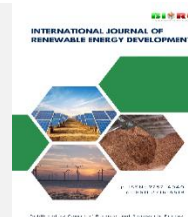




Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: <https://ijred.undip.ac.id>



Research Article

Superior thermal dissipation through natural convection in a passive cooling system using multidirectional tapered fin heat sinks (MTFHS)

Siti Nuraisyah Razali^a , Adnan Ibrahim^{a*} , Ahmad Fazlizan^a , Anwer B. Al-Aasam^a ,
Muhammad Aqil Afham Rahmat^a , Muhammad Amir Aziat bin Ishak^b

^aSolar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

^bSchool of Engineering, Faculty of Innovation & Technology, Taylor's University Lakeside Campus, 47500 Subang Jaya, Selangor, Malaysia

Abstract. The increasing prominence of photovoltaic modules as a cornerstone of sustainable energy systems is well-established. Nevertheless, the deleterious impact of thermal dissipation, often resulting in efficiency losses of 10-15%, remains a significant challenge. Many researches were exploring new cooling techniques to improve the efficiency of solar panels. One promising approach is the Multidirectional Tapered Fin Heat Sink (MTFHS). This innovative design can capture wind from multiple directions, making it more effective outdoors. This study aims to investigate the MTFHS for photovoltaic module cooling. A comprehensive numerical model was developed using COMSOL software simulations to investigate the thermal behavior of photovoltaic modules equipped with multidirectional tapered fins. The model was employed to simulate heat transfer under various solar irradiance levels from 400 W/m² to 1000 W/m² while maintaining a constant 30 °C ambient temperature and 1 m/s wind speed to isolate the impact of solar radiation. Additionally, the direction of incoming airflow was systematically varied from 0° to 90° in 18° increments to analyze its influence. The model considered key multidirectional tapered fin design parameters like fin spacing, number of fins, and fin height. Real-world testing further validated the model's predictions. The findings demonstrate that multidirectional tapered fins significantly reduce PV module temperature, achieving a remarkable 8.61% reduction compared to the bare and conventional rectangular fins. The maximum temperature reached with MTFHS was 56.73 °C. Furthermore, multidirectional tapered fins consistently outperformed other configurations across various wind orientations, achieving temperature reductions of over 10 %. These findings highlight the exceptional effectiveness of multidirectional tapered fins in outdoor environments, especially where wind direction is unpredictable. A correlation analysis revealed excellent agreement (93-96 %) between model and experimental results, further validating the efficacy of the multidirectional tapered fin design.

Keywords: Passive Cooling, Thermal Dissipation, Outdoor Conditions, COMSOL, Multidirectional Tapered Fins



@ The author(s). Published by CBIORE. This is an open access article under the CC BY-SA license (<http://creativecommons.org/licenses/by-sa/4.0/>).

Received: 9th Oct 2024; Revised: 17th January 2025; Accepted: 20th March 2025; Available online: 30th April 2025

1. Introduction

Renewable energy's potential to revolutionize our energy systems goes far beyond its environmental advantages, thanks to its inherent sustainability and abundant availability (Ibrahim *et al.*, 2011; Rahmat *et al.*, 2023, 2022). Embracing and maximizing the potential of renewable energy sources can create a positive feedback loop, where increased efficiency leads to economic growth, which supports further investment in sustainable energy, ultimately contributing to a healthier planet (M. A. A. Bin. Ishak, Ibrahim, Sopian, Fauzan, Rahmat, & Yusaidi, 2023; Ismail *et al.*, 2024). Solar energy's growing prominence as a renewable energy source highlights its potential to revolutionize the global energy landscape and contribute to a more sustainable future (Bassam *et al.*, 2023; M. A. A. Bin. Ishak, Ibrahim, Sopian, Fauzan, Rahmat, & Hamid, 2023; Patel *et al.*, 2020). The heat transmission mechanisms are highly important in cooling the solar panels (Arun *et al.*, 2024; Kanti *et al.*, 2024; Munusamy *et al.*, 2024).

One of the primary challenges facing solar energy is the reduction in photovoltaic efficiency that occurs as the solar

panels become hotter, limiting their overall performance (Assadeg *et al.*, 2023; Razali *et al.*, 2023a). Intense sunlight can cause solar panels to overheat, leading to a noticeable decline in their ability to convert solar energy into electricity (Yusaidi *et al.*, 2024). The adverse effects of high temperatures on solar panels can impede the efficient transmission of electrical current, resulting in a decrease in overall energy generation (Ewe Win Eng *et al.*, 2021; M. A. A. Bin Ishak, Ibrahim, Faizal, Fazlizan, Eng, & Kazem, 2023). Temperature plays a crucial role in the performance of solar modules. Elevated temperatures can lead to various losses that diminish the module's ability to convert sunlight into electricity (Ewe *et al.*, 2022).

As a response to the challenges posed by high temperatures, numerous cooling strategies for photovoltaic modules have been investigated to improve their efficiency (Al-Aasam *et al.*, 2023). Attaching heat sink fins to the underside of solar panels is a promising method for enhancing thermal management and overall efficiency (Kumar Goel *et al.*, 2022). Heat sink fins are designed to efficiently transfer heat away from solar panels, preventing them from overheating (Dey *et al.*, 2022). The primary function of heat sinks is to facilitate the rapid and

* Corresponding author
Email: iadnan@ukm.edu.my (A. Ibrahim)

Table 1
Heat Sink Configurations for Photovoltaic (PV) Applications

Authors	Year	Location	Heat sink configuration	PV size	Remarks
(Bayrak <i>et al.</i> , 2020)	2020	Turkey	Rectangular	75 Wp	Reduced 2.4 °C of panel temperature
(Gomaa <i>et al.</i> , 2020)	2020	Jordan	Rectangular	250 Wp	Improved 5.80 % of power output
(Farhan & Hasan, 2021)	2021	Iraq	Longitudinal	50 Wp	Improved 1.30 % of electrical efficiency
(Hudişteanu <i>et al.</i> , 2021)	2021	Romania	Perforated	320 Wp	Increased 4.99 % of electrical efficiency
(Hernandez-Perez <i>et al.</i> , 2021)	2021	Mexico	Discontinuous	50 Wp	Reduced 5.0 °C of maximum temperature
(Elbreki <i>et al.</i> , 2021)	2021	Malaysia	Lapping	40 Wp	Increased 10.68 % of electrical efficiency
(Ahmad <i>et al.</i> , 2022)	2022	Malaysia	Multilevel height	120 Wp	Reduced 8.45 °C temperature of PV
(Al-Amri <i>et al.</i> , 2022)	2022	UAE	Rectangular	290 Wp	Reduced 6.3 °C of panel temperature
(N. A. S. Elminshawy, El-Damhogi, <i>et al.</i> , 2022)	2022	Egypt	Rectangular	83 Wp	Improved 22.4 % of electrical efficiency
(Alktranee & Bencs, 2023)	2023	Hungary	Rectangular	50 Wp	Improved 5.48 % of electrical efficiency
(Abdallah <i>et al.</i> , 2024)	2024	Palestine	Rectangular	-	Improved 1.6 % of electrical efficiency
(Khelifa <i>et al.</i> , 2024)	2024	Algeria	Skeleton-shaped	200 Wp	Improved 20.14 % of electrical efficiency

efficient transfer of heat away from the photovoltaic module, preventing excessive temperature rise (Xu *et al.*, 2021). The extensive study by Ahmad *et al.* (Ahmad *et al.*, 2021a) offers valuable insights into the diverse fin designs employed for photovoltaic cooling. By examining the configurations presented in Table 1, researchers and engineers can better understand how fin design choices can optimize solar energy systems' thermal performance and overall efficiency.

