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# Enhancing Electrical Power Generation of Solar Panel Through Paraffin Layer Embedded with Metal Foam and Nanoparticles

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**Abstract:** This study presents a detailed numerical study of the melting behavior and thermal performance of a paraffin-based cooling layer integrated beneath a photovoltaic (PV) solar panel to improve its electrical efficiency and thermal stability. Since excessive temperature rise is one of the major factors responsible for reducing the performance and lifespan of PV systems, the development of efficient passive cooling technologies has become increasingly important in modern renewable energy applications. In the present study, paraffin-based phase change material (PCM) is employed as a thermal energy storage medium owing to its capability to absorb the excess heat produced by the PV panel during operation. To improve conductive heat transport and quicken the melting process, ternary hybrid nanoparticles composed of $Al_2O_3$, $TiO_2$, and Ag are dispersed into the paraffin, while porous metal foam is incorporated inside the PCM container to provide highly conductive pathways for thermal diffusion. The simultaneous incorporation of hybrid nanoparticles and porous metal foam markedly improves the thermal response of the cooling layer, thereby enhancing the system's ability to regulate the operating temperature of the PV panel under working conditions. The numerical simulations are carried out using the Galerkin method, while adaptive mesh refinement and an implicit solution technique are employed to accurately capture the transient melting behavior and phase transition process within the PCM enclosure. The obtained results indicate that integrating porous metal foam together with ternary nanoparticles significantly enhances the overall thermal performance of the cooling system. The liquid fraction (LF) of the PCM increases by approximately 33.11%, indicating a significant enhancement in the melting rate and thermal energy absorption capability. Furthermore, the enhanced cooling configuration reduces the PV panel temperature by nearly 1.98% compared with the conventional case. As a consequence of the improved thermal regulation, the electrical efficiency of the PV panel increases by about 20.87% relative to the uncooled PV system. These findings confirm that integrating nano-enhanced PCM with porous metal foam provides a highly promising passive cooling strategy for improving the performance, reliability, and energy conversion efficiency of next-generation PV systems.

**Keywords:** Passive cooling; Melting process; Photovoltaic thermal management; Ternary nanoparticles; Porous metal foam; Galerkin finite element method

## 1 Introduction

The quick advancement of thermal management technologies has led to growing interest in porous metal foams due to their excellent heat transfer characteristics. These materials are widely regarded as effective thermal enhancement structures because they create interconnected conductive pathways that facilitate rapid heat diffusion and improve temperature uniformity within thermal systems. Owing to these favorable properties, porous metal foams have been extensively applied in heat exchangers, electronic cooling devices, and renewable energy technologies to boost conductive heat transfer and overall thermal performance [1–3]. In recent years, ternary hybrid nanoparticles have gained increasing attention as advanced additives for enhancing the thermophysical properties of conventional working fluids and phase change materials (PCMs). Compared with single or binary nanoparticle systems, ternary nanomaterials provide more pronounced improvements in thermal conductivity due to the synergistic interaction among different nanoparticle constituents. Their incorporation can notably enhance heat transfer performance, accelerate thermal response, and improve energy storage capability [4, 5]. PCMs are widely regarded as efficient passive thermal energy storage media. Among different types of PCMs, paraffin-based materials are commonly preferred because of their chemical stability, non-corrosive nature, and good thermal storage characteristics. To address the drawback of low thermal conductivity, considerable research has been devoted to improving PCM heat transfer characteristics through the addition of nanoparticles and metal foam. In this regard, nanoparticles enhance the effective thermal conductivity of the PCM, while porous metal foam facilitates faster heat diffusion and more uniform temperature distribution throughout the phase change process, thereby improving overall thermal performance [6–8]. Photovoltaic (PV) systems play a crucial role in sustainable electricity generation due to their ability to convert solar energy directly into electrical power. However, their performance is highly sensitive to operating temperature, and a rise in temperature significantly reduces electrical efficiency because a large portion of the absorbed solar radiation is dissipated as heat rather than being converted into useful electricity. Therefore, effective thermal management strategies are essential to maintain stable PV operation and to enhance both efficiency and service life. In this context, the use of (PCM) layers beneath PV panels has been widely recognized as a promising passive cooling approach, as PCMs can absorb excess thermal energy and stabilize the panel temperature during operation. Moreover, the integration of PCM with porous metal foam and nano-enhancement techniques has shown greater potential in further improving heat transfer performance, thereby achieving more effective temperature control and enhanced electrical and thermal efficiency under high solar irradiation conditions [9, 10].

