



Transient Thermal Analysis of a Metal Foam-Assisted Ternary Nano-Enhanced Phase Change Material Cooling System for Photovoltaic Thermal Management

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Abstract: Photovoltaic (PV) panels experience significant efficiency degradation under elevated operating temperatures, making effective thermal regulation an important challenge for sustainable solar energy systems. Passive cooling techniques based on phase change materials (PCMs) have attracted considerable attention because of their latent heat storage capability; however, the low thermal conductivity of conventional paraffin-based PCMs restricts heat transfer performance during transient melting processes. This study investigates the thermal behavior of a PV cooling system employing paraffin enhanced with Ag–Al₂O₃–TiO₂ ternary nanoparticles and porous metal foam. A transient numerical model was developed using a Galerkin finite element approach combined with an adaptive mesh refinement technique to accurately capture the movement of the melting front and the associated thermal gradients. The thermal performance of the proposed cooling configuration was evaluated through temperature distribution, liquid fraction evolution, and PV electrical efficiency under transient operating conditions. The results showed that the incorporation of ternary nanoparticles and porous metal foam significantly enhanced heat diffusion and accelerated the melting process within the PCM domain. The liquid fraction increased by approximately 38.66% compared with the conventional PCM configuration, indicating more effective latent heat absorption and faster phase transition behavior. It was also found that the enhanced cooling system reduced the PV panel temperature by nearly 12.75% and improved the PV electrical efficiency by approximately 26.75% relative to the uncooled case. In addition, the incorporation of pure paraffin beneath the PV panel reduced the panel temperature by about 9.94%, confirming the effectiveness of latent heat storage for passive thermal regulation. The results indicate that the simultaneous utilization of ternary nano-enhanced PCM and porous metal foam provides an effective passive cooling strategy for PV thermal management. The proposed configuration offers improved thermal energy dissipation, enhanced phase change heat transfer characteristics, and promising potential for the development of high-performance solar energy systems.

Keywords: Photovoltaic thermal management; Phase change material; Ternary nanoparticles; Metal foam; Latent heat storage; Transient heat transfer

1 Introduction

Phase change materials (PCMs) are extensively recognized as effective heat storage media due to their ability to absorb and release substantial amounts of heat through latent heat during melting and solidification processes. However, despite their strong storage capability, most conventional PCMs exhibit naturally low thermal conductivity [1–3]. The inclusion of nanoparticles within the PCM improves its effective thermal conductivity, thereby strengthening heat transfer and accelerating the melting process. In parallel, the inclusion of porous metal foam enhances thermal diffusion by creating interconnected conductive pathways and increasing the effective heat transfer surface area inside the storage medium, leading to improved overall thermal performance [4–6]. In recent years, advanced techniques for enhancing the thermal performance of PCM have been widely incorporated into photovoltaic (PV) thermal management systems. Since the performance of PV panels is highly sensitive to temperature, excessive heat accumulation during operation can significantly reduce power output and negatively affect long-term reliability. For this reason, PCM-based cooling systems have gained considerable attention as

an effective passive approach for regulating PV temperature and improving overall energy conversion efficiency. In particular, the integration of nano-enhanced PCMs together with porous structures has shown superior thermal regulation capability, as it promotes faster heat absorption, improves thermal conductivity, and helps maintain lower operating temperatures even under high solar irradiation conditions [7–10].

Namuq et al. [11] experimentally examined the integration of straight porous fins within a PCM layer to enhance the thermal management performance of a photovoltaic-thermal system. Their findings showed that incorporating porous fins effectively improved both heat transfer and energy conversion characteristics, leading to increases of approximately 3.1% in photovoltaic conversion efficiency (η_{PV}). Meng and Zhang [12] investigated a triangular tube system filled with CuO–paraffin nanocomposites to enhance thermal performance. Their results indicated that both the inlet temperature and the flow rate had a significant impact on overall performance. For example, Mahamudul et al. [13] utilized commercial RT35 PCM on the rear side of a PV panel and observed a notable thermal performance improvement; Selimefendigil et al. [14] conducted a study on η_{PV} of module equipped with straight porous fins. Their findings indicated that the integration of porous fins into the PV system contributed to an improvement in the overall performance of the PV module. Arifin et al. [15] investigated a PV combined with paraffin layer for thermal management purposes. Their results confirmed that the incorporation of PCM significantly declines the operating temperature of the PV panel by approximately 24–28 °C. In addition, their techno-economic analysis revealed that battery storage represents the dominant cost component of the system, accounting for about 39.6% of the total investment.