The research was motivated by the concern that high temperatures can negatively affect the electrical performance of photovoltaic systems. In the present context, a fin heat sink was implemented in a tropical climate and positioned at an inclination of 15 degrees based on previous studies from (Ağbulut *et al.*, 2021) and (Baghaei Daemei *et al.*, 2019). The study's novelty consists of using Multidirectional Tapered Fin

Heat Sinks (MTFHS) as a groundbreaking passive cooling solution for solar modules. The multidirectional tapered fins outperformed other configurations. Their innovative design can capture wind from multiple directions, making them more effective outdoors. Unlike traditional fins limited to a single direction, the multidirectional design can capture wind from various angles, enhancing cooling efficiency. Figure 1 shows the novelty of Multidirectional Tapered Heat Sink configurations being examined in CFD. A multidirectional tapered fin represents a new approach to heat sink design, specifically tailored to enhance airflow and improve heat transfer within photovoltaic modules. This innovative design departs from previous research focusing on rectangular fin geometries. The MTFHS offers greater versatility, allowing wind to enter through any of its four fin configurations. This study investigates the MTFHS for photovoltaic module cooling. Parametric analysis, numerical simulations under varying solar irradiance and inlet velocity, and experimental validation were conducted. The findings demonstrate the potential of MTFHS to enhance heat transfer and improve PV module efficiency.

2. Simulation Methods

2.1. Fins Design

In this specific research context, our inquiry focused on deploying a heat sink with fins strategically positioned on the posterior surface of a photovoltaic module. The photovoltaic module was utilized in a tropical climate and positioned at an inclination of 15 degrees. The MTFHS's innovative four-junction design and tapered fin configuration enable efficient heat dissipation from all wind directions, enhancing its versatility and performance, as represented in Figure 2. Each junction of the MTFHS consisted of five tapered fins designed to act as heat sinks. The fins varied in height, with the tallest fins located in the center, to facilitate aerodynamic airflow and enhance heat dissipation, as shown in Table 2 (Baghaei Daemei *et al.*, 2019). The primary objective of the proposed multidirectional tapered design is to optimize heat transfer efficiency by facilitating enhanced airflow within the critical region of the photovoltaic (PV) module (Aghaei *et al.*, 2022; Ahmed *et al.*, 2019) This strategic design approach addresses the recent architectural shift in PV modules, where the junction box has been strategically relocated from the module's periphery to its central core (M. A. A. Bin Ishak, Ibrahim, Fazlizan, Fauzan, Sopian, & Rahmat, 2023).

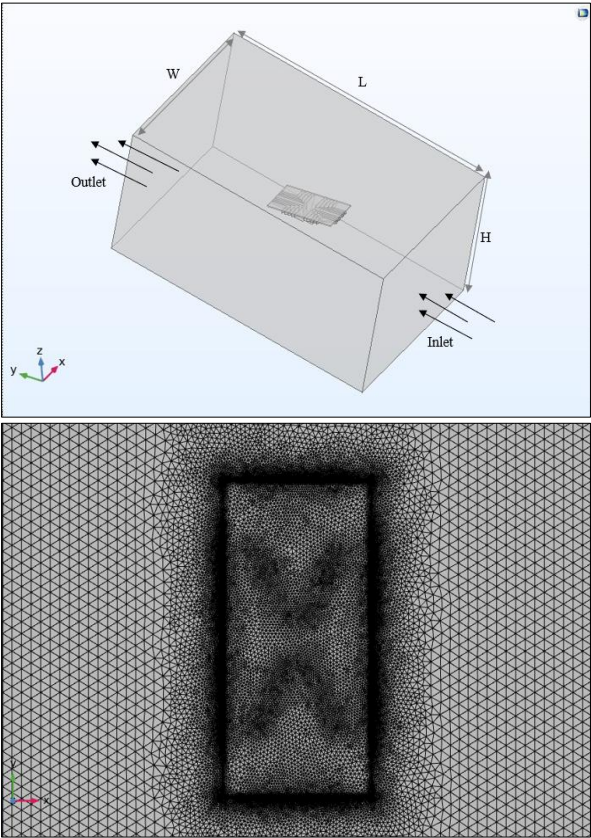


Fig 1. (Top) Computational domain representation (Bottom) Y-directional mesh discretization

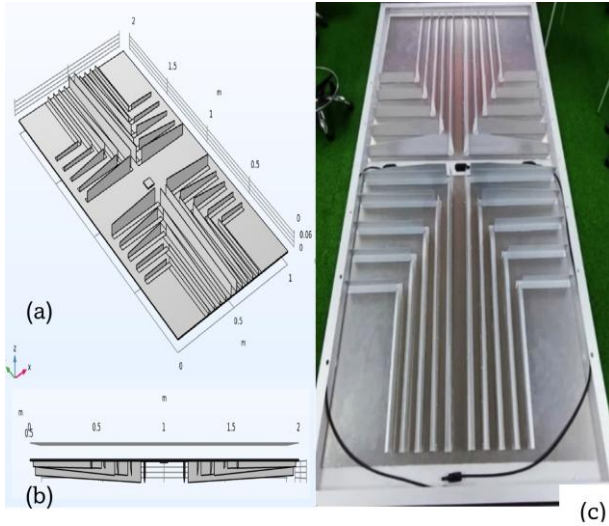


Fig 2 Proposed MTFHS (a) MTFHS mounted at the back side of PV module (b) Side view of MTFHS (c) Sample view of MTFHS geometric specification.

Table 2
Geometric Specifications of MTFHS Design

Parameters	Fins Height (mm)	Fins Length (mm)	Fins Width (mm)	Fins Thickness (mm)
Fins (1)	85	450 & 850	25.4	1.0
Fins (2)	75	400 & 750	25.4	1.0
Fins (3)	65	350 & 650	25.4	1.0
Fins (4)	55	300 & 550	25.4	1.0
Fins (5)	45	250 & 450	25.4	1.0

2.2 Models Equations

The numerical models were solved via the Galerkin Least Squares (GLS) finite element method, employing the AcuSolve Solver as the specific implementation. This computational algorithm guarantees precision in the spatial discretization of the relevant parameters consistent with second-order accuracy. The set of equations that determine fluid flow features is commonly referred to as the Navier-Stokes equations. The equations presented in this context are derived utilizing Cartesian coordinates. The continuity equation for steady flow can be expressed as follows. (Egab *et al.*, 2020; Imad *et al.*, 2023; Luo *et al.*, 2023):

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (1)$$

The variables ρ , u , v , and w denote the quantities of density, velocity along the x-axis, velocity along the y-axis, and velocity along the z-axis, respectively. The three equations that determine momentum are:

$$u \frac{\partial \rho u}{\partial x} + v \frac{\partial \rho v}{\partial y} + w \frac{\partial \rho w}{\partial z} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} \right) \quad (2)$$

$$u \frac{\partial \rho v}{\partial x} + v \frac{\partial \rho v}{\partial y} + w \frac{\partial \rho v}{\partial z} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} \right) + (\rho - \rho_0)g \quad (3)$$

$$u \frac{\partial \rho \omega}{\partial x} + v \frac{\partial \rho \omega}{\partial y} + w \frac{\partial \rho \omega}{\partial z} = \frac{\partial}{\partial x} \left(\alpha \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\alpha \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial T}{\partial z} \right) \quad (4)$$

In the given context, the variable P represents the pressure, while the variable ν symbolizes the fluid's viscosity. The governing equation for the temperature, written as T , can be represented by a single energy equation:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z} \right) \quad (5)$$

The analysis of radiation heat transfer from a surface can be performed through (Armstrong & Hurley, 2010; Yusaidi *et al.*, 2024):

$$Q_{rad} = \sigma \varepsilon (T_W^4 - T_{\infty}^4) \quad (6)$$

Where ε represents the surface emissivity coefficient, these parameter values were drawn from a comparative investigation (Khor *et al.*, 2010). Furthermore, materials such as air, aluminium, glass, two layers of EVA, PV cells, PVF, and aluminium have been allocated within the model.

