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Enhancing the Performance of Photovoltaic Modules via Cooling with Heat Sinks and Fins: A Review

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ABSTRACT

This review offers an overview of key developments that may assist researchers in improving thermal management strategies for photovoltaic systems across different environmental conditions. It's worth noting that temperature significantly affects the efficiency of photovoltaic systems. As operating temperatures rise, energy production decreases, impacting the system's lifetime. The main focus of this research paper, which examines recent developments in thermal management technologies for photovoltaic systems, is the use of fin-based cooling technologies. he efficiency of passive, active, and hybrid cooling technologies was evaluated, focusing on their ability to dissipate heat and increase the efficiency of photovoltaic panels by expanding the heat dissipation surface area. Metal foam fins and heatsinks improve heat transfer. Key findings from numerical simulations and experimental studies are summarized, including the impact of fin design, material selection, and environmental factors on cooling performance. For instance, trapezoidal fins, cylindrical pin fins, and foam-based configurations demonstrate notable temperature reductions and efficiency improvements in various setups. Additionally, the research identifies challenges such as optimal fin spacing, material durability, and cost-effectiveness.

Keywords: Metal foam fins, Heat sinks, Heat transfer, Passive and active cooling, Thermal management.

1. INTRODUCTION

The increasing global demand for renewable energy has amplified the significance of solar panel technology as a sustainable solution. Regretfully, non-renewable resources like fossil fuels are still the primary source of this energy Global warming refers to the long-term increase in Earth's average surface temperature due to human activities, primarily the emission of greenhouse gases. These gases trap heat in the atmosphere, leading to a gradual warming of the planet, according to the US Environmental Protection Agency **(US EPA, 2023).** The primary contributors to global warming are the burning of fossil fuels,

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deforestation, and certain industrial processes, as noted by **(Liu et al., 2007).** Shifting away from fossil fuels, which presently constitute the majority of emissions, towards renewable energy is crucial in tackling the climate emergency **(Kannan and Vakeesan, 2016)**. According to the International Energy Agency (IEA) in its report "Net Zero by 2050," solar energy is expected to become the largest source of global electricity supply, accounting for approximately 20% of total energy demand by 2050 **(International Energy Agency (IEA), 2021)**. But there are drawbacks to solar energy use as well, which still need to be addressed. The temperature of the solar cell rises as a result of converting a large portion of solar radiation into heat **(Gomaa et al., 2020)**. As the operating temperature rises, the electrical efficiency of photovoltaic panels decreases. Specifically, the efficiency drops by approximately 0.08% for every 1°C increase above the standard 25°C, resulting in a corresponding reduction in power output of around 0.65% **(Razzies, 2003)** and including the poor efficiency, high initial cost, and need for energy storage **(Guangul and Chala, 2019)**. Developers and consumers are increasingly focused on the negative effect of high temperatures on the efficiency of solar panels, leading to growing interest in cooling methods such as passive and active systems to help maintain good performance.

To reduce this heat, cooling technologies are used. There are two types of cooling technologies: active and passive, which use air or water. Active cooling requires external energy **(Sharma et al., 2021)**. Passive cooling, on the other hand, does not require any external energy **(AlAmri et al., 2021)**. The use of phase change materials (PCM) to absorb excess heat is considered the third cooling method **(Hussain et al., 2023)**. Most of these methodologies rely on heat sink designs incorporating fins, which significantly expand the surface area available for heat transfer, thereby enhancing cooling efficiency. The increased surface area facilitates more effective heat exchange, thus enabling better regulation of operating temperatures **(Pandya and Karia, 2023)**.

A brief summary of these studies is provided to facilitate comparison for researchers and practitioners. The effectiveness of these methods depends on environmental conditions and solar radiation levels, which help in selecting appropriate cooling techniques. Fin-based cooling technologies can be classified into three primary categories: passive cooling, active cooling, and hybrid cooling. Each can be employed to efficiently disperse heat from electronic devices and systems. These collections encompass a diverse range of cooling solutions that leverage the design and placement of fins to enhance heat transfer efficiency and thermal management capabilities in various applications. **Table 1** provides a summary of the most recent studies reviewed, detailing the cooling technologies used, experimental and climatic conditions, PV panel specifications used, fin or heat sink configurations, and key findings reported in each study.

2. PV COOLING TECHNIQUES

2.1 Passive Cooling Technique

(Do et al., 2012) studied plate-fin heat sinks for CPV cooling, **Fig. 1**, finding that optimal fin spacing depends on temperature differences and angles above 70°. Edge airflow was crucial for design optimization. In Elazig, Turkey, (**Selimefendigil et al., 2018**) installed closed-cell aluminium foam fins (6 mm and 10 mm) below a photovoltaic panel at Firat University's Technology Faculty, **Fig. 2**. It was anticipated by ANN models that the finned PV module would boost output power and efficiency. When compared to the flat module, the 10 mm thick fins produced a peak power differential of 7.26 W at 11:00. The experimental data were accurately matched by the ANN models.

Utilizing aluminium heat sinks with trapezoidal fins decreased PV panel temperatures by 9.4% while increasing power production by 15.3% and efficiency by 19.3%, as shown by **(Hasan, 2018)**. These findings were confirmed by a thermal model with a difference of less than 3%. An enhanced flared-fin heat sink, **Fig. 3**, for CPV systems was evaluated by **(Luo et al., 2019),** who found that 15–18 fins produced the best results and a 10% decrease in thermal resistance. The researchers added a Nusselt number correlation equation, which proved that the design was effective in improving heat transfer without increasing weight or volume. The equation was also verified and confirmed to be accurate, with an error rate of less than 15%. Metal meshes and cooling fins are two passive cooling methods for PV modules that are compared in the study **(Kim et al., 2020)**. Iron and aluminium mesh decreased module temperature by 4.35°C and 6.56°C, respectively, increasing efficiency by 1.44%. Fins reduced the temperature more (3.18°C) than metal meshes (1.49°C), according to CFD simulations, **Fig. 4**. A segmented fin heatsink could lower temperatures by up to 9.4°C (19.6%) when compared to a panel without a heatsink, according to CFD calculations by **(Hernandez-Perez et al., 2019), Fig. 5**. In comparison to conventional fins, experimental studies demonstrated improved hydraulic performance, lower pressure drops, and a 10°C decrease in peak irradiance. Heat sinks raised open-circuit voltage by 0.27 V while lowering temperature by 7.5°C, according to research by **(Krstic et al., 2024**), at the University of Nis in Serbia. They found a temperature difference of roughly 1°C using simulations using ANSYS software, which was in good agreement with experimental findings, **Fig. 6**.