Kant et al. [11] conducted a numerical investigation on PV integrated with RT35 PCM. They showed that both greater wind velocity and increased tilt angle contribute to a decrement in the operating temperature of the PV panels, thereby improving their overall thermal performance. Gan et al. [12] examined the thermophysical behavior of $TiO_2$/water nanofluids and reported that increasing the concentration of surfactant leads to a rise in thermal resistance. Their results further indicated that higher surfactant content negatively affects heat transfer performance. Sheikh et al. [13] investigated the use of multi-layered PCM for PV thermal controlling. Their findings revealed that the multilayer PCM configuration is highly effective in reducing TPV, achieving a maximum temperature reduction of up to 59.6 °C during peak solar radiation periods in hot climatic conditions. Stropnik and Stritih [14] investigated the performance of a PV integrated with RT28HC using both experimental analysis and numerical simulations conducted in TRNSYS software. Their results demonstrated that incorporating PCM into the PV system significantly improved thermal regulation, with the TPV reduced by up to 35.6 °C. Khanna et al. [15] investigated the effect of incorporating rectangular metal fins into a photovoltaic–phase change material system. Their outputs showed that the presence of fins significantly enhanced $\eta_{PV}$. Specifically, the electrical output increased by approximately 12.1% under high-temperature conditions and by about 6.7% under low-temperature conditions compared with the conventional configuration.

The continuous rise in PV operating temperature is still considered a major factor that negatively affects the electrical efficiency and durability of solar energy systems. Although PV technology has witnessed substantial development over recent years, a significant portion of the absorbed solar radiation is converted into heat rather than useful electrical energy, causing the temperature of the PV cells to increase considerably during operation. This thermal accumulation leads to a noticeable decline in electrical output and accelerates material degradation over long-term usage. For this reason, improving the thermal management of PV modules has become an important research topic in the field of renewable energy systems. Among the various cooling approaches proposed in the literature, PCMs have attracted considerable attention as passive cooling media. Paraffin wax is one of the most commonly used PCMs due to its chemical stability, low cost, and favorable thermal storage characteristics. However, its relatively poor thermal conductivity restricts the heat transfer process inside the PCM layer, which limits the cooling capability of the system, particularly under high solar radiation conditions. To mitigate this drawback, previous studies have attempted to improve PCM performance through the incorporation of fins, porous metal structures, or nanoparticles. Nevertheless, most of these investigations focused on applying these enhancement methods separately, while only limited attention has been directed toward combining several advanced enhancement techniques simultaneously within a single PV cooling configuration. Furthermore, earlier investigations generally emphasized either the thermal response of the PCM domain or the electrical behavior of the PV panel independently, without conducting a comprehensive analysis of the coupled thermo-electrical performance of the entire system. In addition, studies involving ternary hybrid nanoparticles integrated with porous media and finned PCM containers remain scarce in the open literature. Accordingly, the present work introduces an integrated passive cooling configuration for PV systems utilizing paraffin-based PCM enhanced with triangular fins, porous metal foam, and ternary hybrid nanoparticles consisting of $Al_2O_3$, $TiO_2$, and Ag. The triangular fins are designed to improve heat spreading and increase the effective heat transfer area inside the PCM enclosure, whereas the porous foam enhances thermal conduction and accelerates heat diffusion within the storage medium. Moreover, the dispersion of ternary nanoparticles into the paraffin contributes. The thermal and electrical performances of the proposed system are numerically investigated using the Galerkin finite element technique to accurately evaluate the transient heat transfer behavior and PV cooling performance. The significance of this study arises from its ability to provide an efficient passive thermal regulation strategy capable of lowering the operating temperature of PV panels and enhancing their electrical efficiency without additional power consumption. Compared with previously reported studies, the proposed configuration offers a more comprehensive thermal enhancement methodology by integrating multiple heat transfer improvement mechanisms into a unified design. Therefore, the findings of this work may contribute to the advancement of high-performance and sustainable PV cooling technologies suitable for future solar energy applications.

## 2 Physical Model and Thermal Management Configuration

In the present work, the Galerkin method is employed to numerically investigate the performance of a PV system combined with a paraffin-based cooling layer positioned beneath the solar panel. The primary objective of the proposed configuration is to reduce the operating temperature of the PV module and consequently improve its electrical efficiency through an advanced passive thermal management approach. To enhance the thermal performance of the PCM layer, the paraffin container is equipped with triangular fins designed to increase the heat transfer surface area and promote more effective thermal distribution inside the storage domain. Furthermore, porous metal foam is incorporated into the PCM enclosure to overcome the low thermal conductivity of pure paraffin and accelerate conductive heat transport throughout the melting region. In addition, ternary hybrid nanoparticles composed of $Al_2O_3$, $TiO_2$, and Ag are dispersed within the paraffin. The thermal behavior and cooling performance of the proposed system are evaluated under three different operating conditions, including a conventional PV panel without cooling, a PV system integrated with pure PCM, and a PV system utilizing nano-enhanced phase change material (NEPCM) combined with porous metal foam. A comprehensive comparison among these cases is performed in terms of temperature distributions, LF evolution, melting characteristics, and PV efficiency using detailed contours and performance plots. The obtained results are utilized to assess the effectiveness of the proposed cooling strategy and to demonstrate the advantages of integrating porous structures and hybrid nanoparticles within the PCM layer for growing the thermal regulation and electrical performance of PV systems. The geometric configuration of the PV panel coupled with the PCM container is presented in Figure 1.