Their average temperature influences the electrical efficiency of PV modules can be expressed as follows (Razali *et al.*, 2023b):

$$\eta_{eff} = \eta_{eff} [1 - \beta_{eff} (T_{cell} - T_{ref})] \quad (7)$$

η_{eff} is the PV module efficiency at STC (1000 W/m², 25 °C). Its actual efficiency is influenced by its average cell temperature T_{cell} , temperature coefficient of the cell β_{eff} , and the reference T_{ref} (25°C) affect its actual performance. Uncertainty analysis quantifies the potential errors in a measurement or calculation, including those due to approximations and inaccuracies. The standard deviation is a common metric used to assess this uncertainty:

$$s = \sqrt{\frac{\sum_i^n (x_i - \bar{x})^2}{n - 1}} \quad (8)$$

x_i , $\bar{x}$, and n indicates measurement means, findings, and measurement sets. The uncertainty (u) expression is shown as follows:

$$u = \frac{s}{\sqrt{n}} \quad (9)$$

2.3 Meshing Independent Analysis

A mesh independence study as shown in Table 3 was performed to assess the impact of mesh resolution on the accuracy of our CFD simulations. Eight different mesh configurations were tested, ranging from coarse to fine. By comparing the results obtained from these simulations, we determined that the solution converges to a mesh-independent state. This ensures that our results are not artifacts of the numerical discretization and can be considered reliable, as depicted in Figure 3.

The mesh-independent analysis was conducted following a method similar to (M. A. A. Bin Ishak, Ibrahim, Sopian, Faizal, Aqil Afham Rahmat, Rahmat, *et al.*, 2023), comparing the average element quality with the number of elements. An examination of eight different mesh configurations determined

Table 3
Mesh differences

Mesh	Number of Element	Average Element Quality	Difference
Extremely coarse	606,749	0.5908	3.13%
Extra coarse	828,666	0.6221	1.15%
Coarser	1,574,054	0.6336	1.31%
Coarse	2,893,226	0.6467	1.54%
Fine	11,604,019	0.6621	1.99%
Finer	34,719,350	0.6820	-0.88%
Extra fine	53,869,000	0.6732	-0.52%
Extremely fine	133,422,046	0.6680	

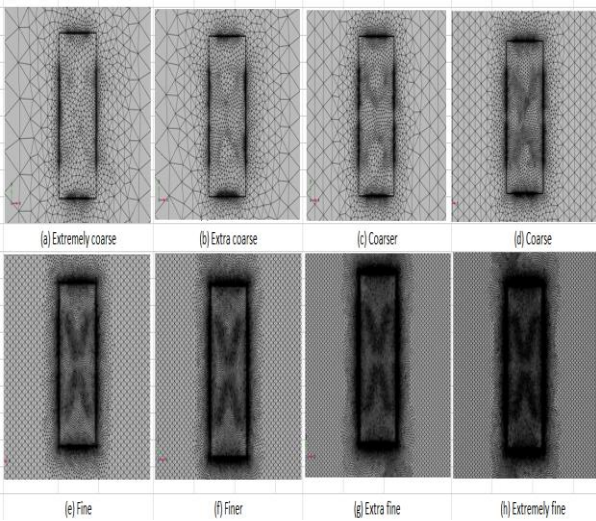


Fig 3 Mesh configurations

that a finer mesh configuration yielded the highest average element quality, as shown in Figure 4. Further refinement of the mesh led to decreased average element quality, indicating that the finer mesh was optimal for the simulation.

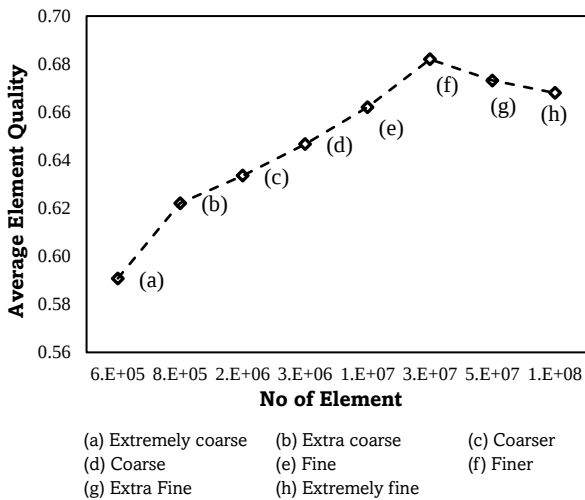


Fig 4 Mesh configurations correlation between average element quality and number of elements

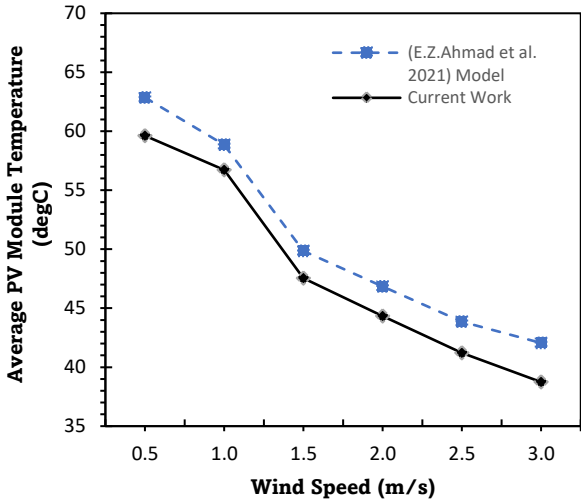


Fig 5 Validation of CFD modeling with prior studies (Ahmad *et al.*, 2021a, 2022).

2.4 Model Validation Analysis

A validation process was conducted (Figure 5) by comparing its results with those of a previous study to ensure the reliability of the CFD model. This step was essential to verify the accuracy of the boundary settings used in the simulation. The model validation process involved replicating the results of previous studies using the newly developed boundary settings (Ahmad *et al.*, 2021b, 2022). The comparison revealed high accuracy, with an average of 93.23 % agreement with the prior CFD results and 96.41 % agreement with the prior experimental results. The high accuracy achieved in the model validation analysis, exceeding 90 %, confirms the reliability and validity of this study's boundary conditions and simulation settings.

3. Experimental Methods

3.1 PV Panels

Silicon wafers have dominated the photovoltaic market for nearly a decade, representing most solar panel production. However, research on cooling these panels is often hindered using small-scale models. While these models provide valuable insights, they may not accurately predict the performance of large-scale systems. The reduced size can lead to unreliable results and may not fully capture the benefits of cooling, potentially limiting our understanding of effective cooling strategies (Nižetić *et al.*, 2021). To address these limitations, this study proposes a comprehensive investigation using large-scale photovoltaic panels with a capacity of 405 Wp (as shown in Figure 6). These panels exhibited an open-circuit voltage of 50.1 V and a short-circuit current of 10.48 A, as detailed in Table 4. The study was conducted under outdoor conditions to ensure real-world applicability. The detailed specifications of photovoltaic panels are shown in Table 4.