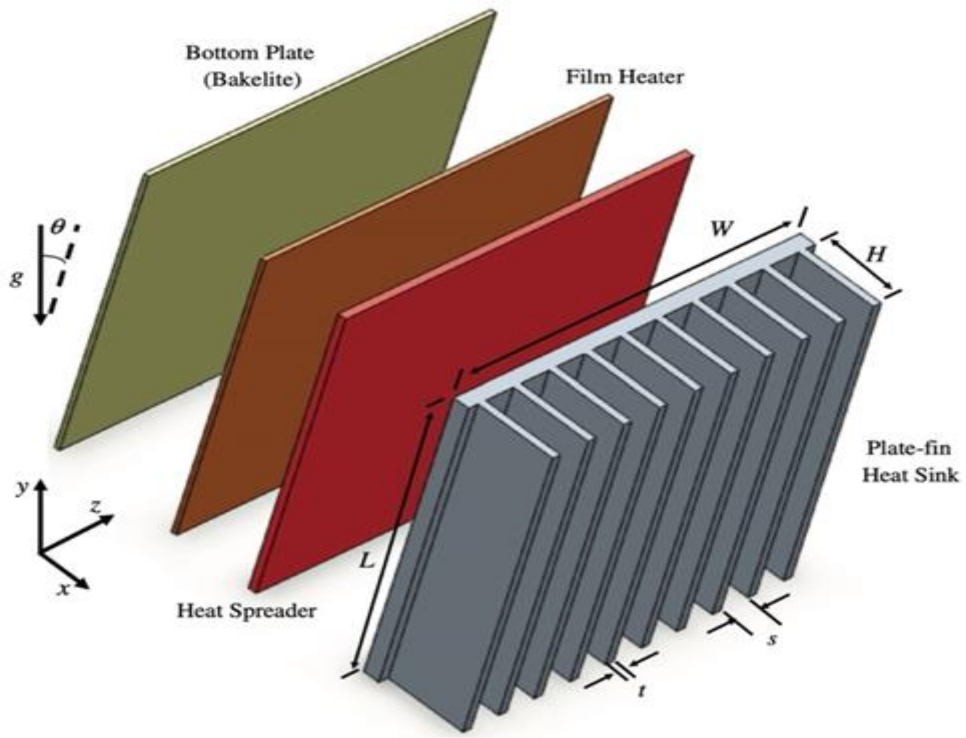


Figure 1. A plate-fin heat sink assembly **(Do et al., 2012)**

Table 1. Summary of the Most Recent Studies on Solar Panel Cooling Techniques (Passive, Active, Hybrid) as Reviewed in This Study

Authors	Title	Year	Study Type	Cooling Technique	Climatic & Operating Conditions	Working Fluid	PV Type & Specifications	Fins/Heat Sink	Main Findings
(Krstic et al., 2024)	Passive cooling of photovoltaic panel by aluminum heat sinks and numerical simulation	2024	Experimental + CFD	Passive Cooling	27°C; Irradiance up to 866 W/m²; Wind ≤2.5 m/s	Air	LUXOR LX-100M/125-36; Polycrystalline; 100 W	36 aluminum sinks; type B2 best	Avg. temp drop: 7.5°C; Max: 10.8°C; Voc↑0.27V; CFD matched experiment (Δ~1°C)
(Hasan and Farhan, 2019)	Enhancing the Efficiency of Photovoltaic Panel Using Open-Cell Copper Metal Foam Fins	2019	Experimental	Passive Cooling	Feb–Apr; Baghdad; rooftop; natural sunlight	Air	Polycrystalline; 50W; 670×540 mm; η=14.54%	Open-cell copper foam, PPI 15, 10 cm, 5 mm thick	Temp↓8.4% (~3.8°C); Power↑4.9%; Eff.↑1%
(Alshibil et al., 2023)	Evaluation of Fin Configurations for an Air-Cooled Hybrid Photovoltaic-Thermal Solar Collector	2023	Experimental + Analytical	Forced Cooling	Oct; I=821–906 W/m²; 21–23°C; air velocity 0.915–1.29 m/s	Air	Polycrystalline, 670×1100 mm, Pmax=60 W	Copper fins: Vertical and Louver (28.5°), 0.05 m height	Louver fins: Elec. Eff. 7.34%, Thermal Eff. 69%, Temp. drop to 40.6°C
(Zhao et al., 2023)	Experimental investigation of the performance of	2023	Experimental	Forced Cooling	Simulated solar (xenon lamps), 200–	Air	Polycrystalline, 350×450 mm	0, 5, or 10 fixed Al fins, 60×150 mm	10 fins: Thermal eff.↑53.6%,

Authors	Title	Year	Study Type	Cooling Technique	Climatic & Operating Conditions	Working Fluid	PV Type & Specifications	Fins/Heat Sink	Main Findings
	an air type photovoltaic thermal collector system with fixed cooling fins				600 W/m², 25–35°C				Overall eff. 69.85%
(Khaled et al., 2022)	Experimental Study on Convective Heat Transfer Using Fins for Cooling PV Cells	2022	Experimental	Hybrid Cooling	Outdoor; 8:30–15:30; up to 777 W/m; 32°C	Water	Monocrystalline silicon, with and without fins	Rectangular helical copper tube heat exchanger + aluminum fins	Finned system: Electrical eff. 9.97%, Power↑38.7% over uncooled

Figure 2. Mounted aluminium foam fins in the back panel (**Selimefendigil et al., 2019**)

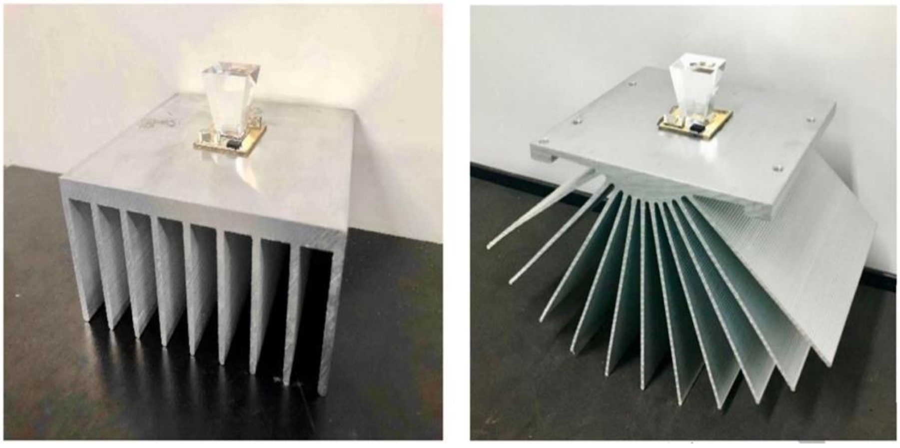


Figure 3. A CPV receiver assembly using a solar cell and an aluminum alloy heat sink **(Luo et al., 2019)**

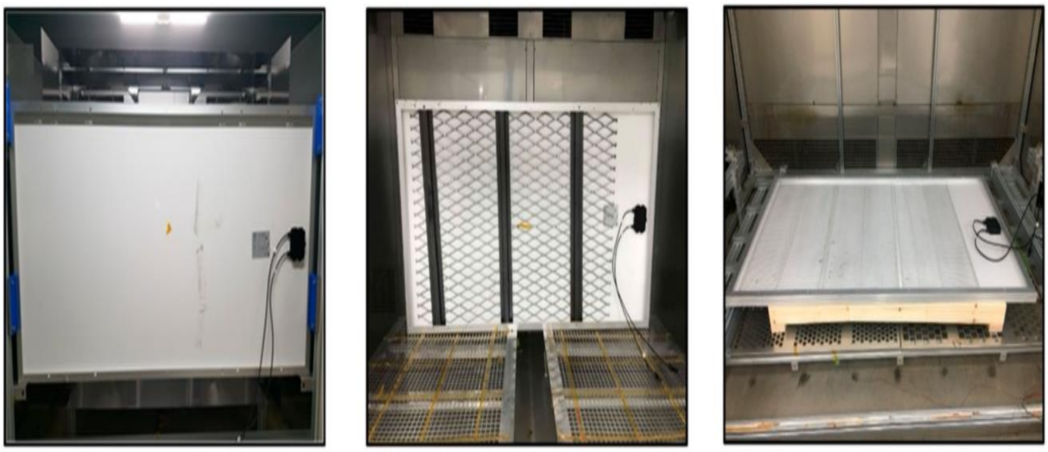


Figure 4. Three cases of the experimental study. **(Kim et al., 2020)**

Figure 5. Aluminium fins in the back panel. **(Hernandez-Perez et al., 2019).**

Figure 6. Back side of the passively cooled panel with heat sinks of different shapes and three investigated heat sinks marked with a black rectangle. **(Krstic et al., 2024**).

