T) hybrid systems. *Energy Conversion and Management: X* 16: 100324. https://doi.org/10.1016/j.ecmx.2022.100324

Ewe, W.E., Fudholi, A., Sopian, K. & Asim, N. 2021. Modeling of bifacial photovoltaic-thermal (PVT) air heater with jet plate. *International Journal of Heat and Technology* 39(4): 1117–1122. https://doi.org/10.18280/ijht.390409

Ewe, W.E., Fudholi, A., Sopian, K., Moshery, R., Asim, N., Nuriana, W. & Ibrahim, A. 2022. Thermo-electro-hydraulic analysis of jet impingement bifacial photovoltaic thermal (JIBPVT) solar air collector. *Energy* 254: 124366. https://doi.org/10.1016/j.energy.2022.124366

Goel, A., Singh, S.N. & Prasad, B.N. 2022. Experimental investigation of thermo-hydraulic efficiency and performance characteristics of an impinging jet-finned type solar air heater. *Sustainable Energy Technologies and Assessments* 52: 102165. https://doi.org/10.1016/j.seta.2022.102165

Ibrahim, A., Othman, M.Y., Ruslan, M.H., Mat, S. & Sopian, K. 2011. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. *Renewable and Sustainable Energy Reviews* 15(1): 352–365. https://doi.org/10.1016/j.rser.2010.09.024

Imad, S., Ibrahim, A., Fazlizan, A., Ishak, A.A., Nawab, F. & Hamid, A.S.A. 2023. Performance analysis of a novel photovoltaic thermal PVT double pass solar air heater with cylindrical PCM capsules using CFD. *International Journal of Renewable Energy Research* 13(3): 1418–1430. https://doi.org/10.20508/ijrer.v13i3.14136.g8814

Ishak, M.A.A.B., Ibrahim, A., Faizal, M., Fazlizan, A., Eng, W. & Kazem, H.A. 2023. The effect of a reversed circular jet impingement on a bifacial module PVT collector energy performance. *Case Studies in Thermal Engineering* 52: 103752. https://doi.org/10.1016/j.csite.2023.103752

Ishak, M.A.A.B., Ibrahim, A., Fazlizan, A., Fauzan, M.F., Sopian, K. & Rahmat, M.A.A. 2023. Exergy performance of a reversed circular flow jet impingement bifacial photovoltaic thermal (PVT) solar collector. *Case Studies in Thermal Engineering* 49: 103322. https://doi.org/10.1016/j.csite.2023.103322

Ishak, M.A.A.B., Ibrahim, A., Sopian, K., Fauzan, M.F., Rahmat, M.A.A. & Hamid, A.S.A. 2023. Heat transfer performance of a novel circular flow jet impingement bifacial photovoltaic thermal PVT solar collector. *International Journal of Renewable Energy Research* 13(2): 818–830. https://doi.org/10.20508/ijrer.v13i2.13886.g8756

Ishak, M.A.A.B., Ibrahim, A., Sopian, K., Fauzan, M.F., Rahmat, A.A. & Yusaidi, N.J. 2023. Performance and economic analysis of a reversed circular flow jet impingement bifacial PVT solar collector. *International Journal of Renewable Energy Development* 12(4): 780–788. https://doi.org/10.14710/ijred.2023.54348

Xu, H., Wang, N., Zhang, C., Qu, Z. & Karimi, F. 2021. Energy conversion performance of a PV/T-PCM system under different thermal regulation strategies. *Energy Conversion and Management* 229: 113660. https://doi.org/10.1016/j.enconman.2020.113660

Yusaidi, N.J., Fauzan, M.F., Abdullah, A.F., Ibrahim, A. & Ishak, A.A. 2024. Theoretical and experimental investigations on the effect of double pass solar air heater with staggered-diamond shaped fins arrangement. *Case Studies in Thermal Engineering* 60: 104619. https://doi.org/10.1016/j.csite.2024.104619