Table 4
Technical Specifications of Selected PV Module

Parameters	Value
Maximum power at STC (Pmax)	405 W
Open-circuit voltage (Voc)	50.1 V
Short-circuit current (Isc)	10.48 A
Maximum operating voltage (Vmp)	42.0 V
Maximum operating current (Imp)	9.65 A
Operating temperature	-40 °C ~ +85 °C
Power temperature coefficient (γ)	-0.35 %/°C
Voltage temperature coefficient (β)	-0.29 %/°C
Current temperature coefficient (α)	0.048 %/°C
Module dimensions (mm)	2008 x 1002 x 40
Module efficiency	20.13 %
Weight	22.5 kg

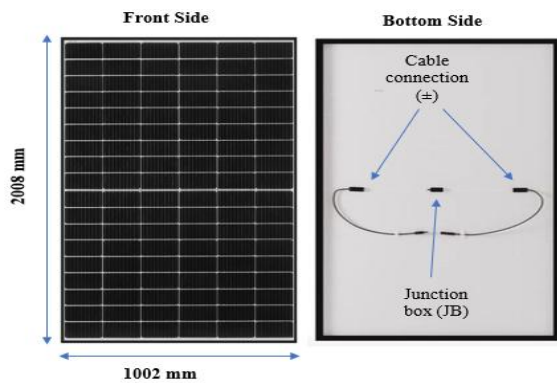


Fig 6 Half-cut cells monocrystalline PV module 405Wp

3.2 The Experimental Rig

The experimental investigation employed half-cut cell monocrystalline PERC PV panels exhibiting a module efficiency of 20.13 %. A novel MTFHS design was affixed to the rear surface of the PV panels, as depicted in Figure 7. Aluminium alloy was utilized as the material for the PV module cooling fins. The temperature distribution across the rear surface of each module was assessed at six distinct locations. A comparative analysis was conducted between a bare PV module and a module equipped with the MTFHS, focusing on their outdoor electrical performance.

The empirical investigation was carried out in a field setting over six months, encompassing a daily timeframe of 11:00 am to 4:00 pm. The PV modules were positioned at a 15°

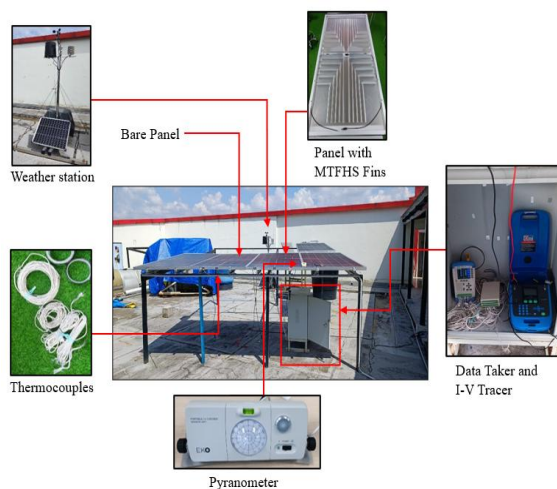


Fig 7 displays the entire test setup.

Table 5
Assessing the reliability of standard tools.

Measurement instruments	Parameters (units)	Model names	Uncertainties
Thermocouples	Temperature (°C)	K-type	± 0.1 °C
Current-voltage checker	Voltage (V), Current (A), Power (W)	MP-11	± 0.65 %
Weather station	Irradiance (W/m²), Wind speed (m/s)	RK600-07	± 1.3 % ± 1.45 %

inclination in accordance with the Malaysian tilt angle guidelines (N. A. S. Elminshawy, Mohamed, *et al.*, 2022a; Mamun *et al.*, 2022; T. Khatib A. Mohamed & Sopian, 2015). Figure 7 illustrates the experimental test rig, including a weather station, I-V curve tracer, and data logger. Additionally, the figure provides a top-down perspective of both bare and MTFHS-equipped modules mounted on a common plane.

3.3 Uncertainty Analysis

To ensure the reliability of our results, we conducted a thorough analysis of the potential uncertainties associated with the data collected during our experiment, as shown in Table 5. We denoted the uncertainties in the independent variables as $W_1, W_2, \dots, W_n$, and calculated the uncertainties in the results (W_R) using the provided formula, where $X_1, X_2, \dots, X_n$ represent the independent variables (Elminshawy, Mohamed, *et al.*, 2022b)(N. Elminshawy *et al.*, 2022).

$$W_R = [(\frac{\partial R}{\partial X_1} W_1)^2 + \frac{\partial R}{\partial X_2} W_2)^2 + \dots + \frac{\partial R}{\partial X_n} W_n)^2]^{\frac{1}{2}} \quad (1)$$

Equation (2) was used to calculate the maximum possible uncertainty in the electrical efficiency:

$$\begin{aligned} \eta_{elec} &= f(I_m, V_m, G) \Rightarrow W_{\eta_{elec}} \\ &= ((\frac{\partial \eta_{elec}}{\partial I_m} W_{I_m})^2 + \frac{\partial \eta_{elec}}{\partial V_m} W_{V_m})^2 + \dots \\ &\quad + \frac{\partial \eta_{elec}}{\partial G_m} W_G)^2)^{\frac{1}{2}} = \pm 0.2 \end{aligned} \quad (2)$$

A 5% error margin was deemed acceptable for assessing electrical efficiency.

4. Results and Discussion

4.1 The effect of parametric parameters on thermal performance

A comprehensive numerical investigation was conducted to evaluate the influence of various design parameters on the thermal performance of the PV module. The study considered a range of fin spacings (10-40 mm), fin numbers (8-20), and fin heights (45-120 mm) under varying solar irradiance levels (400-1000 W/m²). The ambient temperature was maintained at a constant 30 °C, and a steady wind speed of 1 m/s was applied. As depicted in Figure 8 (a), the numerical results demonstrate a notable reduction in PV module temperature from 57.58 °C to 56.65 °C under a solar irradiance of 1000 W/m² when increasing the fin number from 8 to 20 while maintaining a fin spacing of 30 mm. However, the positive impact of increasing