(Cuce et al., 2011)conducted experiments under a solar simulator, showing that heat sinks significantly lowered cell temperature. This improved energy, exergy, and power conversion efficiencies by up to 9%, 13%, and 20%, respectively, while increasing maximum power output by 65 mW at 800 W/m^2. The heat sink dissipated 12 W of heat, compared to 9.6 W for the uncooled cell. In 2014, two PV panel setups were tested, one with cooling fins and one without. The results revealed that the panels with cooling fins achieved 0.3-1.8% higher electrical efficiency and 1.8-11.8% higher power output under varying conditions, **Fig. 7**. According to **(Chen et al., 2014),** this study demonstrated that passive cooling effectively enhances PV panel performance without additional energy consumption.

Also, a 21-degree tilt was used to test two 37W PV panels, one with and one without aluminum fins. The fin-cooled panel's power output increased by 5.5% and its temperature decreased by 4.2%, **Fig. 8**. This straightforward passive cooling method enhanced PV efficiency under natural convection, according to **(Gotmare et al., 2015)**. It was discovered that pin fin heat sinks performed better than plate fin designs, lowering the temperature of the PV system by as much as 11.16°C. In comparison to a PV-only system with a heat sink, the addition of a TE module further reduced the system temperature by around 8.29°C. In their study, (**Pang et al., 2015)** emphasized this. In 2017 and 2018, two 70x35 cm (30W) polycrystalline PV panels- one with and one without aluminum fins- were tested by **(El Mays et al., 2017).** The efficiency increased by 1.77%, the power increased by 1.86W, and the temperature decreased by 6.1°C. Perforated aluminum fins on a 50W PV panel performed better than parallel fins, **Fig. 9**, increasing efficiency by 2% and being more efficient in windy, low-insolation circumstances, according to **(Grubišić-Čabo et al., 2018).** A cooling strategy for PV modules that included conductive, air-passive, and water-passive approaches was examined by **(Idoko et al., 2018)**. The system **Fig. 10** demonstrated a 20.96-watt power gain and at least 3% greater efficiency in testing conducted in Nigeria on a 250-watt panel. Water cooling and an aluminum heat sink were utilized by the system to keep the temperature at 20°C.

Figure 7. PV panels with and without cooling fins. **(Chen et al., 2014).**

Figure 8. Backside of the PV panel with Fins. **(Gotmare et al., 2015)**.

(A) (B)

Figure 9. A) Randomly oriented and perforated Al-fins on backside surface of PV panel B) oriented parallel Al-fins on backside surface of PV pane. **(Grubišić-Čabo et al., 2018)**

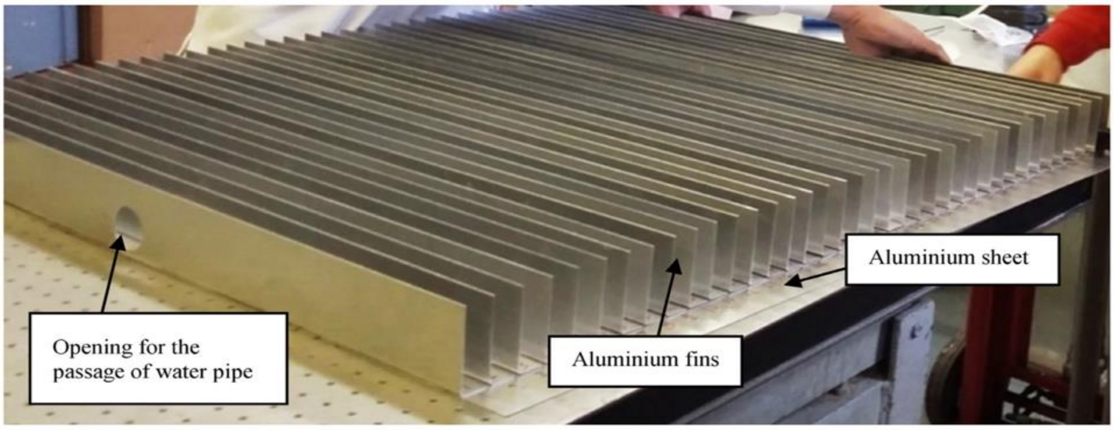


Figure 10. Aluminum heat sink. **(Idoko et al., 2018).**

According to a study by **(Parkunam et al., 2019)** in Shiraz, Iran, a PV panel with a copper heat sink and wick structure has a maximum efficiency of 12.52%, which is 4% higher than an uncooled panel. Copper fins performed aluminum due to copper's thermal conductivity, which increased voltage and current by 6.05%. Combining aluminum foil reflectors with water sprinkling cooling resulted in a 38.55% power increase. A mix of numerical, computational, and experimental research was done by **(Sedaghat et al., 2019)**. 55% of the backside of a PV panel with 6 cm fins added saw a 7.8°C drop in temperature and a 4.16% increase in yearly output. According to numerical analysis, the power output of finned panels increased by 1.8–11.8%, with a 10% increase. Despite a slight underestimation of cooling, simplified models enabled annual performance evaluation. In a study (**Hasan and Farhan**, **2019**).open-cell copper metal foam fins were used for passive cooling of polycrystalline photovoltaic (PV) panels. The longitudinal metal foam fins increased power output by 4.9% and reduced the average panel temperature by 8.4% compared to a reference panel without fins, as shown in **Fig**. **11**. The impact of heat sink fin count and material characteristics on the cooling and efficiency of a 50 W solar cell is investigated in the study **(Arifin et al., 2020)**. Due to copper's strong thermal conductivity and larger surface area, a 15-fin copper heat sink was shown to boost efficiency by 2.74% and lower temperature by 10.2°C when aluminum and copper heat sinks with 5, 10, and 15 fins were tested.

A MATLAB-based simulation study was carried out in 2020 by **(Farhan et al., 2020)** to assess how cylindrical fins affected the performance of PV panels. The findings demonstrated that by lowering the panel's temperature by 13.7°C (with active cooling) and 8.5°C (with passive cooling), the fins improved efficiency and power output. During the summer, an extra 3.32 kWh of power was produced thanks to the ideal fin proportions.**(Hudișteanu et al., 2021)** studied passive and active cooling techniques for photovoltaic panels. In a 2021 study conducted in Saudi Arabia, Hungary, and Indonesia, the results showed that heat sinks increased energy production by up to 6.49% and reduced temperatures by up to 10°C. Horizontal fins with 30 mm diameter perforations achieved the highest performance at low wind speeds and high solar radiation.
In a study **(Hasan and Farhan, 2020)**, the effect of different fin configurations on the temperature and efficiency of photovoltaic solar panels was investigated. The study was conducted in Baghdad, Iraq, and the results showed that the staggered fins reduced the panel temperature by 2-3°C and increased its efficiency by up to 4.7% **Fig. 12**. The study confirms the potential of metal foam fins in improving the performance of photovoltaic solar panels. This experimental study in Baghdad, Iraq, employed a passive cooling method. Two 50 W polycrystalline PV panels, one with longitudinal L-shaped aluminum fins and one without, were tested. The finned panel showed a 2.5 W power increase, and 15.3% efficiency compared to 14% for the unfinned panel **(Farhan and Hasan, 2020)**, **Fig. 13**. Solar cells with and without cooling were examined in an April 2021 study conducted at the Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia. According to the findings, a 10-fin heat sink lowered the temperature to 55.6°C, increasing efficiency to 12.03% and power output to 46.37 W.

