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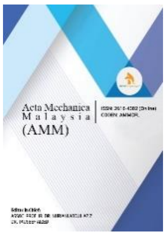

REVIEW ARTICLE

ENHANCEMENT OF PHOTOVOLTAIC AND PHOTOVOLTAIC/THERMAL SOLAR SYSTEMS PERFORMANCE: A RECENT REVIEW OF INTEGRATED COOLING STRATEGIES UTILIZING NANO PHASE CHANGE MATERIALS, NANOFLUIDS, AND FINNED STRUCTURES

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ABSTRACT

The efficiency of Photovoltaic (PV) and Photovoltaic/Thermal (PV/T) solar systems is significantly compromised by the increase in operating temperature. This review paper synthesizes recent advancements in integrated cooling strategies, focusing on the synergistic application of Nano Phase Change Materials (Nano-PCM), Nanofluids, and Finned Structures. Analysis of recent experimental and numerical studies reveals that hybrid cooling techniques, such as the combination of nanofluid circulation with finned PCM heat sinks, can lead to substantial performance improvements. Key findings indicate electrical efficiency enhancements up to 23.9% and thermal efficiency improvements reaching 83.3%, alongside significant PV module temperature reduction (e.g., 24.57 °C decrease). The paper systematically reviews the mechanisms, performance metrics, and optimization challenges associated with each cooling component and their integrated systems, providing a comprehensive overview for future research and practical implementation in high- efficiency solar energy systems.

KEYWORDS

Photovoltaic, PV/T, Cooling, Nano-PCM, Nanofluids, Finned Structures, Hybrid Cooling, Thermal Management

1. INTRODUCTION

The trend of the world to the use of sustainable sources of energy has placed solar power, specifically PV and PV/T systems, as a very important element of the energy mix. The effectiveness of such systems however is negatively proportional to the operating temperature of the solar cells (Kouravand, et al., 2022). An increase in temperature of 1 o C over the standard test condition (STC) temperature (25 C) will result in a reduction in the electrical efficiency of an average silicon PV module by about 0.4-0.5 percent (Atkin, and Farid, 2015). Thermal control is therefore critical in order to maximize the energy output and extend the life cycle of the solar modules. The three innovative methods of thermal management that have been reviewed and their combined use include Nan-PCM with better latent heat storage, Nan fluids with better heat transfer and Finned Structures with better heat dissipation. The aim is to deliver a critical review of the recent literature (Kouravand et al., 2022; Shakibi et al., 2023; Atkin & Farid, 2015; Aydın & Kayri, 2024; Bassam et al., 2023; Alktranee et al., 2025; Elsaid et al., 2025; Radhi et al., 2025; Elbreki et al., 2020; Salehi et al., 2023; Kosinska et al., 2023; Ibrahim et al., 2023), on the combined implementation of these technologies to improve the electrical and thermal performance of both PV and PV/T systems.

2. COOLING STRASTRATEGIES AND MECHANISMS.

2.1 Phase Change Materials (PCM) and Nano-PCM.

PCM takes advantage of the latent heat of fusion and absorbs the big quantities of heat but the temperature of the system is kept constant and thus they are highly efficient in passive PV cooling (Atkin & Farid, 2015). The primary issue with conventional PCM is that they lack thermal conductivity; hence, the rate of heat transfer is low, Nano-PCM: PCM is highly improved by the addition of nanoparticles (Nano-PCM) in terms of thermal conductivity and the capacity to store energy (Shakibi et al., 2023). An investigation on a PVT unit indicated that the use of Nano-PCM enhanced forced and natural convection thermal energy storage by 21.2 and 20.7 percent of pure PCM respectively (Shakibi et al., 2023).