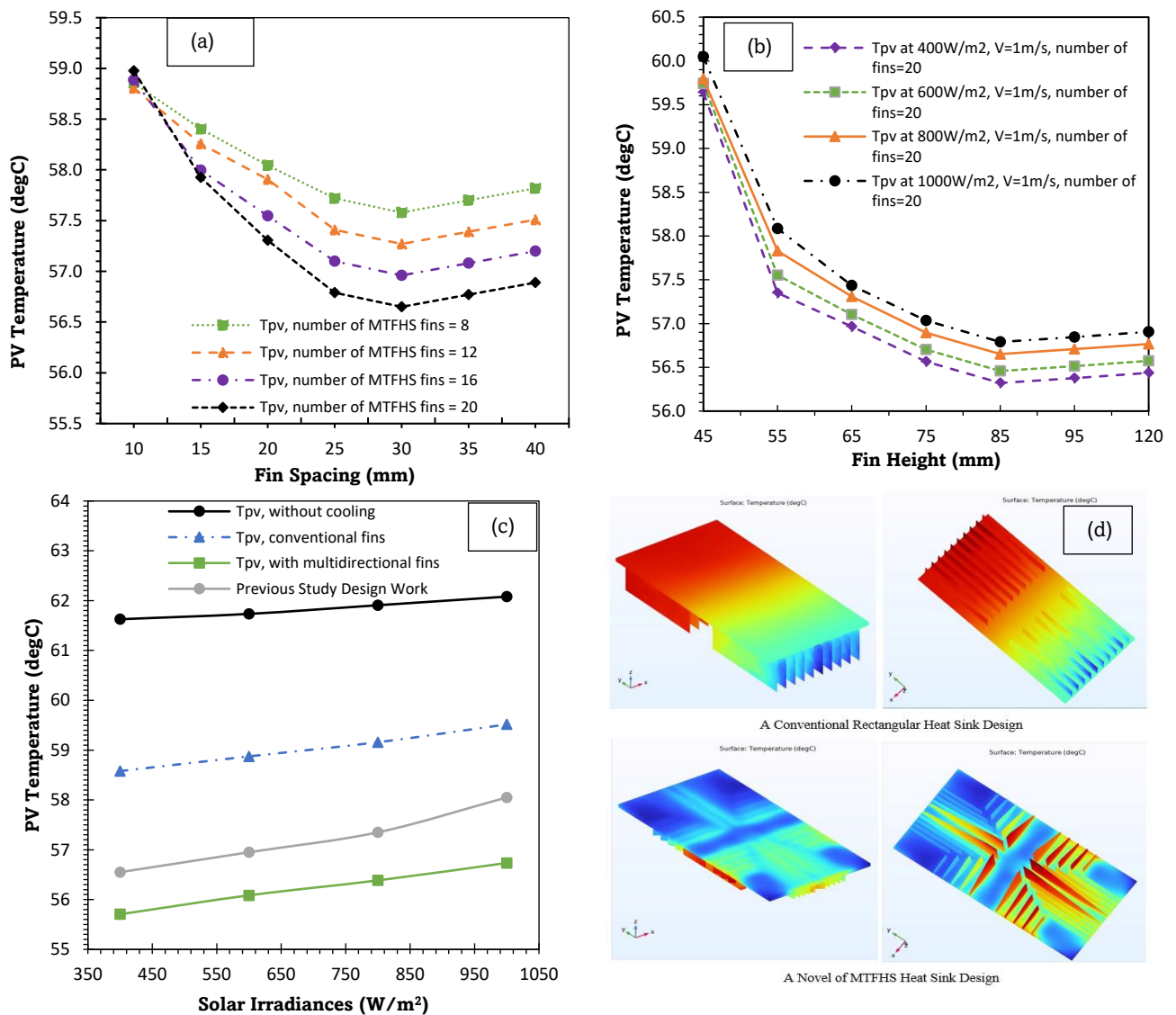


Figure 8 (a) Correlation between fin spacing and fin number on their influence on PV module temperature under 1000 W/m² solar irradiance. (b) Correlation between fin height and PV module thermal performance under different solar irradiance conditions (400-1000 W/m²). (c) Comparative analysis of PV module temperature under different cooling fin configurations: no fins, conventional rectangular fins, and innovative MTFHS fins, (d) Contrasting the surface temperatures of conventional rectangular fin and innovative MTFHS fin configurations

fin spacing on heat transfer performance gradually diminishes beyond 30 mm. This suggests that flow development within the fin heat sink may be constrained at larger spacings, limiting its ability to enhance heat dissipation.

As illustrated in Figure 8 (b), the multidirectional tapered design incorporates a gradual increase in fin height from 45 mm to the highest fins. To ensure that aerodynamic airflow could pass freely from the rear of the PV module to the critical junction box region, a minimum fin height of 45 mm was selected. This clearance was necessary to avoid obstructions that might impede airflow and hinder heat dissipation. The PV module's temperature exhibits a clear downward trend, decreasing from 60.1 °C to 58.08 °C at a fin height of 55 mm. This trend continues, with a gradual temperature reduction to 56.73 °C at a fin height of 85 mm. Beyond 85 mm, however, a slight temperature increase is observed. The observed increases in temperature at fin heights exceeding 85 mm are likely due to forming of a thicker thermal boundary layer, which hinders heat transfer. This suggests that 85 mm represents the optimal fin

height for maximizing heat dissipation through natural convection.

Figure 8 (c) presents a comparative analysis of the thermal performance of PV modules equipped with various heat sink configurations. Four PV module configurations were considered: a module without cooling, a module with previous work fins, a module with conventional rectangular fins, and a module with novel MTFHS. The results demonstrate the superior thermal performance of the MTFHS, which achieved an 8.61 % temperature reduction compared to the bare module, reaching a maximum temperature of 56.73 °C. In contrast, the conventional rectangular fins and previous work fins resulted in significantly lower temperature reductions of 4.13 % and 2.26 %, respectively, with maximum temperatures of 59.52 °C and 58.05 °C. The MTFHS introduces a novel approach to heat dissipation in PV modules. Figure 8 (d) illustrates that its unique multidirectional tapered fin design significantly increases the surface area available for heat exchange, outperforming conventional rectangular fins. Unlike traditional fins limited to

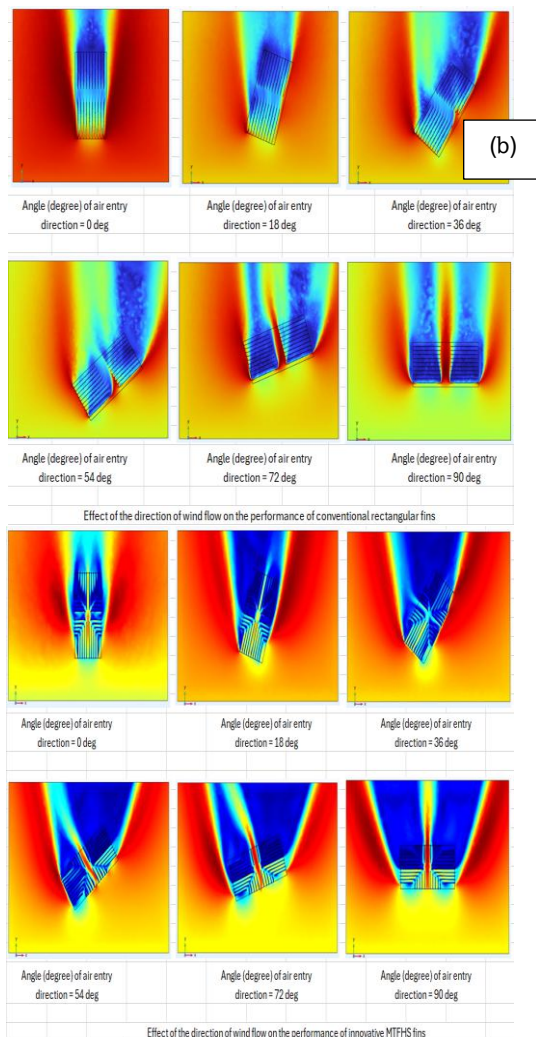
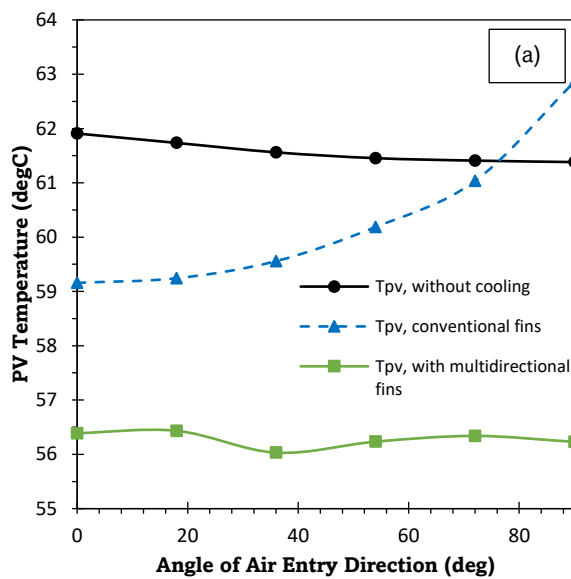


Figure 9 (a) Effect of the wind flow direction on the fins' performance in terms of heat transfer and temperature variation. **(b)** Effect of wind flow direction on the performance of both conventional rectangular and MTFHS fins was evaluated through CFD analysis

a single direction, the MTFHS can effectively capture wind flow from various angles, enhancing its cooling efficiency. This adaptability is particularly beneficial in outdoor environments where wind direction and solar irradiance fluctuate, making the MTFHS a promising solution for improving PV module performance in real-world conditions.