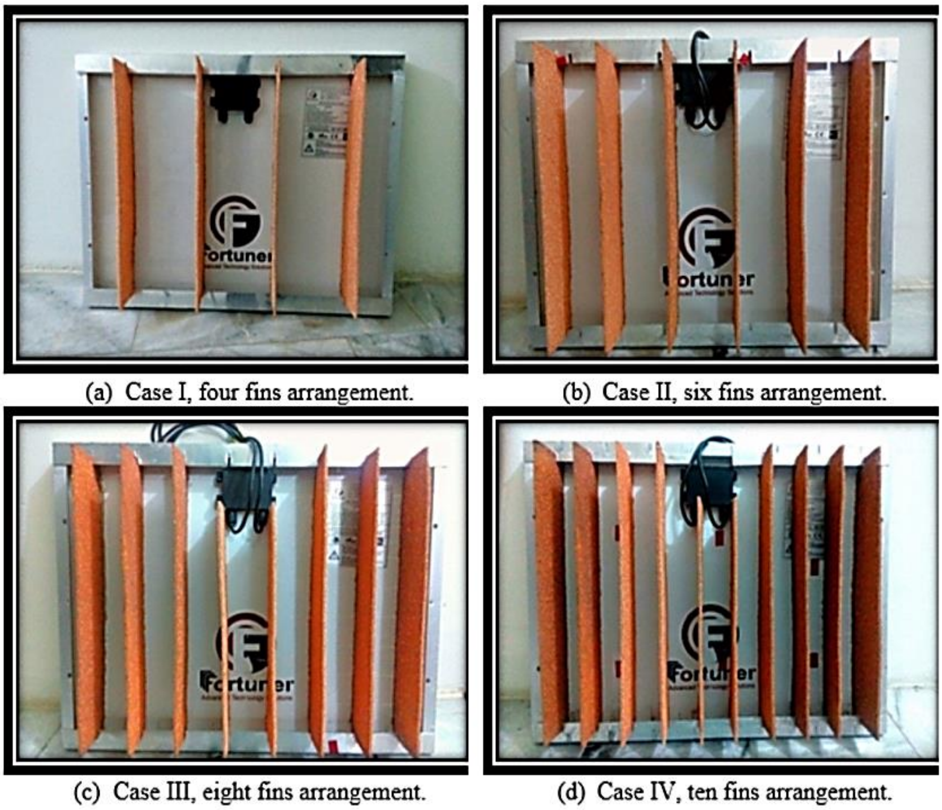

(a) Case I, four fins arrangement. (b) Case II, six fins arrangement.
(c) Case III, eight fins arrangement. (d) Case IV, ten fins arrangement.

Figure 11. Fins arrangements. (**Hasan and Farhan**, **2019**).

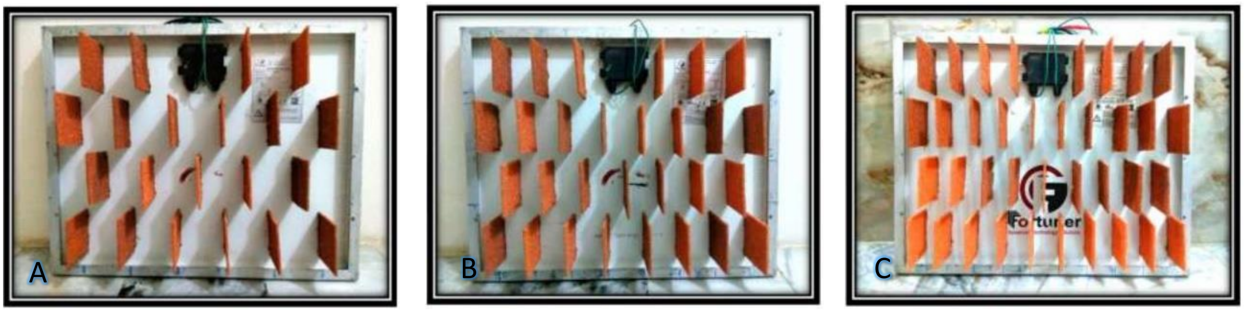


Figure 12. Staggered metal foam fin configurations. (A) First configurations. (B) Second configuration. (C) Third configuration **(Hasan and Farhan, 2020)**.

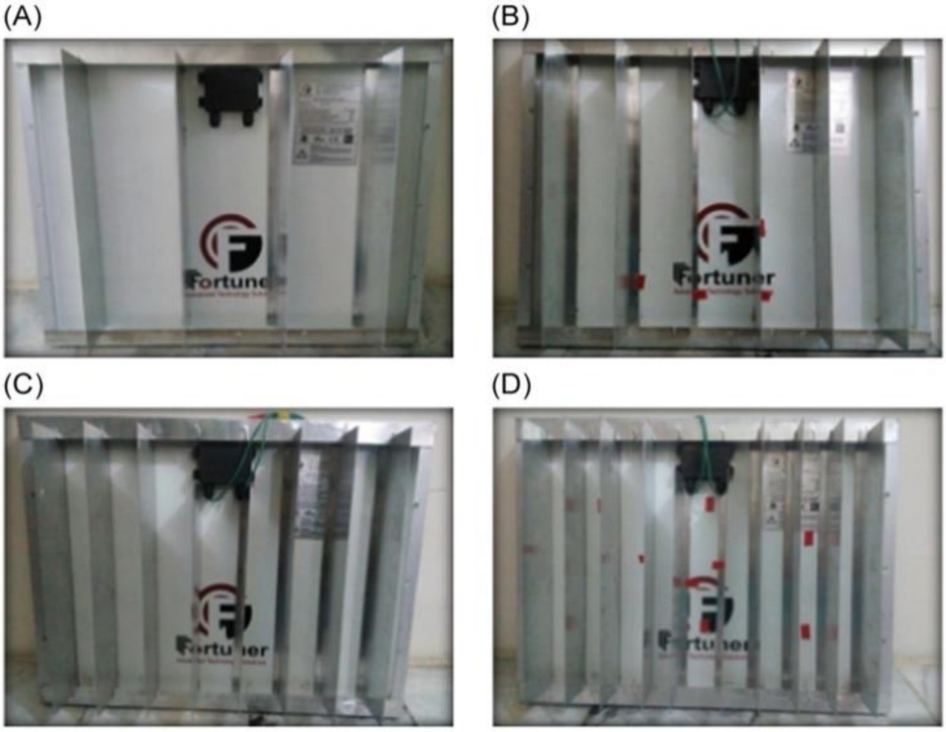


Figure 13. Longitudinal fin configurations (A) 4 Fins. (B) 6 Fins. (C) 8 Fins. (D) 10 Fins

In contrast, the cells without cooling had 64.6°C, 9.50% efficiency, and 36.63 W **(Kusuma et al., 2021)**.In Dezful, Iran, **(Firoozzadeh et al., 2022)** investigated enhancing PV panel performance with aluminium fins and mirrors. In addition to lowering panel temperature by 10°C, fins and a 30° mirror tilt produced a 13.1% efficiency jump and a 4.1W power increase.**(Hughes et al., 2011)** used solar load data from a Dubai warehouse with Insulated Concrete Forms (ICFs) in UAE circumstances to show that a finned heat pipe system, **Fig. 14**, efficiently cooled PV panels. Micro-fins, studied by **(Micheli et al., 2015)**, effectively cooled concentrating photovoltaic systems, increasing mass-specific power by up to 50% and offering a lighter, more efficient alternative to conventional heat sinks. Internal fins within a PCM-integrated PV system were studied by **(Nehari et al., 2016)**, revealing that 25–35 mm fins optimized cooling by enhancing heat transfer. Longer fins and rear fins proved less effective. **(Amr et al., 2019)** developed analytical models to study heat transfer in solar PV modules with and without fins. Their study found that fins reduced module temperature, increasing the output power from 152.6 W to 170.9 W, and improving electrical efficiency from 11.7% to 13.1%. **(Egab et al., 2020)** studied the effect of air-cooled radiators with different fin arrangements on the cooling of solar panels. Using ANSYS-Fluent models, they analyzed different numbers of fins and different slot configurations. The results showed that adding slots improved the cooling efficiency by 12%, while increasing the number of fins reduced the panel temperature by 50% **Fig. 15**.