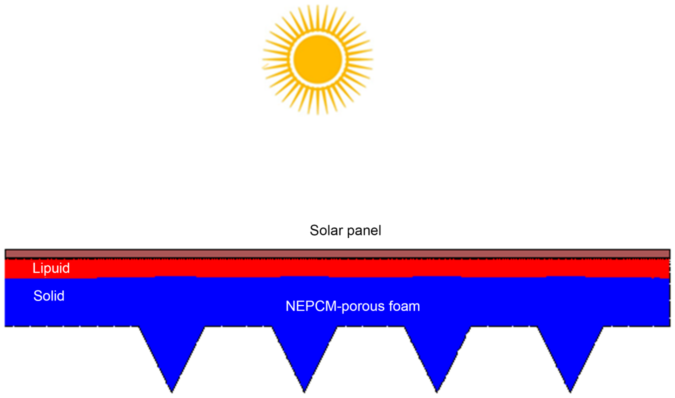

**Figure 1.** Layout of photovoltaic (PV) module integrated with nano-enhanced phase change material (NEPCM) and porous metal foam cooling layer

In the present thermal model, the PV panel is treated as a unified solid layer that exchanges heat with the surrounding environment through its upper surface, while simultaneously transferring thermal energy to the PCM layer positioned beneath it. As a result, the computational domain is divided into two thermally coupled regions: the PV section and the PCM enclosure. The heat transfer mechanisms and thermal interaction between these two domains are governed by the mathematical formulations and conservation equations [16, 17].

$$\begin{cases} T > (T_m + T_0) \Rightarrow & \lambda = 1 \\ (-T_0 + T_m) < T < (T_0 + T_m) \Rightarrow & \lambda = (1 - (-T + 0.5T_0 + T_m)/T_0) \\ T < (T_m - T_0) \Rightarrow & \lambda = 0 \end{cases} \tag{1}$$

$$\begin{gathered} \left(\frac{\partial^2 T_{PCM}}{\partial x^2} + \frac{\partial^2 T_{PCM}}{\partial y^2}\right) k_{eq} = (\rho C_p)_{eq} \frac{\partial T_{PCM}}{\partial t} + \frac{\partial \lambda}{\partial t}(L\rho)_{Tnf}, k_{eq} = ((1-\gamma)k_{GI} + \gamma k_{Tnf}), \\ (\rho C_p)_{eq} = \left((1-\gamma)(\rho C_p)_{GI} + \gamma (\rho C_p)_{Tnf}\right) \end{gathered} \tag{2}$$

$$
\begin{aligned}
&\left( \left(C_p\right)_{PV} \rho_{PV} \right) \frac{\partial T_{PV}}{\partial t} = \left(T_\infty - T_{PV}\right) \frac{h_w}{\delta_{PV}} + \left(1 - \eta_{PV}\right) \frac{\alpha_{PV}}{\delta_{PV}} G \\
&+ k_{PV} \left( \frac{\partial^2 T_{PV}}{\partial y^2} + \frac{\partial^2 T_{PV}}{\partial x^2} \right) - \varepsilon_{PV} \frac{\sigma}{\delta_{PV}} \left( T_{PV}^4 - T_{sky}^4 \right), \\
&\eta_{PV} = 14.1\% \left[ 1 - 0.0042 \left( T_{PV} - T_{ref} \right) \right]
\end{aligned}
\tag{3}
$$

Paraffin RT-25 is selected as the PCM in the present study owing to its favorable thermal energy storage characteristics. The thermophysical properties employed in the numerical simulations were obtained from the literature [18]. The addition of these nanoparticles enhances the thermal conductivity and thermophysical properties of the PCM, leading to more efficient thermal energy absorption and heat diffusion during the melting process. The mathematical relations and effective property formulations adopted for the ternary NEPCM are based on established correlations [19]. The required property formulations have been presented previously [19]. In the present study, the melting behavior of PCM is numerically investigated as a passive cooling approach for controlling the operating temperature of the PV panel and improving its electrical performance. The thermal regulation capability of the PCM layer is analyzed through transient simulations to evaluate its effectiveness in absorbing excess heat generated during PV operation. The computational analysis is performed using the FLEXPDE software package. To improve the accuracy of the numerical results and accurately capture the motion of the melting front, an adaptive mesh refinement method is applied across the entire computational domain. In addition, the governing equations are solved using the Galerkin finite element approach, which provides high computational stability and reliable accuracy for modeling transient thermal transport phenomena. More comprehensive information regarding the numerical procedure and implementation of the FLEXPDE solver can be found in previous studies [17]. The thermal boundary conditions are selected to represent practical operating conditions of PV systems exposed to solar radiation. The solar irradiation intensity, ambient temperature, and convective heat transfer coefficient associated with wind effects are specified as 600 W/m$^2$, 25 °C, and 10 W/m$^2$·K, respectively.