2.2 Nanofluids

Nanofluids are suspensions of nanoparticles (e.g., Al2O3, MWCNT, Aluminum, Carbon Black) in a base fluid (e.g., water), and have better thermal properties. than the traditional coolants (Kouravand et al., 2022). They can be applied in the active cooling mechanism like PV/T collectors to remove heat in the absorber plate effectively. It was demonstrated that nanofluid application in a CPV-T system was also among the essential components in the solution of the most efficient cooling performance (Kouravand et al., 2022). Solar collectors are also improved by using hybrid nanofluids, which include MWCNT-Al2O3 (Alktranee et al., 2025). In water cooling, nanofluid experimental studies with Aluminum nanoparticles revealed an increase in solar panel efficiency and the power output by an average of 13.5 and 13.7 percent respectively (Salehi et al., 2023). In the PVT system, it was observed that the temperature decreased by 20.0 o C at noontime when Al2O3 nanofluid was used as compared to an uncooled system, and electrical conversion efficiency was increased by 15.5 percent (Ibrahim et al., 2023).

Moreover, Carbon Black nanofluids have been considered to drive pump-free solar thermal systems, where the natural convection can be used to

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achieve effective heat transfer and this indicates that passive PV/T cooler can be used (Kosinska et al., 2023).

2.3 Finned Structures

Passive elements, including heat sinks and finned tubes, are of a finned nature and are aimed at enhancing the surface area of heat transfer, which enhances heat dissipation (Atkin & Farid, 2015). P6ssive Cooling with Fins: Another new technology that employed l6pping fins and a planar reflector resulted in a large PV module temperature drop of 24.57. °C (64.3 o C 39.73 o C), increasing electrical efficiency by 9.81 to 11.2%. (Elbreki et al., 2020). This shows the efficiency of optimized fin geometry when applied to passive cooling. Integration with PCM: Fins are commonly combined with PCM to address the issue of PCM low thermal conductivity, which results in a very effective finned PCM heat sink (Kouravand et al., 2022; Atkin & Farid, 2015; Radhi et al., 2025). PCM infused graphite and aluminium fines usage was explored to control the temperature of the PV panel (Atkin & Farid, 2015). Combination with N6nofluids: Finned channels come in to play too in active cooling to promote the convective heat transfer between the nanofluid and the absorber plate (Aydın & Kayri, 2024; Bassam et al., 2023). A new plate-finned cooling system was explored on the inner part with the use of nanofluids in PVT systems (Aydın & Kayri, 2024).

3. INTEGRATED AND HYBRID COOLING SYSTEMS: PERFORMANCE ANALYSIS

The combination of these three technologies in hybrid cooling systems that are synergistic in nature leads to the greatest benefits in their performance.

Table 1: Comparative Analysis of the Twelve Selected Research Papers on Photovoltaic and Photovoltaic/Thermal Solar System

Reference	System Type	Integrated Cooling Strategy	Key Performance Enhancement
(Kouravand et al., 2022)	CPV-T	Nanofluid + Finned PCM Heatsink	Electrical Efficiency: up to 17.02%; Thermal Efficiency: up to 61.25%; PV Temp. Reduction: 26.6 °C
(Bassam et al., 2023)	PVT	Nano-PCM + Micro-fins Tube + Nanofluid	Electrical Efficiency: up to 23.9%; Thermal Efficiency: up to 17.5%; Max Thermal Efficacy: 83.3%
(Shakibi et al., 2023)	PVT	Nano-PCM + Finned Collector	Thermal Energy Storage: +21.2% (Forced Convection)
(Ibrahim et al., 2023)	PVT	Al2O3 Nanofluid + Serpentine Coil	Electrical Efficiency: +15.5%; PV Temp. Reduction: 20.0 °C
(Salehi et al., 2023)	PV	Aluminum Nanofluid + Heatsink	Electrical Efficiency: +13.5%; PV Temp. Reduction: 13.08–16.34 °C
(Elbreki et al., 2020)	PV	Lapping Fins + Planar Reflector	Electrical Efficiency: +1.39% (from 9.81% to 11.2%); PV Temp. Reduction: 24.57 °C
(Aydın & Kayri, 2024)	PVT	Inner Plate-Finned Cooling + Nanofluids	Enhanced Electrical and Thermal Performance (Experimental/Mathematical Analysis)
(Radhi et al., 2025)	PV/T	PCM + Finned Tube Heat Exchanger	Improved overall PV/T system performance
(Atkin & Farid, 2015)	PV	PCM Infused Graphite + Aluminium Fins	Regulated PV panel temperature
(Alktranee et al., 2025)	FPSC	PCM Bags + Hybrid Nanofluid	Energy Gain: max 26%
(Elsaid et al., 2025)	PV/T-PCM	PCM + Nanofluid	Enhanced solar energy absorption
(Kosinska et al., 2023)	Solar Thermal	Carbon Black Nanofluid (PumpFree)	Enhanced heat transfer via natural convection (Applicable to passive PV/T)