Microscale pin-fin heat sinks for ultrahigh concentrating photovoltaic (UHCPV) systems were investigated in a study **(AlFalah et al., 2020)**. Circular pin-fins lowered the solar cell temperature by 23.28% at 10,000 suns, according to simulations, and kept it below 80°C at up to 12,000 suns. It was discovered that aluminum was an affordable material. For increased dependability and efficiency, the study recommends additional optimization. Using aluminum metal foams in a solar PVT air system resulted in a 25–40K drop in photovoltaic cell temperatures, a 3–5% increase in electrical efficiency, and a maximum thermal efficiency of 85% at the ideal thickness of the porous layer. According to **(Tahmasbi et al., 2021).** Excessive thickness decreased heat transfer. In their evaluation of a truncated multi-level fin heat sink (MLFHS) for cooling solar modules, **(Ahmad et al., 2021)** found that it improved electrical production by 2.87% and reduced temperature by 6.13%. Because of the increased air turbulence and boundary layer disruption, the MLFHS performed better than traditional heat sinks. According to **(Mustafa et al., 2022)**, incorporating porous metal foam into a ∇-shaped PVT system increased outlet air temperature, decreased PV panel temperature, and enhanced energy and exergy performance. Two CPV systems were studied experimentally and numerically by **(Yousif and Kassim, 2023)** one with fins and PCM (CPV/FPCM) and one without PCM as **Fig. 16**. The fins improved heat distribution and increased efficiency by 3.182% during peak hours, while the CPV/FPCM combination lowered solar cell temperatures by up to 6°C.

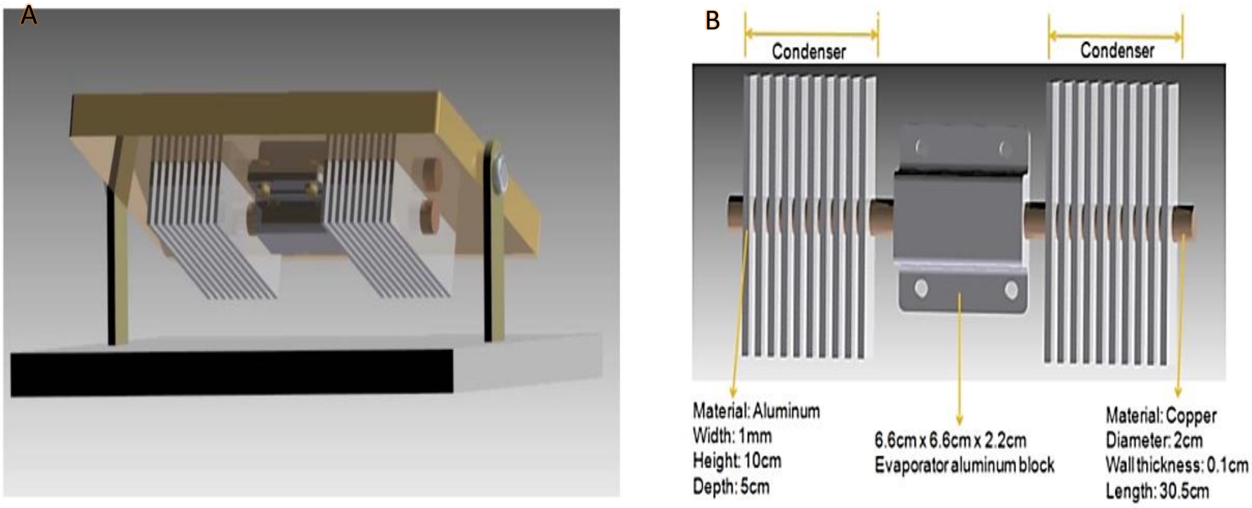


Figure 14. (A) Rear profile of finned heat pipe assembly, (B) Fin arrangement on heat pipe

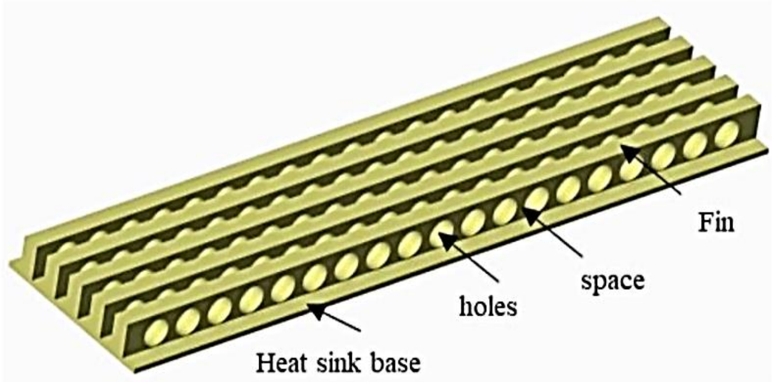


Figure 15. The geometry of the model. **(Egab et al., 2020).**

A B

Figure 16. A) Container without PCM, B) Container with PCM. **(Yousif and Kassim, 2023)**

2.2 Active Cooling Techniques

The application of pin-finned heatsinks and MWCNT nanofluids in HCPV/T systems was investigated by **(Dey et al., 2022).** According to CFD simulations, staggered circular pin-fins containing 0.5% to 2% MWCNT increased efficiency to 42.2% and lowered cell temperature by up to 18 K. as **Fig. 17.** The system, as reported by (**Teo et al., 2012)**, utilized a parallel array of ducts and an inlet/outlet manifold to ensure uniform airflow distribution, with simulation results closely matching experimental data. According to a study done in Lviv, Ukraine, aluminum heat sinks can efficiently lower the temperature of photovoltaic (PV) panels by 12.5°C, improving their efficiency. Under 1000 W/m^2 irradiation, there was a 2.6% increase in efficiency, an 18.67% increase in power output, and a 10% increase in open circuit voltage, according to CFD simulations and measurements **(Arifin et al., 2020)**,
A study conducted at the University of Ontario Institute of Technology in Oshawa, Ontario, Canada, by **(Kumar and Rosen, 2011)** evaluated a double-pass photovoltaic/thermal (PV/T) solar air heater, **Fig. 18.** The addition of fins in the lower air channel reduced the cell temperature from 82°C to 66°C, increasing thermal efficiency to 15.5% and electrical efficiency to 10.5%. The fins significantly enhanced heat transfer, improving overall system performance. **(Sukesh et al., 2015)** The study examines the heat transfer performance of a photovoltaic-thermal (PVT) absorber system. Copper proved the most effective material, with shorter, thinner fins (1-2 mm) enhancing heat extraction. The findings stress the importance of optimizing material, fin design, and absorber thickness to improve thermal efficiency. In research published in Energy Procedia 85 (2016), **(Popovici et al., 2016).**

optimized air-cooled heat sinks for PV panels using ANSYS-Fluent. The most efficient rib angle was 45°, which increased energy production and decreased panel temperature. According to simulations, rib heights of 0.05 and 0.03 meters reduced temperatures by 1 and 2 degrees Celsius, respectively **Fig. 19**. Using MATLAB simulations, **(Jobair, 2017)** discovered that triangular fins are more effective than rectangular ones at increasing the efficiency of PV panels **Fig. 20**.