Although numerous cooling techniques have been proposed for PV systems, thermal accumulation within PV panels during high solar irradiation remains a critical issue that negatively affects electrical efficiency and operational durability. A large number of previous investigations have focused on the application of PCMs as passive cooling media because of their ability to absorb excessive heat through latent heat storage. Despite the promising thermal storage capability of paraffin-based PCMs, their practical performance is still constrained by weak thermal conductivity, which limits heat diffusion and slows the melting process under continuous thermal loading. To improve the thermal response of PCM cooling systems, different enhancement approaches such as nanoparticle dispersion and porous metal structures have been examined in earlier studies. However, most of the available publications have concentrated on either mono-nanoparticle additives or standalone porous foam configurations. Furthermore, limited attention has been directed toward the joint influence of ternary nanoparticles and metal foam within PCM for PV cooling applications. In addition, the transient phase change behavior and thermal characteristics of such integrated systems under realistic operating conditions have not been sufficiently explored in the literature. Accordingly, a clear research gap exists regarding the simultaneous implementation of Ag–Al₂O₃–TiO₂ ternary nanoparticles and metal foam in paraffin-based cooling systems for advanced PV thermal regulation. The novelty of the present work arises from the development of an integrated passive cooling configuration employing RT-25 paraffin enhanced with Ag–Al₂O₃–TiO₂ ternary nanoparticles and porous metal foam simultaneously. This hybrid enhancement strategy is intended to intensify thermal conductivity, improve heat propagation, and accelerate the melting process within the PCM domain, thereby providing more efficient temperature control for the PV panel. Another important contribution of the present study is the detailed transient numerical investigation of the melting process using a Galerkin approach combined with adaptive meshing. The adaptive grid technique enables accurate tracking of the moving melting front and provides precise prediction of the thermo-physical behavior inside the cooling layer during operation. The importance of this work also lies in its ability to combine multiple thermal enhancement mechanisms within a single cooling structure. The simultaneous utilization of ternary nanoparticles and porous foam is expected to produce superior thermal regulation compared with conventional PCM cooling systems or single-enhancement techniques reported in earlier publications. Consequently, the proposed configuration can achieve lower PV operating temperatures, faster thermal energy absorption, and higher electrical efficiency, making it a promising solution for the development of high-performance and sustainable PV energy systems.

2 Mathematical Modeling of the Photovoltaic–Phase Change Material Cooling System

The present study focuses on improving the performance of a PV panel through the integration of a passive cooling system positioned beneath the solar module. A paraffin-based PCM container is incorporated at the bottom of the panel to absorb excess thermal energy generated during operation and to reduce the temperature rise of the PV surface. Since the electrical efficiency of solar panels decreases significantly at elevated temperatures, efficient thermal management becomes essential for maintaining stable and high-performance operation. The melting behavior of the PCM is numerically investigated using a Galerkin-based finite element method. During the phase transition process, paraffin absorbs a considerable amount of thermal energy in the form of latent heat, which contributes to lowering the operating temperature of the PV panel. However, the inherently low thermal conductivity of pure paraffin restricts heat transfer rates and slows down the melting process. To overcome this limitation and improve thermal energy storage performance, metal foam and ternary nanoparticles consisting of Ag, Al₂O₃, and TiO₂ are incorporated into the PCM domain. The simultaneous application of porous metal foam and nano-additives enhances

conductive heat transfer, accelerates the melting rate, and improves thermal diffusion throughout the enclosure. An adaptive mesh refinement technique is also implemented to accurately track the movement of the melting front and to resolve the steep thermal gradients that develop during the transient phase change process. This numerical approach improves the precision of the simulation and provides a more reliable prediction of the thermo-physical behavior inside the cooling layer. The thermal performance of the proposed configuration is evaluated through temperature and liquid fraction contours, which illustrate the heat propagation and phase transition characteristics within the PCM region. In addition, comparative analyses of PV temperature and electrical efficiency are presented to examine the effectiveness of the enhanced cooling strategy. Figure 1 depicts the proposed cooling configuration, including the paraffin enclosure with rectangular fins mounted beneath the PV to improve thermal energy transfer between the PV module and the cooling domain.

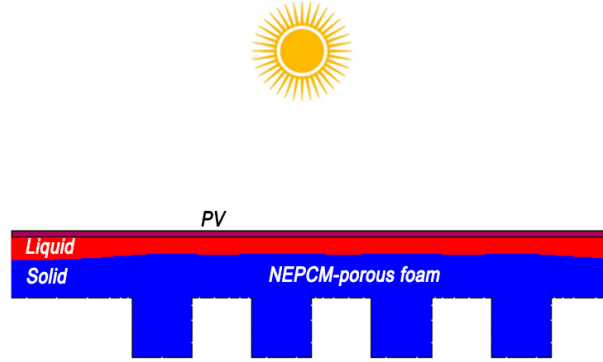


Figure 1. Schematic representation of photovoltaic (PV) panel with nano-enhanced phase change material-based porous foam thermal management system

In the present analysis, the PV panel is treated as a homogeneous layer exposed to heat dissipation from its upper surface, while simultaneously exchanging thermal energy with the PCM region located beneath it. Therefore, the computational model is composed of two thermally coupled domains, including the PV section and the PCM enclosure, which are governed by the conservation equations reported in the studies [16–18].