4.2 The effect of altering the angle

A series of outdoor environments were conducted to evaluate the practical performance of the proposed MTFHS fins under real-world conditions. The PV modules were subjected to natural convection, with the inlet velocity vector systematically adjusted from 0° to 90° in increments of 18° to simulate various wind directions, as illustrated in Figure 9 (a). The results demonstrated the superior thermal performance of the MTFHS compared to both bare modules and those equipped with conventional rectangular fins, which represent a common approach in previous research. The MTFHS's unique multidirectional design enables it to capture wind flow from various angles, significantly enhancing its cooling efficiency. This passive cooling mechanism improves the thermal performance of the PV modules and reduces the need for additional cooling equipment, leading to economic benefits. Even without any cooling fins, the PV module temperature decreased slightly to 61.4 °C. However, the conventional rectangular fins gradually increased temperature from 59.2 °C to 62.8 °C as the inlet velocity vector approached 90°. In contrast, the MTFHS consistently outperformed the other configurations across all wind orientations, achieving a temperature reduction of over 10 %. These findings underscore the inherent advantages of the MTFHS design, particularly in outdoor environments where wind direction and solar irradiance are unpredictable. The innovative MTFHS effectively captures and dissipates heat from the PV module, regardless of the wind's orientation, resulting in significantly lower temperatures than traditional cooling solutions, as depicted in Figure 9 (b).

4.3 Experimental and validation results

The I-V-P curves of the PV module with and without a cooling system are presented in Figure 10. The output power was monitored at 1-minute intervals while the current-voltage, output power, and PV module temperature were simultaneously recorded. An optimal tilt angle of 15 degrees was selected. The analysis reveals that the I-V-P characteristics of the bare PV module without cooling were influenced by varying solar irradiance levels (400-1000 W/m²). This resulted in a noticeable increase in short-circuit current from 9.21 A to 9.27 A, demonstrating their effectiveness in improving electrical performance through enhanced heat dissipation, as shown in Figure 10 (a). Figure 10 (b) demonstrates that MTFHS significantly increases solar module output (290 W versus 243 W). In outdoor environments, especially with high solar irradiance, maintaining the ideal 25 °C module temperature is challenging. This leads to lower actual output compared to STC (405 W). In addition, a comparative analysis of numerical simulations conducted using CFD and experimental data for a PV module equipped with an MTFHS fin is presented in Figure 10 (c). The results reveal a high degree of correlation (93-96 %) between numerical and experimental outcomes, indicating the

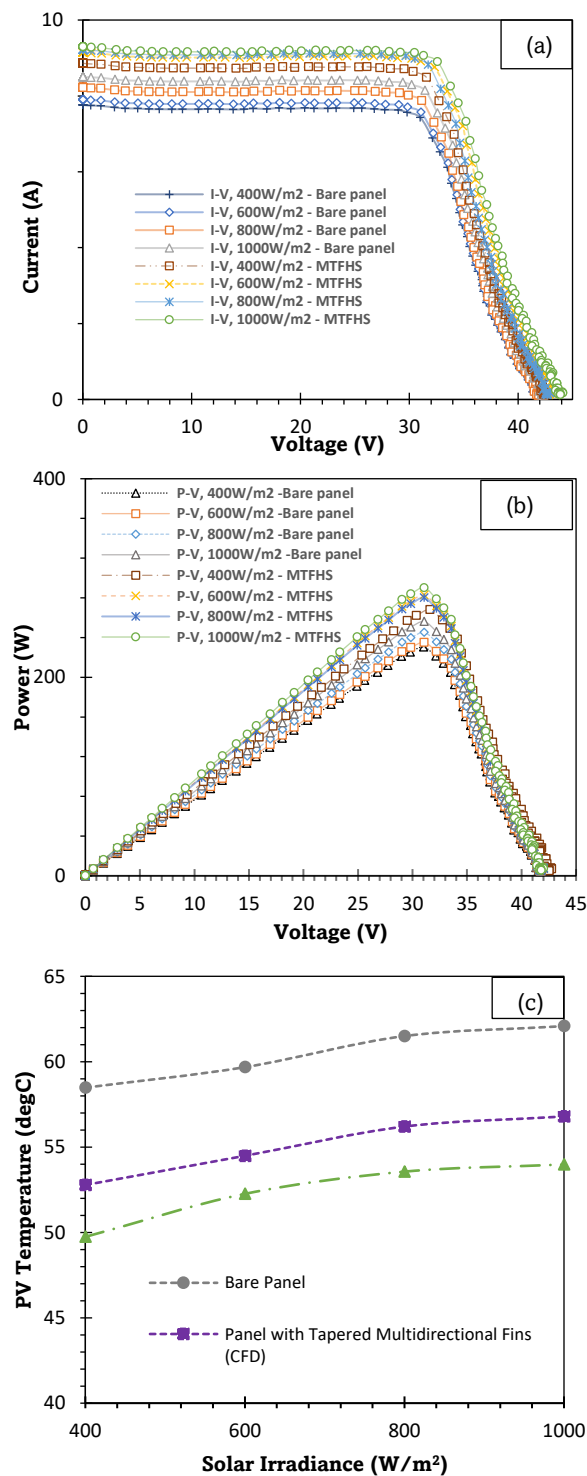


Figure 10 (a) I-V Curve analysis based on experimental results, **(b)** P-V Curve analysis based on experimental results, **(c)** Comparative analysis of numerical simulations results and experimental data for bare module and MTFHS design

accuracy of the CFD model in predicting the thermal performance of the PV module.

5. Conclusion

This study utilizes CFD to investigate the influence of multidirectional tapered fins on the thermal characteristics and reliability of PV modules. The primary objective is to evaluate the effectiveness of MTFHS in improving the performance of PV

modules under real-world conditions. A comparative analysis was conducted between PV modules equipped with MTFHS, conventional rectangular fins, previous work fins, and a standard bare PV module to achieve this. Our findings demonstrate that MTFHS significantly reduces PV module temperature, achieving a remarkable 8.61% reduction compared to the bare, conventional rectangular fins and previous work fins. The maximum temperature reached with MTFHS was 56.73 °C. MTFHS consistently outperformed

other configurations across various wind orientations, achieving temperature reductions of over 10 %. These findings highlight the exceptional effectiveness of MTFHS in outdoor environments, especially where wind direction and solar irradiance are unpredictable. The innovative MTFHS effectively captures and dissipates heat from the PV module, regardless of the wind's orientation, resulting in significantly lower temperatures than traditional cooling solutions.

The superior thermal performance of the MTFHS can be attributed to their enhanced heat transfer characteristics. The multidirectional tapered fin design significantly increases the surface area for heat exchange, outperforming conventional rectangular fins. Unlike traditional fins limited to a single direction, the MTFHS can effectively capture wind flow from various angles, enhancing its cooling efficiency. This adaptability is particularly beneficial in outdoor environments where wind direction and solar irradiance fluctuate, making the MTFHS a promising solution for improving PV module performance in real-world conditions. A correlation analysis revealed excellent agreement (93-96 %) between model and experimental results, further validating the efficacy of the MTFHS design.

In summary, the innovative MTFHS heat sink fins demonstrated their effectiveness in reducing PV module temperature across various solar irradiance conditions. These findings highlight the potential of MTFHS to improve the efficiency and longevity of PV modules, particularly in regions with high ambient temperatures and intense solar radiation. Future research should focus on optimizing the design of MTFHS to enhance their thermal performance further and explore their integration with other PV cooling technologies.

Acknowledgement

Sincerely thank the Solar Thermal and Sustainable Technology Group, under Sustainable Resources, Nature and Smart Living Cluster, Kumpulan Penyelidikan Universiti (KPU) and Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia, for their invaluable support and guidance throughout this project.