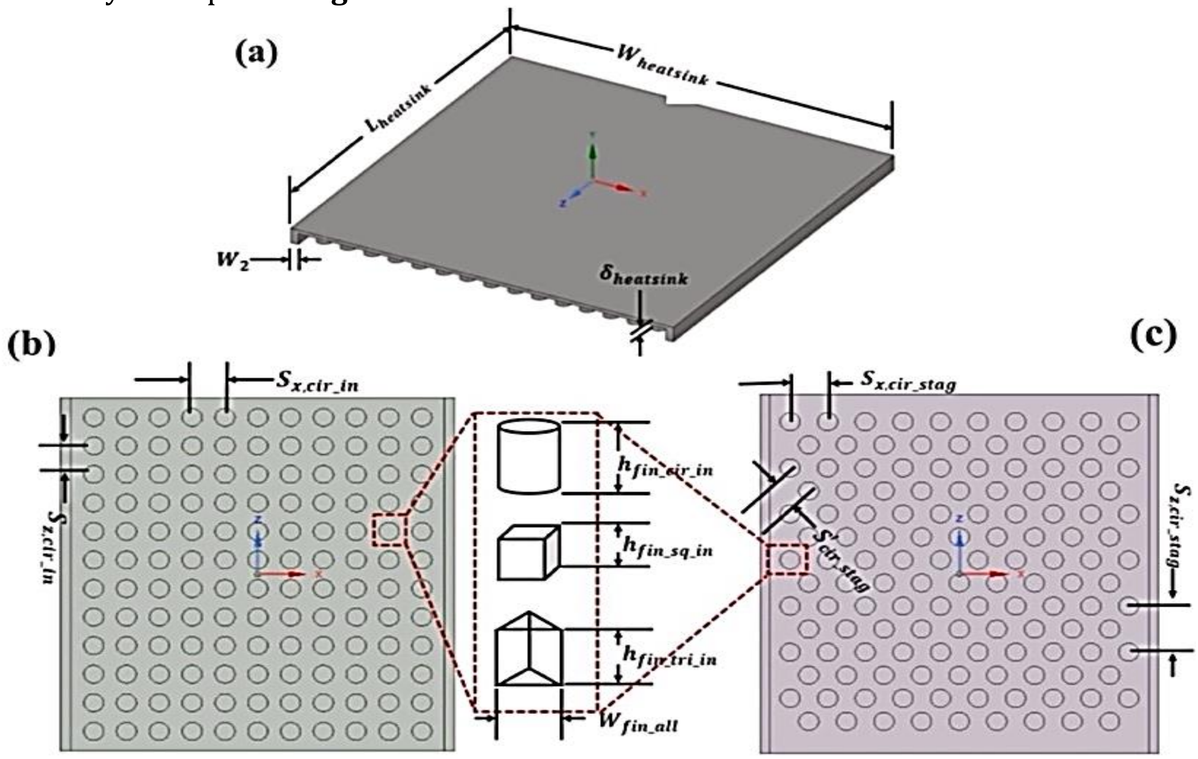


Figure 17. (a) Pin-fin heatsink (b) Pin-fin heatsink in inline arrangements (c) Pin-fin heatsink in staggered arrangements. **(Dey et al., 2022)**

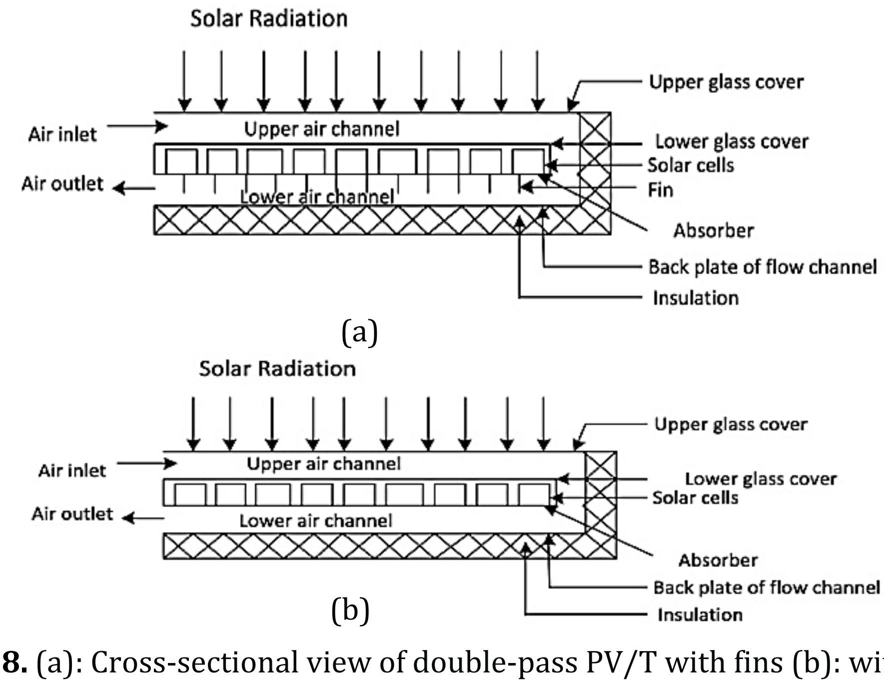


Figure 18. (a): Cross-sectional view of double-pass PV/T with fins (b): without fins. **(Kumar and Rosen, 2011).**

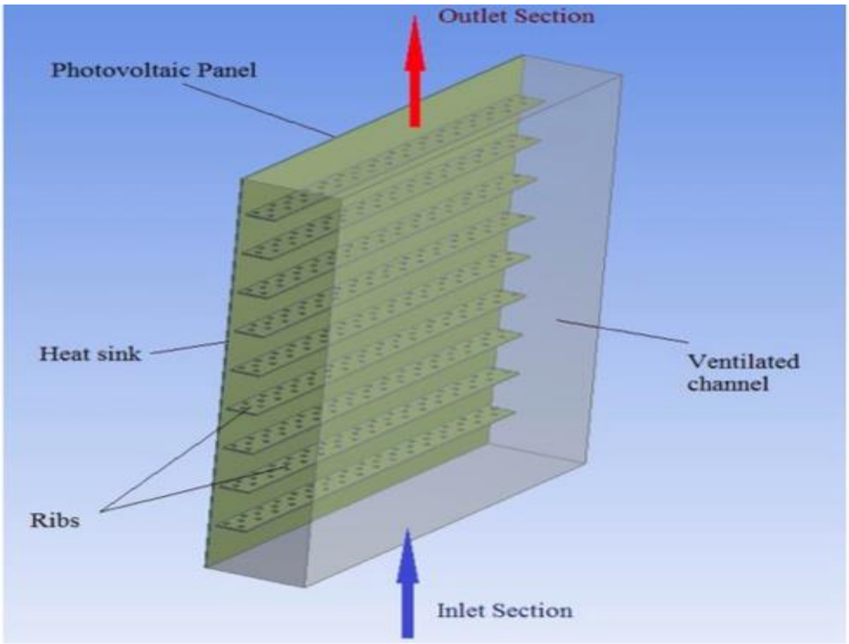
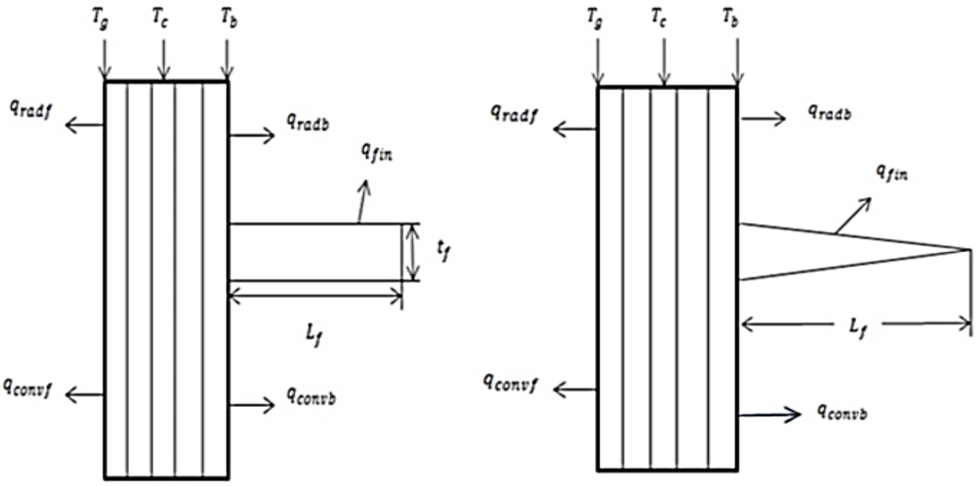


Figure 19. Ventilated PV/T with Heat Sink and Ribs. **(Popovici et al., 2016)**



(a) **(b)**

Figure 20. a) Cell with rectangular fin b) with triangular fin. **(Jobair, 2017)**

Triangular fin efficiency increased by 25% and rectangular fin efficiency by 14% when fluid velocity was increased from 0.25 m/s to 8 m/s. Efficiency was raised by 13% with longer fins and by up to 3% with thicker fins. For both kinds, however, efficiency was lowered by 19% with greater fin spacing. Triangular fins demonstrated a higher potential for performance improvement; nonetheless, experimental confirmation is necessary. **(Ajel et al., 2023)** conducted a study at the University of Technology-Iraq and Karabük University that compared PV/T collectors with spherical (Model-S) and cubic (Model-C) fins. Because of improved heat absorption and fluid contact, Model-S lowered PV panel temperatures by 9.8% and improved performance by 25.3%, highlighting the significance of flow rate optimization and fin design. Adding cooling fins and increasing airflow significantly improved system performance, achieving a maximum thermal efficiency of 56.19% and boosting PV efficiency by up to 0.81%. **(Mojumder et al., 2016)** attributed these improvements to enhanced heat transfer and better convective cooling of PV cells, **Fig. 21**.