## 3 Results and Discussion

In the current investigation, the Galerkin finite element method is employed to analyze the behavior of a PV system integrated with a paraffin-based PCM layer located beneath the solar panel. The PCM layer is utilized as a thermal management medium to absorb excess heat generated during PV operation, thereby reducing TPCM and improving performance. Additionally, porous metal foam is embedded within the PCM layer to overcome the low thermal conductivity of paraffin and accelerate heat diffusion throughout the storage region. Furthermore, ternary hybrid nanoparticles composed of $Al_2O_3$, $TiO_2$, and Ag are dispersed into the paraffin to develop NEPCM with superior thermal properties. The combined influence of these enhancement techniques on the PV cooling performance is evaluated through three different operating conditions, namely: a conventional PV system without cooling, a PV system cooled using pure PCM, and a PV system employing NEPCM integrated with porous metal foam. The thermal behavior and PV performance are comparatively assessed using contour distributions, temperature variations, and efficiency plots to demonstrate the effectiveness of the offered thermal regulation approach.

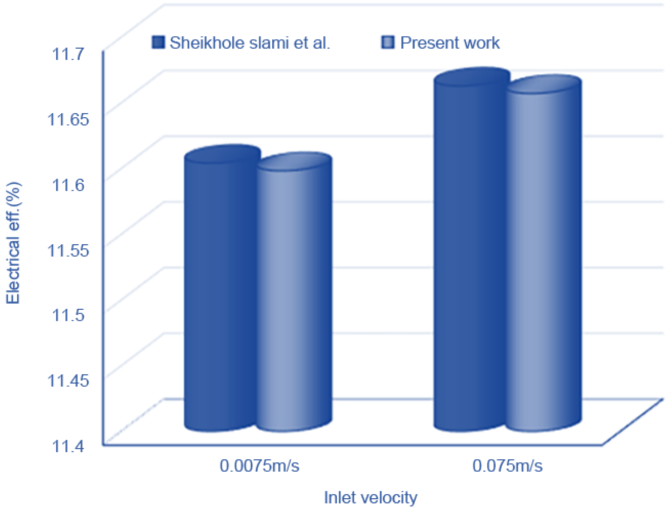

**Figure 2.** Comparison of present numerical results with available literature for model validation [20]

To verify the accuracy and reliability of the present numerical model, the developed computational code was validated against previously published results [20]. The same numerical procedure and governing equations were adapted to reproduce the reference case, and the obtained outputs were compared in terms of LF evolution during the melting process. As illustrated in Figure 2, an excellent agreement can be observed between the present numerical predictions and the published data, confirming the validity and robustness of the implemented model for simulating phase change heat transfer phenomena within the PCM domain. Furthermore, to enhance the accuracy and stability of the numerical solution, an adaptive mesh refinement approach is adopted, as shown in Figure 3. The primary objective of utilizing the adaptive grid approach is to generate a denser and more refined mesh distribution near the melting front region, where large temperature gradients and rapid phase transition variations occur. This strategy allows the numerical model to capture the transient movement of the solid–liquid interface with higher accuracy while reducing computational errors associated with coarse mesh distributions. In addition, the adaptive grid method enhances the overall computational efficiency by concentrating the mesh elements only in critical regions instead of uniformly refining the entire computational domain. Consequently, the adopted meshing approach contributes significantly to improving the quality and accuracy of the melting process simulation within the PCM enclosure.