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

$$\eta_{PV} = \eta_{ref} [1 - \beta_{ref} (T_{PV} - T_{ref})], \quad \beta_{ref} = 0.0042(1/K), \quad \eta_{ref} = 14.1\%$$

$$\begin{aligned} &(\gamma (\rho C_p)_{Tnf} + (1 - \gamma) (\rho C_p)_{GI}) \frac{\partial T_{PCM}}{\partial t} \\ &= (\gamma k_{Tnf} + (1 - \gamma) k_{GI}) \left(\frac{\partial^2 T_{PCM}}{\partial y^2} + \frac{\partial^2 T_{PCM}}{\partial x^2} \right) + (L\rho)_{Tnf} \frac{\partial S}{\partial t} \end{aligned} \quad (2)$$

$$\begin{cases} T > (T_m + T_0) \Rightarrow & S = 0 \\ (-T_0 + T_m) < T < (T_0 + T_m) \Rightarrow & S = (-T + 0.5T_0 + T_m) / T_0 \\ T < (T_m - T_0) \Rightarrow & S = 1 \end{cases} \quad (3)$$

$$LF = 1 - S$$

Paraffin RT-25 is selected as the PCM employed in the present study [19]. In order to improve the thermal response and heat transfer capability of the PCM, ternary nanoparticles are uniformly incorporated into the paraffin matrix. The addition of these nano-additives enhances the effective thermal conductivity and overall thermo-physical performance of the storage medium. The mathematical correlations and formulations related to the ternary nano-enhanced phase change material (NEPCM) are adopted from the studies [20, 21].

$$\rho_{Tnf} = (1 - \phi_1) [(1 - \phi_2) ((1 - \phi_3) \rho_f + \rho_{s3} \phi_3) + \rho_{s2} \phi_2] + \rho_{s1} \phi_1 \quad (4)$$

$$(\rho C_p)_{Tnf} = (1 - \phi_1) [(1 - \phi_2) ((1 - \phi_3) (\rho C_p)_f + (\rho C_p)_{s3} \phi_3) + (\rho C_p)_{s2} \phi_2] + (\rho C_p)_{s1} \phi_1 \quad (5)$$

$$\frac{k_{\text{nf}}}{k_{\text{f}}} = \frac{k_{\text{s3}} + 2k_{\text{f}} - 2\phi_3 (k_{\text{f}} - k_{\text{s3}})}{k_{\text{s3}} + 2k_{\text{f}} + \phi_3 (k_{\text{f}} - k_{\text{s3}})} \quad (6)$$

$$\frac{k_{\text{hnf}}}{k_{\text{nf}}} = \frac{k_{\text{s2}} + 2k_{\text{nf}} - 2\phi_2 (k_{\text{nf}} - k_{\text{s2}})}{k_{\text{s2}} + 2k_{\text{nf}} + \phi_2 (k_{\text{nf}} - k_{\text{s2}})} \quad (7)$$

$$\frac{k_{\text{Thnf}}}{k_{\text{hnf}}} = \frac{k_{\text{s1}} + 2k_{\text{hnf}} - 2\phi_1 (k_{\text{hnf}} - k_{\text{s1}})}{k_{\text{s1}} + 2k_{\text{hnf}} + \phi_1 (k_{\text{hnf}} - k_{\text{s1}})} \quad (8)$$

$$(\rho L)_{\text{Thnf}} = (\rho L)_{\text{f}} (1 - \phi_1) (1 - \phi_2) (1 - \phi_3) \quad (9)$$

In the present study, the phase transition behavior of the PCM is numerically analyzed to assess its effectiveness in regulating the operating temperature of the PV panel and enhancing its electrical performance. The computational analysis is performed using FLEX PDE software, in which an adaptive meshing technique is applied to precisely track the transient melting interface and thermal gradients during the simulation process. The governing equations are discretized and solved using the Galerkin approach, providing reliable numerical stability and high computational accuracy. Additional information regarding the numerical procedure and software implementation can be found in the previous publications of Sheikholeslami [17]. The applied solar radiation intensity, ambient temperature, and wind-induced convective heat transfer coefficient are taken as 600 W/m^2 , $25 \text{ }^\circ\text{C}$, and $10 \text{ W/m}^2\cdot\text{K}$, respectively. Thermal insulation is imposed on all side boundaries of the system, whereas the upper surface of the PV panel is subjected to both convective and radiative heat losses to represent realistic environmental conditions. The transient numerical simulation is conducted over a period of three hours to examine the thermal response and cooling performance of the proposed system during operation.