References

- Abdallah, R., Haddad, T., Zayed, M., Juaidi, A., & Salameh, T. (2024). An evaluation of the use of air cooling to enhance photovoltaic performance. *Thermal Science and Engineering Progress*, 47, 102341. <https://doi.org/https://doi.org/10.1016/j.tsep.2023.102341>
- Ağbulut, Ü., Gürel, A. E., & Biçen, Y. (2021). Prediction of daily global solar radiation using different machine learning algorithms: Evaluation and comparison. *Renewable and Sustainable Energy Reviews*, 135, 110114. <https://doi.org/https://doi.org/10.1016/j.rser.2020.110114>
- Aghaei, M., Fairbrother, A., Gok, A., Ahmad, S., Kazim, S., Lobato, K., Oreski, G., Reinders, A., Schmitz, J., Theelen, M., Yilmaz, P., & Kettle, J. (2022). Review of degradation and failure phenomena in photovoltaic modules. *Renewable and Sustainable Energy Reviews*, 159(February), 112160. <https://doi.org/10.1016/j.rser.2022.112160>
- Ahmad, E. Z., Fazlizan, A., Jarimi, H., Sopian, K., & Ibrahim, A. (2021a). 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/https://doi.org/10.1016/j.csite.2021.101578>
- Ahmad, E. Z., Fazlizan, A., Jarimi, H., Sopian, K., & Ibrahim, A. (2021b). 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(March), 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/https://doi.org/10.1016/j.csite.2022.101811>
- Ahmed, B., Necaibia, A., Slimani, A., Dabou, R., Ziane, A., & Sahouane, N. (2019). A Demonstrative Overview of Photovoltaic Systems Faults. *2019 1st Global Power, Energy and Communication Conference (GPECOM)*, 281-285. <https://doi.org/10.1109/GPECOM.2019.8778567>
- Al-Aasam, A. B., Ibrahim, A., Sopian, K., Abdulsahib M, B., & 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(January), 103299. <https://doi.org/10.1016/j.csite.2023.103299>
- Al-Amri, F., Saeed, F., & Mujeebu, M. A. (2022). Novel dual-function racking structure for passive cooling of solar PV panels – thermal performance analysis. *Renewable Energy*, 198, 100-113. <https://doi.org/https://doi.org/10.1016/j.renene.2022.08.047>
- Alktranee, M., & Bencs, P. (2023). Experimental comparative study on using different cooling techniques with photovoltaic modules. *Journal of Thermal Analysis and Calorimetry*, 148(9), 3805-3817. <https://doi.org/10.1007/s10973-022-11940-1>
- Armstrong, S., & Hurley, W. G. (2010). A thermal model for photovoltaic panels under varying atmospheric conditions. *Applied Thermal Engineering*, 30(11), 1488-1495. <https://doi.org/https://doi.org/10.1016/j.applthermaleng.2010.03.012>
- Arun, M., Barik, D., Sharma, P., Gürel, A. E., Ağbulut, Ü., Medhi, B. J., & Bora, B. J. (2024). Experimental and CFD analysis of dimple tube parabolic trough solar water heater with various nanofluids. *Applied Nanoscience*, 14(2), 291-337. <https://doi.org/10.1007/s13204-023-02977-1>
- Assadeg, J., Sopian, K., Ibrahim, A., Fudholi, A., Fatima, N., 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), 125-135. <https://doi.org/10.20508/ijrer.v13i1.13880.g8668>
- Baghaei Daemei, A., Khotbehsara, E. M., Nobarani, E. M., & Bahrami, P. (2019). Study on wind aerodynamic and flow characteristics of triangular-shaped tall buildings and CFD simulation in order to assess drag coefficient. *Ain Shams Engineering Journal*, 10(3), 541-548. <https://doi.org/https://doi.org/10.1016/j.asej.2018.08.008>
- 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(November 2022), 102883. <https://doi.org/10.1016/j.csite.2023.102883>
- Bayrak, F., Oztop, H. F., & Selimefendigil, F. (2020). Experimental study for the application of different cooling techniques in photovoltaic (PV) panels. *Energy Conversion and Management*, 212, 112789. <https://doi.org/https://doi.org/10.1016/j.enconman.2020.112789>
- Dey, A., Ahmed, Z. U., & Ramijul Alam, M. (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(November), 100324. <https://doi.org/10.1016/j.ecmx.2022.100324>
- Egab, K., Okab, A., Dywan, H. S., & Oudah, S. K. (2020). Enhancing a solar panel cooling system using an air heat sink with different fin configurations. *IOP Conference Series: Materials Science and Engineering*, 671(1), 12133. <https://doi.org/10.1088/1757-899X/671/1/012133>