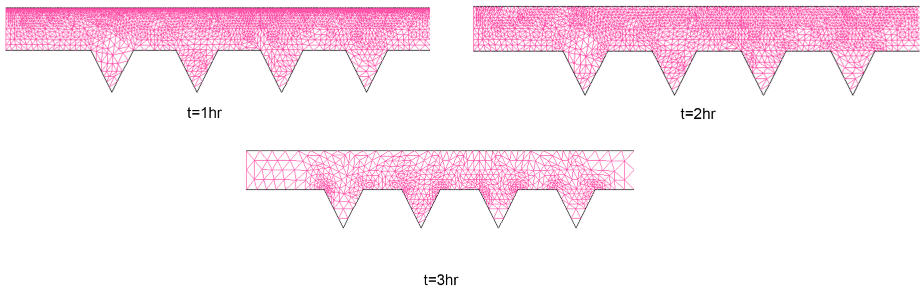

**Figure 3.** Variation of mesh refinement over time

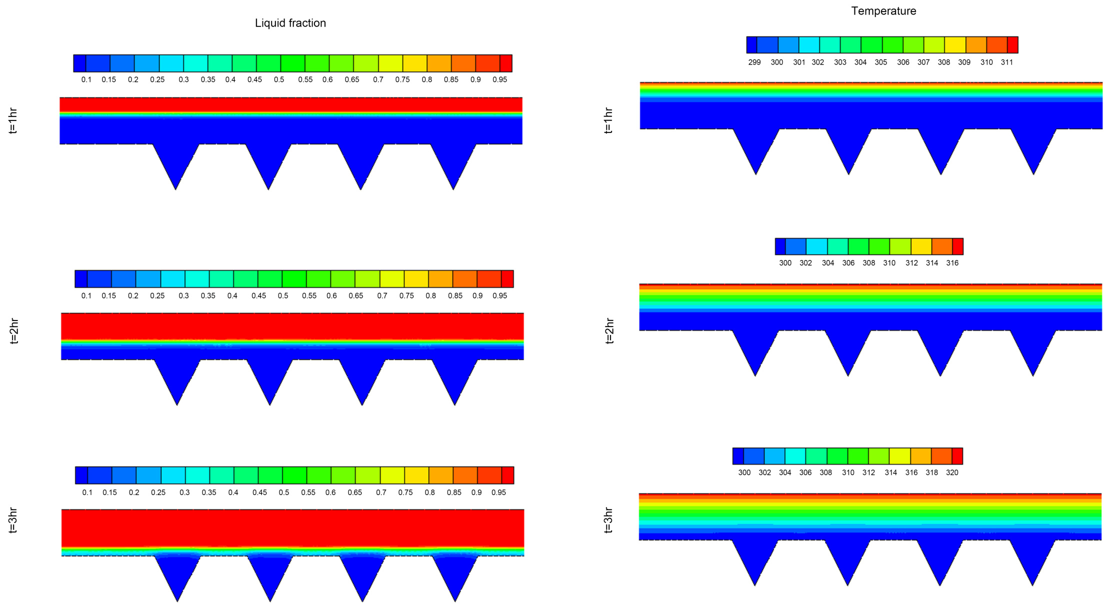

**Figure 4.** Liquid fraction (LF) and temperature contours in the pure paraffin phase change material (PCM) domain

To examine the effect of adding ternary nanoparticles and porous metal foam to the paraffin layer, the thermal behavior and melting characteristics of the PCM domain are presented in Figures 4 and 5 through temperature and LF contour plots. In addition, the evolution of the melting front during the phase transition process is presented in Figure 6. The obtained contour distributions provide a clear visualization of the transient heat transfer process within the PCM tank and demonstrate the effectiveness of the proposed thermal enhancement techniques in accelerating the melting behavior and improving heat absorption capability. The results indicate that the paraffin layer gradually absorbs heat generated from the PV panel located above the PCM container. Consequently, the upper region of the paraffin becomes warmer first, causing the melting process to initiate near the top surface adjacent to the PV panel. As the heating process continues, the melting front propagates downward toward the lower regions of the enclosure due to the continuous transfer of thermal energy from the solar panel to the PCM layer. It can also be observed that the incorporation of ternary additives and metal foam significantly accelerates the movement of the melting front compared with the pure paraffin case. This phenomenon is primarily attributed to the increase in effective thermal conductivity within the PCM region, which enhances conductive heat transfer and facilitates faster thermal diffusion throughout the storage domain. As time progresses, both the temperature of the paraffin and the amount of melted PCM continuously increase. The average temperature of the paraffin rises from 306.99 K to 314.94 K when porous metal foam and nanoparticles are incorporated into the PCM layer, confirming the improvement in thermal transport capability. Furthermore, complete melting of the nano-enhanced PCM occurs after approximately 10025.89 s, whereas the pure paraffin configuration still exhibits incomplete melting under the same operating period. After three hours of operation, the LF of the pure paraffin case reaches only 0.75, while the NEPCM–porous foam configuration achieves complete melting. These findings demonstrate that the melting rate improves by nearly 33.11% when transitioning from pure paraffin to the nano-enhanced porous foam system.