3 Results and Discussion

The performance of the proposed PV cooling system is evaluated through a detailed transient analysis of the melting process inside the PCM domain. The obtained numerical results provide a comprehensive understanding of the heat transfer characteristics and phase transition behavior occurring within the cooling layer during panel operation. Particular attention is given to the influence of metal foam and ternary nanoparticles on thermal regulation and PV efficiency enhancement. To illustrate the thermo-physical behavior of the system, the results are presented in terms of temperature distribution and liquid fraction contours, which describe the evolution of heat propagation and melting front movement inside the PCM region. In addition, the temporal variations of key performance parameters, including PV temperature, PCM temperature, liquid fraction, and electrical efficiency, are carefully analyzed and discussed. Comparative assessments are also carried out to examine the effectiveness of pure PCM and nano-enhanced porous PCM configurations in controlling panel temperature and improving energy conversion efficiency. The numerical findings reveal that the incorporation of porous metal foam and Ag–Al₂O₃–TiO₂ ternary nanoparticles significantly improves the thermal response of the cooling layer by accelerating the melting process and enhancing heat transfer within the PCM domain. As a consequence, lower PV operating temperatures and higher electrical efficiencies are achieved compared with the conventional uncooled and pure PCM cases.

Figure 2 presents the validation procedure performed to evaluate the reliability of the developed numerical model. For this purpose, the configuration reported in the previous study [22], which consists of a PV layer coupled with a paraffin domain, was re-simulated using the present Galerkin-based numerical code. The obtained outputs were compared with the published data, and a close agreement was observed between both sets of results. This consistency confirms the correctness of the implemented numerical formulation and demonstrates the capability of the present model to accurately predict the thermal behavior and melting characteristics of the PCM system. Figure 3 illustrates the adaptive mesh distribution employed during the numerical simulation. It can be observed that the regions containing denser computational grids continuously shift within the domain according to the instantaneous position of the melting front. This adaptive meshing strategy is essential because the melting interface is associated with strong temperature gradients and rapid phase transition behavior, which require higher spatial resolution for accurate numerical prediction. Therefore, increasing the mesh density near the melting front enhances the precision of capturing the transient heat transfer and phase change phenomena while also improving computational efficiency by avoiding unnecessary refinement in regions with lower thermal variations.

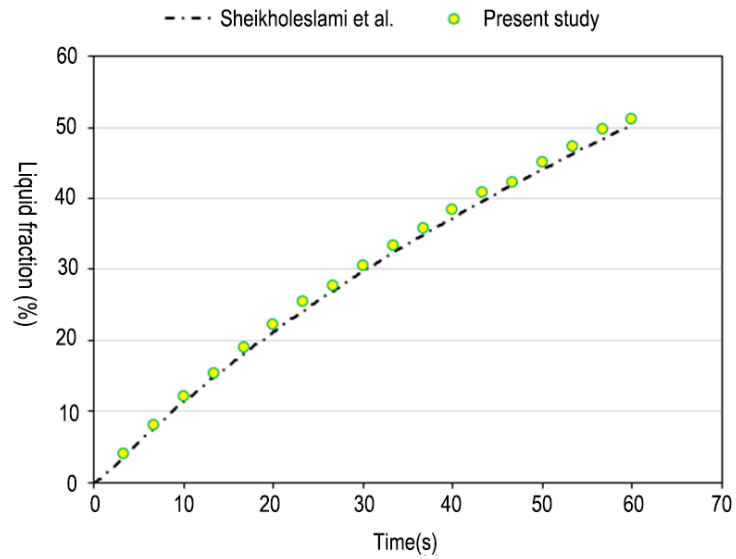


Figure 2. Verification of the numerical model using benchmark results from previous study [22]