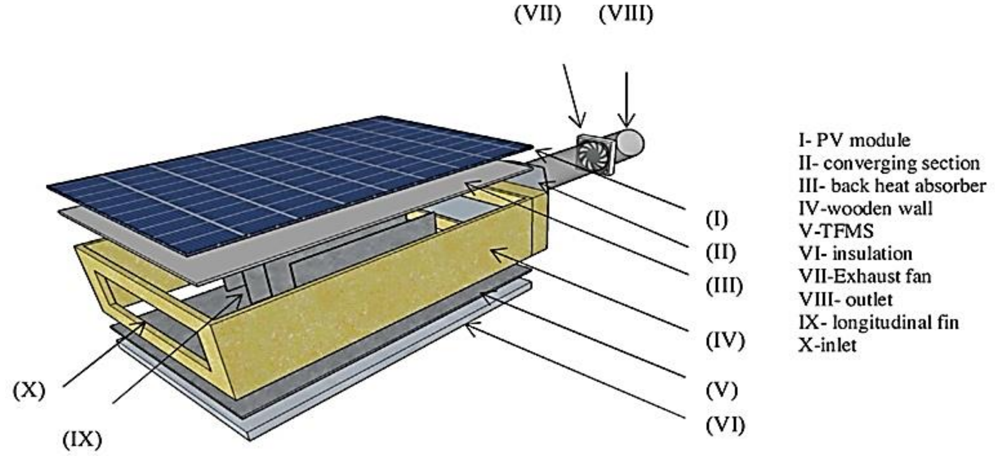


Figure 21. Schematic of the modified PV/T collector design. **(Mojumder et al., 2016)**

Through enhanced airflow and heat transmission, louvre fins increased thermal efficiency by 48% and 54% over vertical fins and unfinned units, respectively **Fig. 22**, according to a study by**(Alshibil et al., 2023)** at the Solar Energy Laboratory, Hungarian University of Agriculture and Life Sciences. In a lab setting**, (Zhao et al., 2023)** examined a polycrystalline PV panel using a solar simulator (200–600 W/m^2). Electrical efficiency stayed at roughly 16 percent, but thermal efficiency rose from 10.72% (no fins) to 53.60% (10 fins).

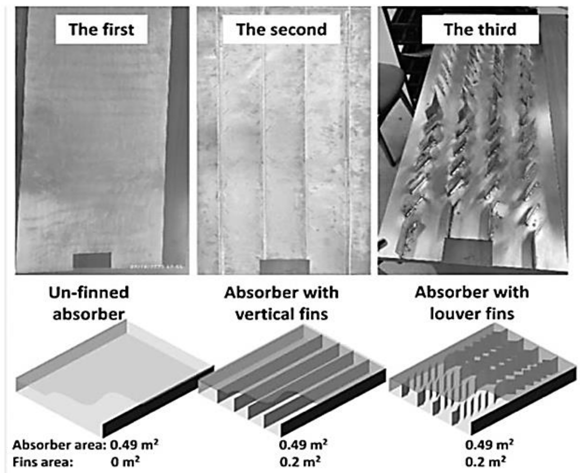


Figure 22. PV/T Absorbers: Plain, Vertical Fins, Louver Fins. **(Alshibil et al., 2023)**
Overall efficiency went up from 26.27% to 69.85%, with 5 fins achieving 61.08%. The form of fins in **Fig. 23**.

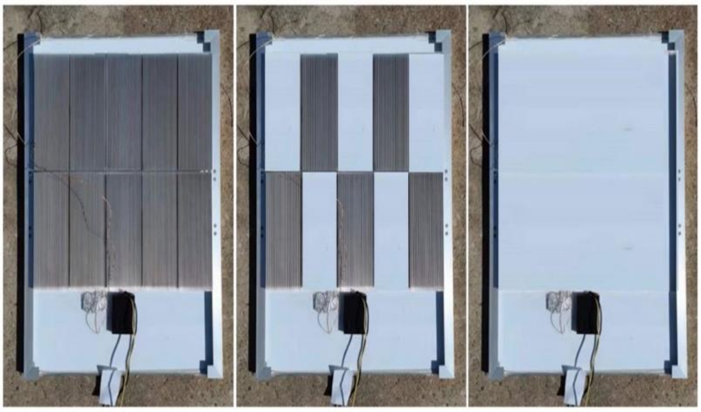


Figure 23. Fin configuration for ten, five, zero. **(Zhao et al., 2023)**

2.3 Hybrid Cooling Techniques

Three reflector materials (aluminium foil, silvered glass plane mirror, and convex spherical mirror) and four cooling systems (water sprinkling, passive heat sink, active air cooling, and closed-loop water cooling) **Fig. 24**, were tested in two locations: Busan, South Korea, and Arusha, Tanzania. The study by **(Khan et al., 2017)** found that aluminum foil was the most cost-effective option, increasing output power by up to 28.47%. Water sprinkling reduced panel temperature by 8-13.14%, boosting output by 13.14%.
CFD was utilized in a study by **(Ahmed and Nabil, 2017)** to examine cooling methods for hybrid photovoltaic-thermal (PV/T) collectors at Tlemcen University in Algeria. Under intense solar radiation, PCM-based cooling outperformed the other two systems by reducing cell temperature by 9°C and increasing electrical efficiency by 0.5%.In Zarqa, Jordan, a study **(Gomaa et al., 2020)** examined the effects of fin and water-cooling techniques on photovoltaic systems. Fins cooling decreased PV temperature by 13.4°C and increased efficiency by 7.5% over four months, while water cooling decreased PV temperature by 17.2°C and increased efficiency by 11.3%. **(Bayrak et al., 2020)** studied several cooling methods for polycrystalline photovoltaics, such as thermoelectric modules (TEMs), aluminum fins, and phase change materials (PCMs) such as $CaCl_{22}H_2O$ and biphenyls. They found that power output increased with the use of PCMs with lower melting points, resulting in higher power outputs of 47.88 W and 44.36 W, respectively.
(Wang et al., 2023) conducted research at the University of Technology in Anhui and the University of Henan Province to evaluate the impact of active- cooling and aluminum fins on PV panel performance. Using CFD models,(**Khelifa et al.**, **2023**) they identified the optimal fin height and spacing as 80 mm and 6 mm, respectively, which reduced the panel temperature by 35.38°C. This configuration increased efficiency by 2.25% and boosted electricity output by 14.6%.
A PV/T bi-fluid system cooled by air and water was examined by from the Applied Research Unit in Renewable Energies in Algeria. They tested three different configurations (no fins, 20 fins, and 40 fins) as **Fig. 25** and discovered that while thermal efficiency somewhat reduced with higher water flow rates, it rose with more fins and higher solar radiation. The maximum efficiency of 54.25% was attained with 40 fins and a water flow rate of 0.01 kg/s.