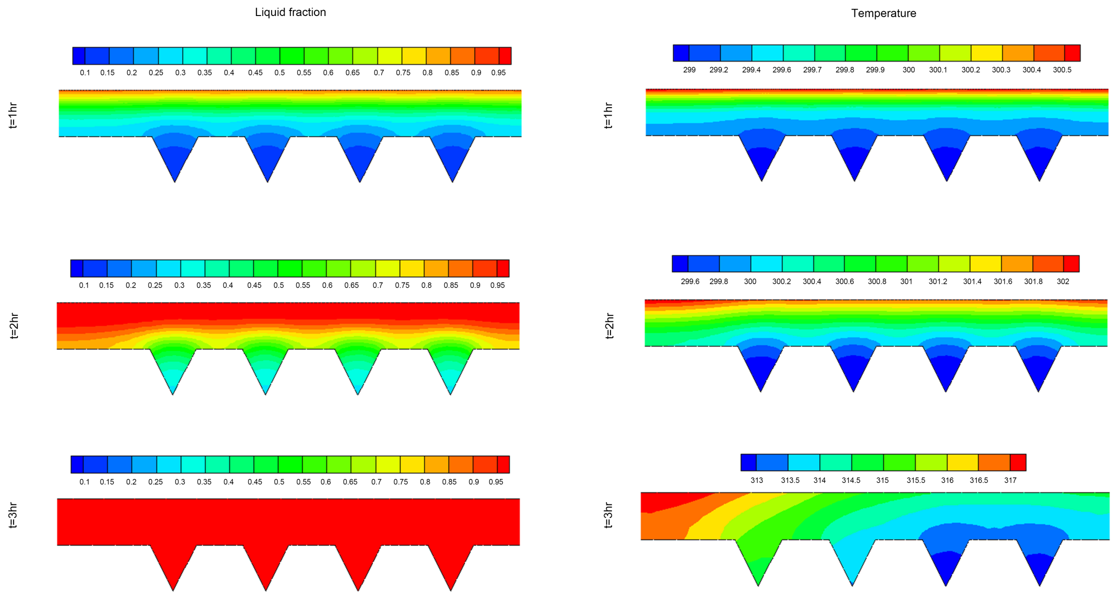

**Figure 5.** Liquid fraction (LF) and temperature contours in the nano-enhanced phase change material (NEPCM)-porous foam domain

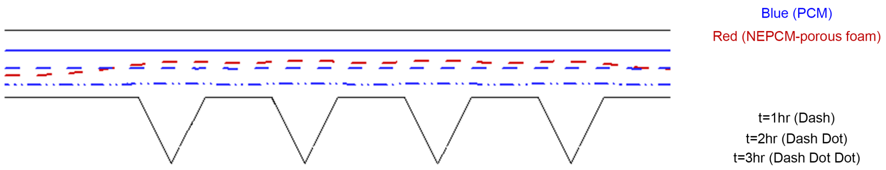

**Figure 6.** Evolution of melting front in the phase change material (PCM) for the studied cases

Figure 7 depicts the temporal variation of the average values of the main thermal and electrical parameters. The outputs reveal that both the paraffin temperature and the PV panel temperature gradually increase with operating time due to continuous exposure to solar radiation. Similarly, the LF increases progressively as the melting process advances inside the PCM domain. In contrast, the PV efficiency depicts a decreasing trend with time because the increase in PV operating temperature negatively affects the electrical conversion. However, the addition of porous metal foam and ternary nanoparticles substantially improves the thermal management performance of the system by increasing the LF and enhancing heat absorption within the PCM layer. This improved cooling capability effectively reduces the PV operating temperature, which consequently contributes to maintaining higher PV efficiency compared with the conventional and pure PCM cases.