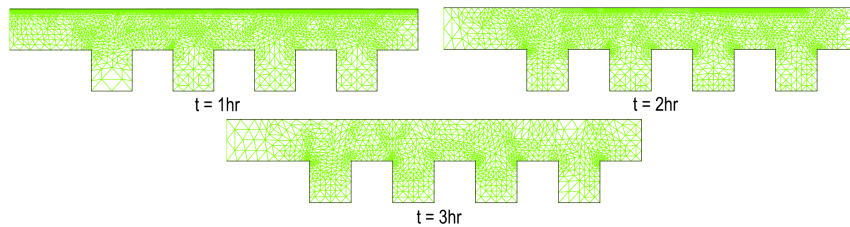


Figure 3. Adaptive mesh structure at three different time levels

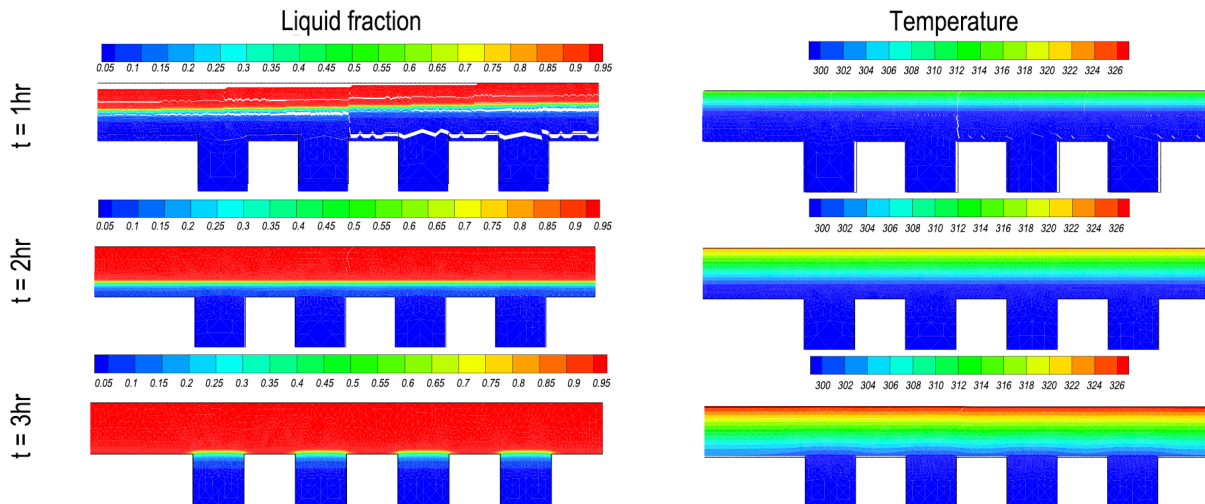


Figure 4. Thermal and phase change behavior of pure phase change material (PCM): Liquid fraction (LF) and temperature distribution

Figure 4 and Figure 5 present the contours of liquid fraction (LF) and temperature distribution within the paraffin domain for the investigated cooling configurations, while Figure 6 illustrates the evolution of the melting front during the transient process. The obtained results provide a detailed description of the phase transition behavior and thermal propagation inside the PCM enclosure under continuous solar heating conditions. It is observed that the melting process initiates near the upper region of the enclosure, where the PV panel acts as a heated surface. As time

progresses, the melting front gradually moves downward toward the bottom region of the container. This behavior is mainly attributed to the dominant role of conductive heat transfer resulting from the relatively small dimensions of the enclosure and the direct thermal interaction between the PV panel and the PCM layer. In addition, the isotherms tend to follow the geometric shape of the container, which further confirms the dominance of conduction within the storage domain. The influence of ternary nanoparticles and porous metal foam becomes clearly noticeable in the enhanced configuration. The incorporation of these additives intensifies internal heat diffusion and accelerates thermal transport throughout the paraffin region, leading to a more uniform temperature distribution and faster phase transition. Consequently, the melting behavior becomes more pronounced, and the movement of the melting front occurs at a significantly higher rate compared with the pure PCM case. After three hours of operation, the liquid fraction increases from 0.72 in the conventional paraffin configuration to complete melting (LF = 1) when metal foam and nanoparticles are introduced. Furthermore, the average paraffin temperature rises from 308.73 K to 316.41 K. These results clearly indicate that the combined utilization of ternary nanoparticles and metal foam substantially improves the thermal energy absorption capability of the PCM layer.