The experimental results demonstrate the superior performance of hybrid systems. For instance, the PVT system combining Nano-PCM, micro-fins, and nanofluid achieved the highest electrical efficiency enhancement of 23.9% (Bassam et al., 2023). The significant temperature reduction achieved by passive cooling with lapping fins (24.57 °C) and the high electrical efficiency gain from Al2O3 nanofluid cooling (15.5%) further underscore the effectiveness of these integrated strategies (Elbreki et al., 2020; Ibrahim et al., 2023).

4. VISUAL COMPARISON OF COOLING STRATEGIES

To provide a visual context for the discussed cooling strategies, this section presents a selection of figures from the reviewed literature. These images illustrate the experimental setups and showcase the performance improvements achieved through the integration of Nano-PCM, Nanofluids, and Finned Structures.

4.1 Experimental Setups

The following figure provides a schematic view of a PVT experimental rig, illustrating the typical components and their arrangement in a hybrid cooling system (Bassam et al., 2023).

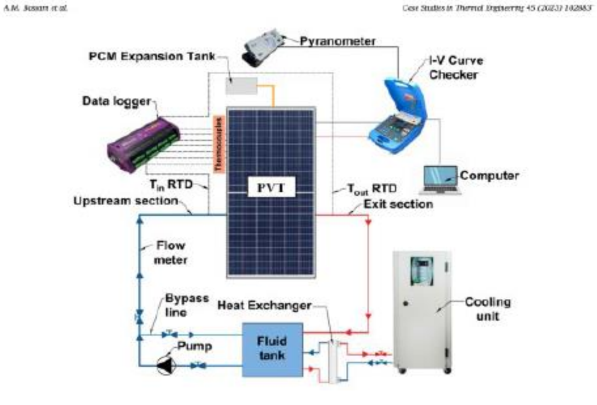

Figure 1: schematic diagram of a Photovoltaic/Thermal (PVT) experimental

Figure 1: A schematic diagram of a Photovoltaic/Thermal (PVT) experimental setup, showing the integration of a PVT collector, a fluid tank, a pump, a heat exchanger, and a cooling unit. Source:

Table 2: Photovoltaic thermal collector specifications (Bassam et al., 2023).

Module	**BS-30P**	**Absorber plate**	**640 mm × 360 mm**
Rated Max. Power (Pmax)	30W	Sheet and tube	Din: 12.7 mm
The voltage at Maximum Power (VMP)	18.31V		Din: 12.0 mm
Current Max. Power (IMP)	1.64A	Center-to-center space	Model: 70 mm 9 tube
Open-Circuit Voltage (VOC)	21.97V	PCM container	(640 × 360 ×25)mm
Short-Circuit Current (ISC)	1.75A		
Tolerance	±3%		
Max. System Voltage	1000V		
Series fuses' maximum rating	10A		

4.2 Performance Enhancement: Temperature Reduction and Efficiency Gain

The following figures demonstrate the tangible benefits of the cooling strategies. The first graph, shows the significant temperature reduction of a PV module achieved with lapping fins from (Elbreki et al., 2020). The second graph, illustrates the corresponding enhancement in electrical efficiency (Ibrahim et al., 2023).