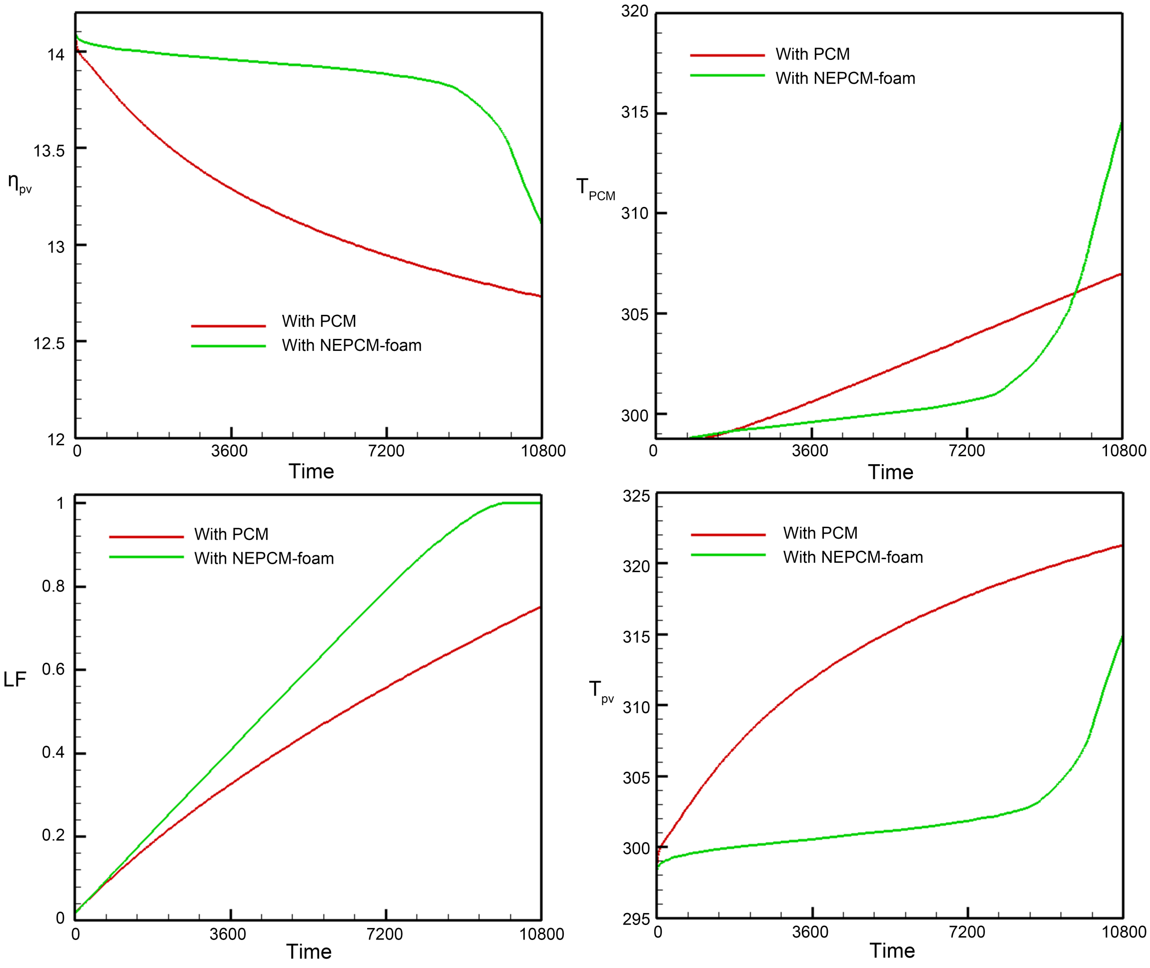

**Figure 7.** Temporal evolution of $T_{PV}$, $T_{PCM}$, liquid fraction (LF) and $\eta_{PV}$

Figure 8 presents the variation of the LF and TPCM for the two investigated PCM configurations, namely pure paraffin and nano-enhanced PCM integrated with porous metal foam. The results clearly indicate that adding ternary nanoparticles together with porous metal foam markedly enhances the thermal performance of the PCM layer. The highly conductive porous structure accelerates heat diffusion within the paraffin domain, leading to a faster melting process and a more uniform temperature distribution. As a result, the LF increases by 33.11% compared with the pure paraffin case, indicating a considerable enhancement in the melting rate and thermal energy absorption capability. In addition, the average temperature of the PCM region increases by nearly 2.48%, which confirms the effectiveness of the proposed enhancement techniques in strengthening conductive heat transfer throughout the storage layer. Figure 9 compares the performances of the PV system under different cooling conditions, including the uncooled PV panel, PV cooled with pure paraffin, and PV cooled using nano-enhanced PCM combined with porous metal foam. The results reveal that integrating a paraffin container beneath the PV panel plays a significant role in reducing the operating temperature of the solar cell due to the latent heat absorption capability of the PCM during the melting process. Consequently, the PV temperature decreases by approximately 9.01%, leading to an improvement in PV efficiency of about 17.39% compared with the conventional uncooled panel. Moreover, further enhancement is achieved after incorporating ternary nanoparticles and porous metal foam into the PCM layer. The improved thermal conductivity of the NEPCM-porous foam system allows more efficient heat extraction from the PV panel, resulting in an additional temperature reduction of nearly 1.98% relative to the pure PCM configuration. This enhanced cooling performance contributes directly to improving the electrical conversion efficiency of the PV system by approximately 2.96%. Overall, the implementation of the proposed advanced cooling strategy leads to a total decrement in PV operating temperature of around 10.82%, while the PV efficiency increases by nearly 20.87% compared with the uncooled case.

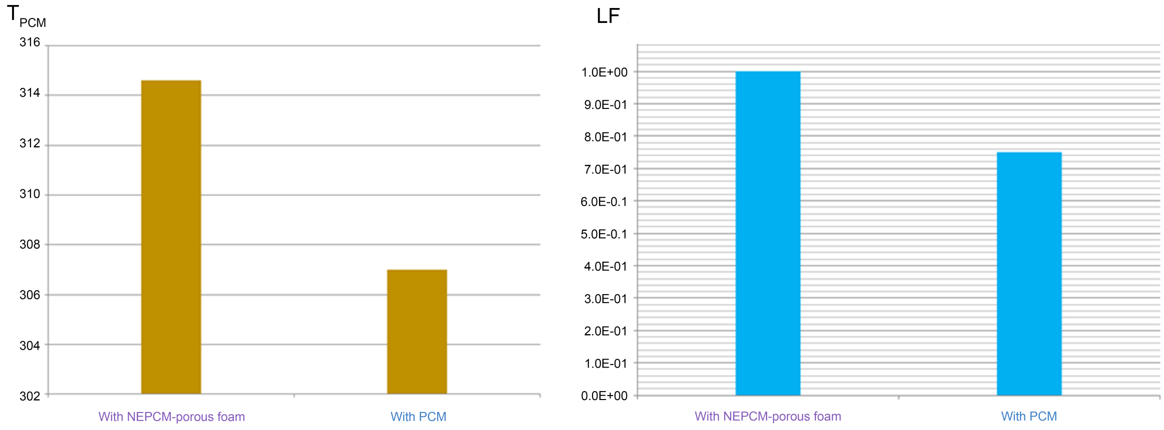

**Figure 8.** Impact of enhancement techniques on phase change material (PCM) temperature and melting fraction at 3 h

Note: LF: liquid fraction; NEPCM: nano-enhanced phase change material.