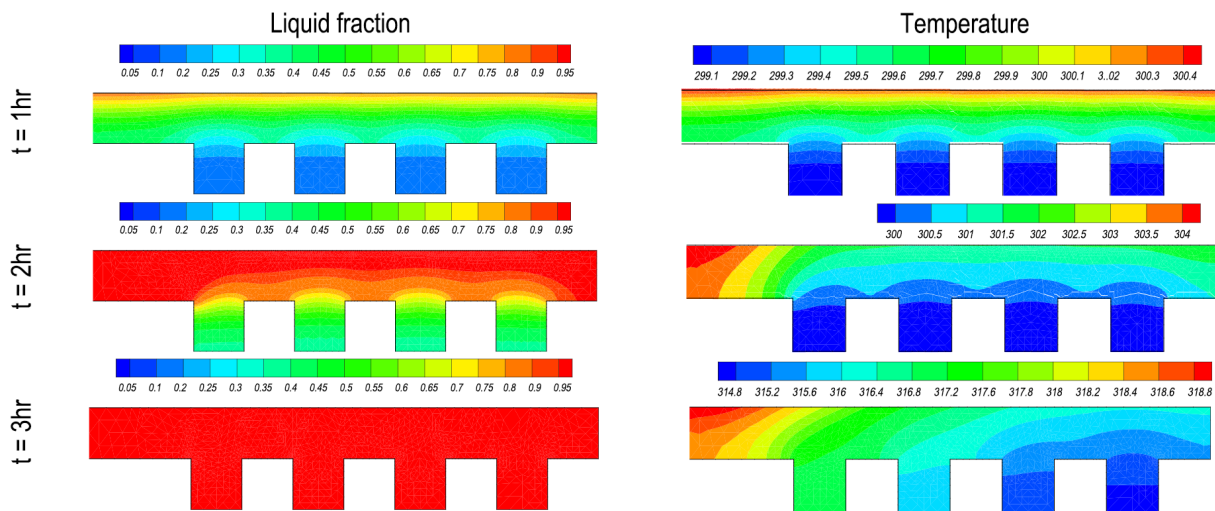


Figure 5. Thermal and phase change behavior of nano-enhanced phase change material-porous foam: Liquid fraction (LF) and temperature distribution

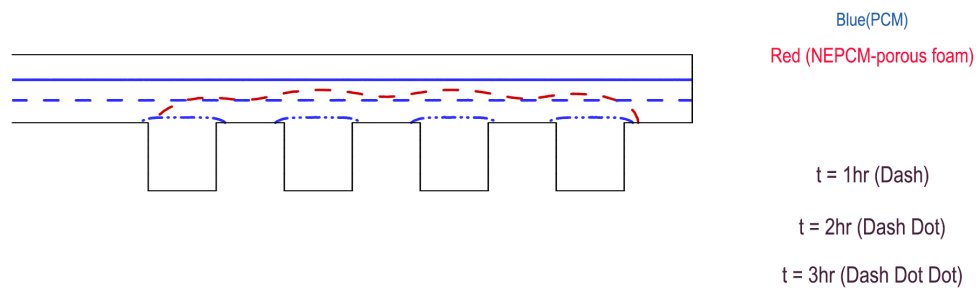


Figure 6. Temporal comparison of solid-liquid interface for all cases

Note: PCM = phase change material; NEPCM = nano-enhanced phase change material.

Figure 7 portrays the temporal variation of the main thermo-physical and electrical parameters of the system. The results demonstrate that both paraffin temperature and PV panel temperature increase gradually with time because of continuous solar energy absorption. However, the enhanced PCM configuration containing metal foam and ternary nanoparticles exhibits a more effective thermal response. In this case, the paraffin temperature increases more rapidly due to intensified heat transfer inside the enclosure, while the PV panel temperature is significantly reduced owing to improved thermal regulation. The liquid fraction also shows a continuous increase over time as the melting process progresses. The presence of porous foam accelerates the phase transition process and results in a greater LF compared with the pure PCM configuration. In contrast, the PV electrical efficiency exhibits a decreasing trend with time because the rise in panel temperature negatively affects electrical conversion performance. Nevertheless, the incorporation of nanoparticles and porous foam effectively mitigates this thermal deterioration by maintaining lower

PV operating temperatures, thereby leading to noticeable enhancement in PV efficiency throughout the operating period.

Figure 8 portrays the variations of LF and temperature within the paraffin domain after three hours of operation. The results clearly demonstrate that the incorporation of metal foam and ternary nanoparticles considerably improves the thermal performance of the PCM layer. Due to the enhancement in thermal conductivity and heat diffusion inside the enclosure, the melting rate of paraffin is significantly accelerated. Consequently, the liquid fraction increases by approximately 38.66% compared with the conventional PCM case, indicating more effective latent heat absorption and faster phase transition behavior. In addition, the average temperature of the paraffin region rises by nearly 2.48%, which confirms the improved capability of the enhanced PCM to absorb and distribute thermal energy throughout the storage domain.