Figure 24. A) closed loop water cooled system, B) arrangement of fans for an active air-cooled system, C) solar panel with heat sinks. **(Khan et al., 2017)**

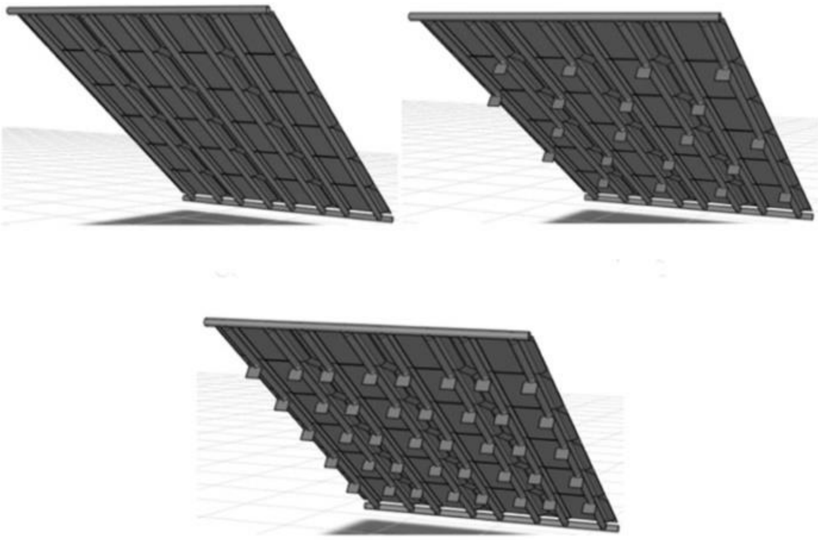


Figure 25. Schematic view of 3D PVT configurations.(**Khelifa et al**. , **2023**)

In Baghdad, Iraq, **(Hasan et al., 2019)** investigated cooling system for solar panels that included cylindrical pin fins and a wet wood wool pad. The system increased efficiency by 31.5%, output power by 32.7%, and panel temperature by 26%.By reaching 76.85 W and 9.97% efficiency, a 38.7% power increase over the uncooled module**, (Khaled et al., 2022)** In Egypt, it was discovered that a fin-cooled PV system with a rectangular helical heat exchanger worked better than uncooled and water-cooled modules **Fig. 26**.

(A) **(B)**

Figure 26. (A) A serpentine shape, (**B)** A rectangular helical shape of copper tube with fins. **(Khaled et al., 2022).**

3. CONCLUSIONS

In this review, we highlight the effectiveness of fin-based cooling systems in reducing efficiency losses caused by high solar panel temperatures. Passive cooling methods, including advanced fin geometries such as perforated, segmented, and open-cell foam fins, have proven highly effective in improving heat dissipation under natural convection. These designs significantly reduce solar panel temperatures, making them practical and energy-efficient solutions. Active cooling systems, despite their high energy consumption, achieve excellent thermal management and are suitable for areas with high solar radiation and high temperatures. Hybrid methods, which combine passive and active cooling techniques, also significantly enhance cooling performance. For example, the combination of thermoelectric modules (TEMs), phase change materials (PCMs), and aluminum fins has demonstrated exceptional cooling capabilities, improving panel performance under a variety of conditions. Computer modeling tools, including computational fluid dynamics (CFD), have played a significant role in improving fin designs. These tools enable fine-tuning of designs such as fin thickness, spacing, material selection, and airflow dynamics, ensuring efficiency and effectiveness. Experimental tests have studied the performance of innovative configurations, such as trapezoidal, cylindrical, and flared fins, especially when combined with highly conductive materials such as copper and aluminum. Studies conducted in various climate regions, including Turkey, Iraq, and Nigeria, highlight the practicality of these solutions, such as pin-shaped cylindrical fins integrated with wet wood wool pads or copper heat sinks with wick structures, especially in hot and dry regions. Future research should focus on enhancing the durability and cost-effectiveness of fin-based cooling systems, while exploring innovative materials and hybrid methods to improve thermal management. These developments will pave the way for scalable, efficient, and sustainable solar photovoltaic systems to meet the growing global demand for renewable energy.

NOMENCLATURE

Symbol	Definition	Symbol	Definition
PV	Photovoltaic	Mf	Mass Flow Rate (kg/s)
H	Efficiency(%)	PPI	Pores Per Inch (1/inch)
Pmax/ PMPP	Maximum Power Point(W)	PCM	Phase Change Material
Voc	Open-Circuit Voltage(V)	CFD	Computational Fluid Dynamics
Isc	Short-Circuit Current(A)	PVT	Photovoltaic Thermal
T	Temperature (°C, K)	HCPV/T	High Concentration Photovoltaic/Thermal
Tcell	Cell Temperature (°C)	TE	Thermoelectric
Tamb	Ambient Temperature (°C)	Perforated fins	Fins with holes/perforations
ΔT	Temperature Difference (°C)	Al	Aluminum
G	Solar Irradiance(W/m^2)	Cu	Copper
Q	Heat Transfer Rate(W)	Nanofluid	cooling fluid with nanoparticles
CR	Concentration Ratio	PMMA	Polymethyl Methacrylate (material)
Nu	Nusselt Number	MWCNT	Multi-Walled Carbon Nanotube (nanoparticle)
Re	Reynolds Number		

Credit Authorship Contribution Statement

Mustafa Muhammed Ali: Writing – review & editing, Writing – original draft, Conceptualization, Visualization. Ammar Ali: Supervision, Validation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تحسين أداء الوحدات الكهروضوئية من خلال التبريد باستخدام المبددات الحرارية والزعانف: دراسة مراجعة

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قسم الطاقة ، كلية الهندسة ، جامعة بغداد ، بغداد، العراق

الخلاصة

تقدم هذه المراجعة نظرة عامة على أبرز التطورات التي قد تدعم الباحثين في تعزيز استراتيجيات الإدارة الحرارية لأنظمة الخلايا الكهروضوئية (PV) تحت ظروف بيئية متنوعة. وفي هذا السياق، تُعد درجة الحرارة عاملًا حاسمًا يؤثر بشكل كبير على كفاءة أنظمة الخلايا الكهروضوئية، حيث يؤدي ارتفاع درجات التشغيل إلى انخفاض الإنتاج الكهربائي للألواح الشمسية. بناءً على هذه الاعتبارات، يتم استعراض التطورات الحديثة في تقنيات الإدارة الحرارية، مع تركيز خاص على أساليب التبريد المعتمدة على الزعانف .وقد تم تقييم كفاءة تقنيات التبريد السلبية والنشطة والهجينة، مع التأكيد على فعاليتها في تبديد الحرارة وتحسين أداء الأنظمة الكهروضوئية من خلال زيادة مساحة السطح المخصصة لتصريف الحرارة.ومن الجدير بالذكر أن دمج زعانف الرغوة المعدنية والمبددات الحرارية قد أظهر تحسينات كبيرة في الأداء الحراري. تُلخّص هذه المراجعة النتائج الرئيسية المستخلصة من الدراسات العددية والتحقيقات التجريبية، مع تسليط الضوء على تأثير كل من هندسة الزعانف، وخصائص المواد، والظروف البيئية على كفاءة التبريد. فعلى سبيل المثال، أظهرت التكوينات مثل الزعانف شبه المنحرفة، والزعانف الأسطوانية الدقيقة، والهياكل الرغوية، تخفيضات ملحوظة في درجات حرارة التشغيل، إلى جانب تحسينات مقابلة في الأداء الكهربائي.علاوة على ذلك، تحدد هذه المراجعة التحديات المستمرة، بما في ذلك تحسين تباعد الزعانف، ومتانة المواد، والجدوى الاقتصادية، مع اقتراح توجهات محتملة للبحث والتطوير المستقبلي.

الكلمات المفتاحية: زعانف الرغوة المعدنية، مشتت الحرارة، انتقال الحرارة، التبريد السلبي و التبريد النشط، الإدارة الحرارية.