- Elbreki, A. M., Muftah, A. F., Sopian, K., Jarimi, H., Fazlizan, A., & Ibrahim, A. (2021). Experimental and economic analysis of passive cooling PV module using fins and planar reflector. *Case Studies in Thermal Engineering*, 23, 100801. <https://doi.org/https://doi.org/10.1016/j.csite.2020.100801>
- Elminshawy, N. A. S., El-Damhogi, D. G., Ibrahim, I. A., Elminshawy, A., & Osama, A. (2022). Assessment of floating photovoltaic productivity with fins-assisted passive cooling. *Applied Energy*, 325, 119810. <https://doi.org/https://doi.org/10.1016/j.apenergy.2022.119810>
- Elminshawy, N. A. S., Mohamed, A. M. I., Osama, A., Amin, I., Bassam, A. M., & Oterkus, E. (2022a). Performance and potential of a novel floating photovoltaic system in Egyptian winter climate on calm water surface. *International Journal of Hydrogen Energy*, 47(25), 12798–12814. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.02.034>
- Elminshawy, N. A. S., Mohamed, A. M. I., Osama, A., Amin, I., Bassam, A. M., & Oterkus, E. (2022b). Performance and potential of a novel floating photovoltaic system in Egyptian winter climate on calm water surface. *International Journal of Hydrogen Energy*, 47(25), 12798–12814. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.02.034>
- Elminshawy, N., Elminshawy, A., Osama, A., Bassyouni, M., & Arıcı, M. (2022). Experimental performance analysis of enhanced concentrated photovoltaic utilizing various mass flow rates of Al2O3-nanofluid: Energy, exergy, and exergoeconomic study. *Sustainable Energy Technologies and Assessments*, 53, 102723. <https://doi.org/https://doi.org/10.1016/j.seta.2022.102723>
- Ewe, W. Eng., Fudholi, Ahmad., Sopian, Kamaruzzaman., Moshery, R., Asim, N., Nuriana, Wahidin., & Ibrahim, Adnan. (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>
- Ewe Win Eng, Ahmad Fudholi, Kamaruzzaman Sopian, & Nilofar Asim. (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>
- Farhan, A. A., & Hasan, D. J. (2021). An experimental investigation to augment the efficiency of photovoltaic panels by using longitudinal fins. *Heat Transfer*, 50(2), 1748–1757. <https://doi.org/https://doi.org/10.1002/htj.21951>
- Gomaa, M. R., Hammad, W., Al-Dhaifallah, M., & Rezk, H. (2020). Performance enhancement of grid-tied PV system through proposed design cooling techniques: An experimental study and comparative analysis. *Solar Energy*, 211, 1110–1127. <https://doi.org/https://doi.org/10.1016/j.solener.2020.10.062>
- Hernandez-Perez, J. G., Carrillo, J. G., Bassam, A., Flota-Banuelos, M., & Patino-Lopez, L. D. (2021). Thermal performance of a discontinuous finned heatsink profile for PV passive cooling. *Applied Thermal Engineering*, 184, 116238. <https://doi.org/https://doi.org/10.1016/j.applthermaleng.2020.116238>
- Hudisteanu, S. V., Țurcanu, F. E., Cherecheș, N. C., Popovici, C. G., Verdeș, M., & Huditeanu, I. (2021). Enhancement of PV Panel Power Production by Passive Cooling Using Heat Sinks with Perforated Fins. *Applied Sciences*, 11(23). <https://doi.org/10.3390/app112311323>
- 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., Sopian, K., Fazlizan, A., & Ishak, M. A. A. Bin. (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). <https://doi.org/https://doi.org/10.20508/ijrer.v13i3.14136.g8814>
- Ishak, M. A. A. Bin, 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(November), 103752. <https://doi.org/10.1016/j.csite.2023.103752>
- Ishak, M. A. A. Bin, Ibrahim, A., Fazlizan, A., Fauzan, M. F., Sopian, K., & Rahmat, A. A. (2023). Exergy performance of a reversed circular flow jet impingement bifacial photovoltaic thermal (PVT) solar collector. *Case Studies in Thermal Engineering*, 49(May), 103322. <https://doi.org/10.1016/j.csite.2023.103322>
- Ishak, M. A. A. Bin, Ibrahim, A., Sopian, K., Faizal, M., Aqil Afham Rahmat, M., Rahmat, A., Sufiyan, A., & Hamid, A. (2023). Heat Transfer Performance of a Novel Circular Flow Jet Impingement Bifacial Photovoltaic Thermal PVT Solar Collector. 13(2). <https://doi.org/https://doi.org/10.20508/ijrer.v13i2.13886.g8756>
- Ishak, M. A. A. Bin., Ibrahim, Adnan., Sopian, Kamaruzzaman., Fauzan, M. Faizal., Rahmat, M. A. Afham., & Hamid, A. Sufiyan Abd. (2023). Classification of Jet Impingement Solar Collectors – A Recent Development in Solar Energy Technology. *International Journal of Renewable Energy Research-IJREER*, 13(2), 802–817. <https://doi.org/https://doi.org/10.20508/ijrer.v13i2.13884.g8755>
- Ishak, M. A. A. Bin., Ibrahim, Adnan., Sopian, Kamaruzzaman., Fauzan, M. Faizal., Rahmat, M. A. Afham., & Yusaidi, N. Jannah. (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/https://doi.org/10.14710/ijred.2023.54348>
- Ismail, F. B., Rahmat, M. A. A., Kazem, H. A., Al-Obaidi, A. Sh. M., & Ridwan, M. S. (2024). Maximizing energy via solar-powered smart irrigation: An approach utilizing a single-axis solar tracking mechanism. *Irrigation and Drainage*, 73(3), 829–845. <https://doi.org/https://doi.org/10.1002/ird.2937>
- Kanti, P. K., Shrivastav, A. P., Sharma, P., & Maiya, M. P. (2024). Thermal performance enhancement of metal hydride reactor for hydrogen storage with graphene oxide nanofluid: Model prediction with machine learning. *International Journal of Hydrogen Energy*, 52, 470–484. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2023.03.361>
- Khelifa, A., El Hadi Attia, M., Harby, K., Elnaby Kabeel, A., Abdel-Aziz, M. M., & Abdelgaied, M. (2024). Experimental and economic evaluation on the performance improvement of a solar photovoltaic thermal system with skeleton-shaped fins. *Applied Thermal Engineering*, 248, 123180. <https://doi.org/https://doi.org/10.1016/j.applthermaleng.2024.123180>
- Khor, Y. K., Hung, Y. M., & Lim, B. K. (2010). On the role of radiation view factor in thermal performance of straight-fin heat sinks. *International Communications in Heat and Mass Transfer*, 37(8), 1087–1095. <https://doi.org/https://doi.org/10.1016/j.icheatmasstransfer.2010.06.012>
- kumar 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(PB), 102165. <https://doi.org/10.1016/j.seta.2022.102165>
- Luo, C., Li, C., Wan, X., & Zhao, Z. (2023). Convective Heat Transfer Coefficient of Insulation Paper–Oil Contact Surface of Transformer Vertical Oil Channel. *Coatings*, 13(1). <https://doi.org/10.3390/coatings13010081>
- Mamun, M. A. A., Islam, M. M., Hasanuzzaman, M., & Selvaraj, J. (2022). Effect of tilt angle on the performance and electrical parameters of a PV module: Comparative indoor and outdoor experimental investigation. *Energy and Built Environment*, 3(3), 278–290. <https://doi.org/https://doi.org/10.1016/j.enbenv.2021.02.001>
- Munusamy, A., Barik, D., Sharma, P., Medhi, B. J., & Bora, B. J. (2024). Performance analysis of parabolic type solar water heater by

- using copper-dimpled tube with aluminum coating. *Environmental Science and Pollution Research*, 31(53), 62376–62391. <https://doi.org/10.1007/s11356-022-25071-5>
- Nižetić, S., Jurčević, M., Čoko, D., & Anđić, M. (2021). A novel and effective passive cooling strategy for photovoltaic panel. *Renewable and Sustainable Energy Reviews*, 145, 111164. <https://doi.org/https://doi.org/10.1016/j.rser.2021.111164>
- Patel, M. T., Vijayan, R. A., Asadpour, R., Varadharajaperumal, M., Khan, M. R., & Alam, M. A. (2020). Temperature-dependent energy gain of bifacial PV farms : A global perspective. *Applied Energy*, 276(May), 115405. <https://doi.org/10.1016/j.apenergy.2020.115405>
- Rahmat, M. A. A., Mohamed, H., Zuhdi, A. W. M., & Roslan, M. E. B. M. (2023). Developing a spreadsheet-based simulator for solar rooftop installation assessment. *AIP Conference Proceedings*, 2544(1), 40052. <https://doi.org/10.1063/5.0119883>
- Rahmat, M. A. Afham., Hamid, A. S. Abd., Lu, Yuanshen., Ishak, M. A. A. Bin., Suheel, S. Zishan., Fazlizan, Ahmad., & Ibrahim, Adnan. (2022). An Analysis of Renewable Energy Technology Integration Investments in Malaysia Using HOMER Pro. *Sustainability (Switzerland)*, 14(20). <https://doi.org/10.3390/su142013684>
- Razali, S. N., Ibrahim, A., Fazlizan, A., Fauzan, M. F., Ajeel, R. K., Zairah Ahmad, E., Ewe, W. E., & Kazem, H. A. (2023a). Performance enhancement of photovoltaic modules with passive cooling multidirectional tapered fin heat sinks (MTFHS). *Case Studies in Thermal Engineering*, 50, 103400. <https://doi.org/https://doi.org/10.1016/j.csite.2023.103400>
- Razali, S. N., Ibrahim, A., Fazlizan, A., Fauzan, M. F., Ajeel, R. K., Zairah Ahmad, E., Ewe, W. E., & Kazem, H. A. (2023b). Performance enhancement of photovoltaic modules with passive cooling multidirectional tapered fin heat sinks (MTFHS). *Case Studies in Thermal Engineering*, 50, 103400. <https://doi.org/https://doi.org/10.1016/j.csite.2023.103400>
- T. Khatib A. Mohamed, M. M., & Sopian, K. (2015). Optimization of the Tilt Angle of Solar Panels for Malaysia. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 37(6), 606–613. <https://doi.org/10.1080/15567036.2011.588680>
- 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(December 2020), 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(May), 104619. <https://doi.org/10.1016/j.csite.2024.104619>



© 2025. The Author(s). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution-ShareAlike 4.0 (CC BY-SA) International License (<http://creativecommons.org/licenses/by-sa/4.0/>)