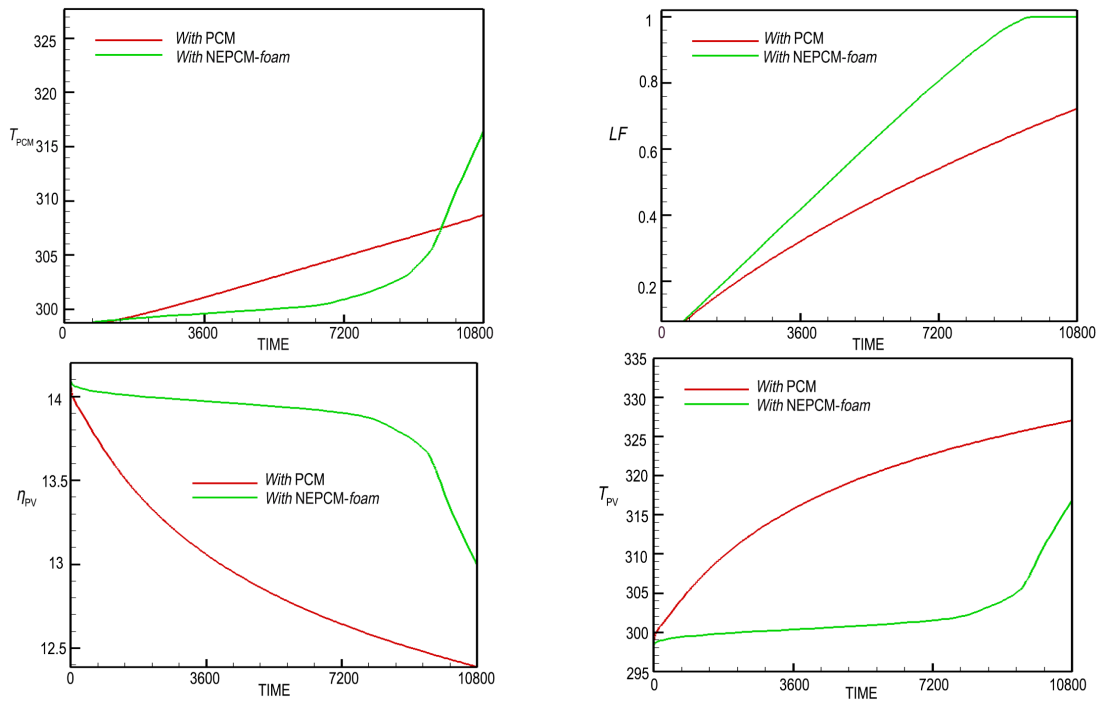


Figure 7. Variation of T_{PV} , T_{PCM} , LF and η_{PV} parameters with time

Note: T_{PCM} = phase change material temperature; LF = liquid fraction; η_{PV} = photovoltaic conversion efficiency; T_{PV} = photovoltaic panel temperature; PCM = phase change material; NEPCM = nano-enhanced phase change material.

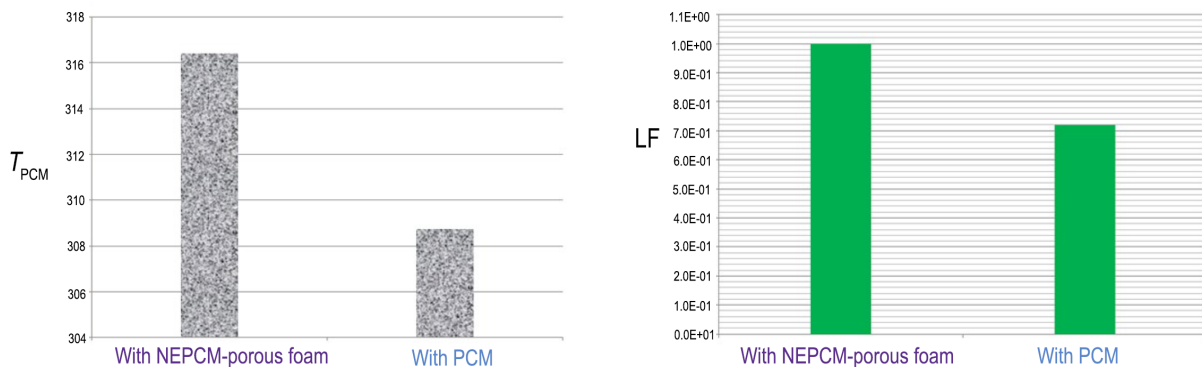


Figure 8. Effect of nano-additives and porous metal foam on PCM thermal behavior after 3 hr

Note: T_{PCM} = phase change material temperature; LF = liquid fraction; PCM = phase change material; NEPCM = nano-enhanced phase change material.

Figure 9 presents the influence of different cooling configurations on the behavior of the PV. The outputs reveal that integrating a cooling enclosure filled with pure paraffin beneath the PV module provides noticeable thermal regulation, leading to an enhancement of approximately 20.85% in PV efficiency compared with the uncooled system. This development is mainly associated with the latent heat storage capability of paraffin, which reduces

thermal accumulation on the panel surface during operation. As a result, the PV panel temperature decreases by approximately 9.94%, demonstrating the strong cooling capability of the proposed hybrid configuration. Moreover, the nano-enhanced PCM integrated with metal foam exhibits the highest thermal performance among all investigated cases. The panel temperature is reduced by nearly 12.75%, while the PV electrical efficiency increases by about 26.75%.