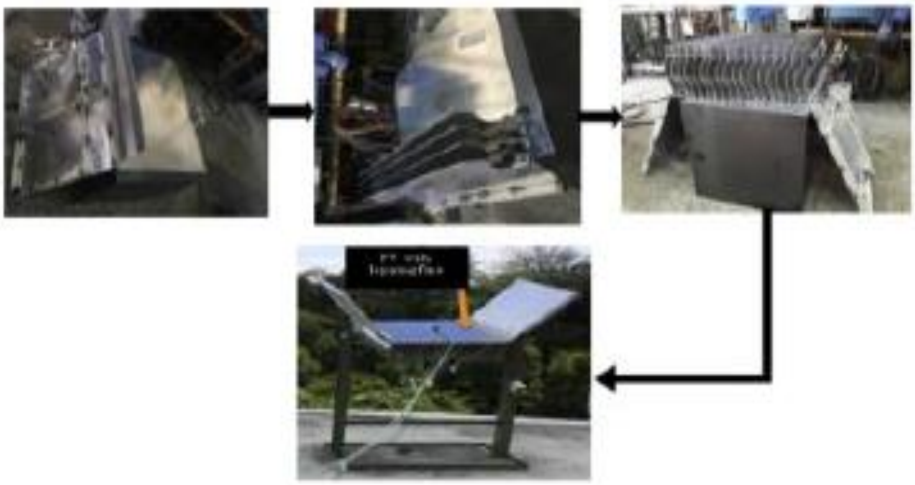

Figure 2: stages of lapping fins with planar reflector

Figure 2: A graph showing the effect of lapping fin height and spacing on PV module temperature reduction. The results indicate that an optimal fin configuration can lead to a significant decrease in the module's operating temperature. Source: (Ibrahim et al., 2023)


(a) Cold Fluid Heat Exchanger (b) Fluid Pump (c) Pyranometer (d) Temperature Sensor

(e) Flow Rate Sensor (f) Digital Multimeter (g) Polyethylene Pipes (h) Fluid Tank

Figure 3: Tools of the Experimental work

Figure 3: A comparison of the electrical efficiency of a PV panel with and without Al2O3 nanofluid cooling. The graph clearly shows a significant improvement in efficiency for the cooled panel. Source: (Ibrahim et al., 2023)

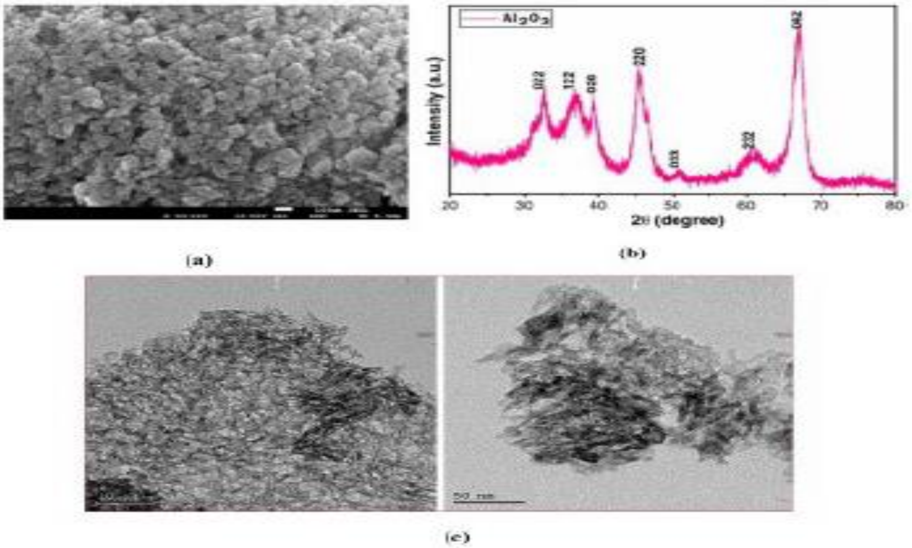

Figure 4: (a) Scanning electrical of Al2O3 (b) XRD pattern of Al2O3 (c)TEM pattern of Al2O3

5. CONCLUSION

Nan-PCM, Nan fluids, and Finned Structures combined is an extremely efficient avenue in thermal management and performance improvement of PV and PV/T systems. The literature that has been reviewed confirms that such hybrid strategies are effective in reducing the adverse impacts of high operating temperatures thereby significantly increasing both electrical and thermal deficiencies. Optimized fin geometries and other Nan fluid compositions have been found to be very effective. The future needs are to optimize the geometry of finned design, investigate new hybrid Nan fluid and economically viable and stable Nan fluid using Nan-PCM in need of long-term stability and optimize the formulations, and the possibility of the pump-free Nan fluid system.

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