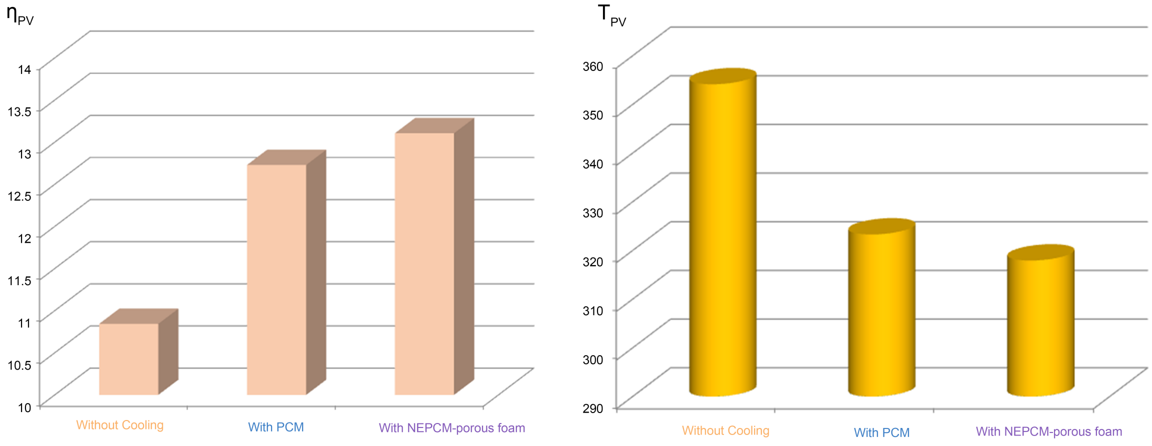

**Figure 9.** Comparison of photovoltaic efficiency and temperature across different configurations after 3 h

Note: NEPCM: nano-enhanced phase change material.

## 4 Conclusion

The present study successfully demonstrated the effectiveness of integrating a paraffin-based PCM layer beneath the PV panel. The thermal behavior of the proposed configuration was numerically investigated using the Galerkin method, considering the combined effects of triangular fins, metal foam, and ternary hybrid nanoparticles dispersed within the PCM. The incorporation of triangular fins contributed to enhancing heat transfer by increasing the contact surface area inside the storage domain, while the porous foam significantly accelerated thermal conduction within the paraffin layer. A comparative analysis was conducted for three operating conditions, including a conventional PV system without cooling, a PV system cooled by pure PCM, and a PV system employing nano-enhanced PCM integrated with porous metal foam. The obtained outputs showed that the combined cooling strategy effectively reduced the PV operating temperature and consequently improved the $\eta_{PV}$ of the solar panel compared with the other investigated cases. The findings of the present study demonstrate that integrating NEPCM and porous metal foam beneath the PV panel significantly improves the thermal regulation performance of the system. The temperature of the paraffin layer was observed to increase from 306.99 K to 314.94 K due to the enhancement of thermal conduction resulting from the incorporation of ternary nanoparticles and porous foam. The improved conductive heat transfer accelerated the melting behavior of paraffin, leading to complete melting after approximately 10025.89

s. In contrast, the pure paraffin case exhibited a slower thermal response, where the LF reached only 0.75 after three hours of operation, while the NEPCM–porous foam configuration achieved full melting under the same conditions. The results further proved that the melting rate increased by nearly 33.11% when transitioning from pure paraffin to the nano-enhanced porous foam configuration. Moreover, the operation of the offered cooling system substantially reduced the operating temperature of the PV panel, resulting in a temperature reduction of approximately 10.82% compared with the uncooled PV system. This thermal improvement directly contributed to enhancing the electrical performance of the panel, where the PV efficiency increased by nearly 20.87%. In addition, the incorporation of nanoparticles and metal foam improved the LF and thermal response of the PCM by about 33.11% and 2.48%, respectively. The enhanced thermal management capability also reduced the PV temperature by approximately 1.98% relative to the pure PCM case, leading to an additional improvement in electrical efficiency of around 2.96%. Overall, the obtained results confirm that the combined application of ternary nanoparticles and metal foam within the PCM layer provides an effective passive cooling strategy for improving the thermal stability and energy conversion efficiency of PV systems.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The author declare no conflicts of interest.

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