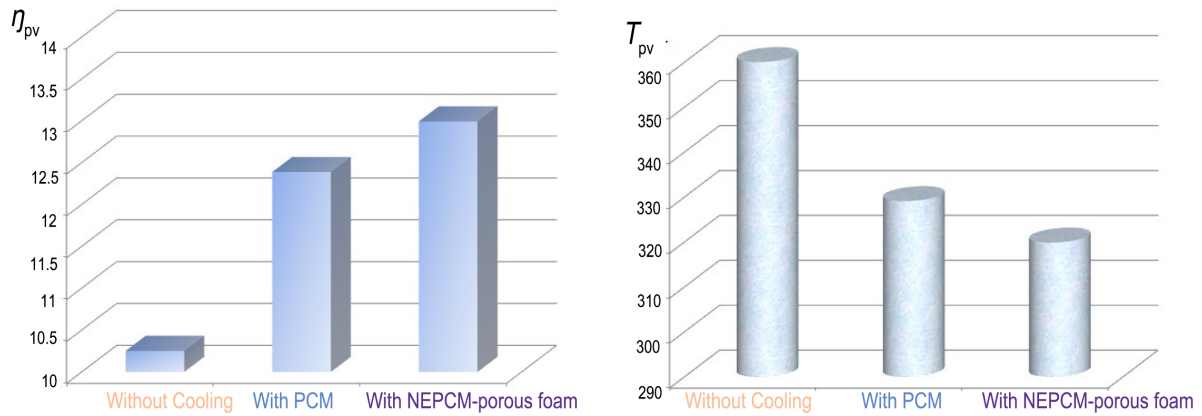


Figure 9. Effect of various cooling cases on η_{PV} and T_{PV} after 3 hours

Note: η_{PV} = photovoltaic conversion efficiency; T_{PV} = photovoltaic panel temperature; PCM = phase change material; NEPCM = nano-enhanced phase change material.

4 Conclusion

The present investigation demonstrates the strong potential of employing a paraffin-based cooling layer enhanced with metal foam and ternary nanoparticles for improving the thermal management of PV panels. The numerical analysis confirmed that the incorporation of Ag–Al₂O₃–TiO₂ nanoparticles together with porous metal foam significantly intensified heat transfer within the PCM region and accelerated the melting process. As a result, more effective thermal energy absorption was achieved, leading to a noticeable reduction in PV operating temperature. The transient thermal behavior, represented through temperature and liquid fraction distributions, revealed that the enhanced cooling configuration provided more uniform heat diffusion and faster phase transition compared with the conventional pure PCM case. Consequently, the electrical performance of the PV panel was considerably improved due to the lower operating temperature maintained throughout the simulation period. The obtained findings indicate that the simultaneous utilization of nano-enhanced PCM and porous structures can provide an efficient and reliable passive cooling solution for advanced PV thermal management applications. The present study confirms the effectiveness of the proposed hybrid cooling configuration in improving the performance of PV panels. The numerical results revealed that the melting process initiated near the upper heated region of the enclosure and gradually propagated toward the lower section of the PCM domain due to the direct thermal interaction between the PV panel and the cooling layer. In addition, the temperature contours followed the geometric shape of the enclosure, indicating the dominant influence of conductive heat transfer during the melting process. This thermal behavior became more significant when ternary nanoparticles and metal foam were incorporated into the PCM, owing to the enhancement in thermal conductivity and internal heat diffusion. The incorporation of nano-enhanced PCM combined with porous metal foam substantially accelerated the melting characteristics of the cooling medium. After three hours of operation, the liquid fraction increased from 0.72 in the conventional configuration to complete melting in the enhanced case, demonstrating the strong capability of the proposed design to absorb and distribute thermal energy more efficiently. Furthermore, the enhanced cooling configuration reduced the PV panel temperature by approximately 12.75%, which consequently resulted in a remarkable increase of nearly 26.75% in PV electrical efficiency. A reduction of approximately 9.94% in panel temperature was achieved, while the liquid fraction and PCM temperature increased by about 38.66% and 2.48%, respectively. These findings indicate that the addition of nanoparticles and porous structures effectively intensifies the melting process and enhances thermal energy storage capability within the cooling domain. Moreover, even the incorporation of a pure paraffin enclosure beneath the PV panel provided noticeable thermal benefits, leading to an enhancement of approximately 20.85% in PV efficiency compared with the uncooled system. Overall, the obtained results demonstrate that the simultaneous use of nano-enhanced PCM and metal foam offers a highly promising passive cooling strategy for advanced PV thermal management applications, particularly under conditions of high solar thermal loading.

Data Availability

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

Conflicts of Interest

The authors declare no conflict of interest.

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