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Improved Performance Assessment of Photovoltaic Systems Using Paraffin-Based Phase Change Materials and Innovative Container Designs

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Abstract. Integrating Phase Change Material (PCM) in Photovoltaic Thermal (PVT) systems is an effective solution to improve the cooling efficiency of solar panels. This study modeled and analyzed three configurations of paraffin-based PCM containers using the Computational Fluid Dynamics (CFD) approach, with radiation intensities of 300, 600, 900, and 1200 W/m². The temperature distribution analysis showed that Model 1, with its design lacking additional partitions, produced a more homogeneous heat distribution and maintained lower PV-cell temperatures than Models 2 and 3. Model 1 recorded a maximum temperature of 27.4°C at its highest intensity, while Model 2 and Model 3 reached 28.5°C and 27.5°C, respectively. Efficiency evaluations show that the Model 1 also produces the highest thermal efficiency, reaching 11.7% at 1200 W/m², compared with the Model 2 at 10.5% and the Model 3 at 11.2%. The Model 1's superior performance is attributed to the PCM's ability to absorb latent heat effectively, slow the rise in PV cell temperature, and maintain stable energy conversion efficiency. Based on these results, Model 1 is recommended as the optimal configuration for PVT-PCM systems to improve thermal efficiency, maintain PV-cell performance, and extend the operational life of solar collector systems.

Introduction

The use of solar energy is skyrocketing as the need for clean and sustainable energy increases in various sectors [1,2]. One of the main technologies of concern is the solar collector system, which functions to absorb solar radiation and convert it into heat energy [3,4]. Thermal collectors have an essential role in water heater applications, drying systems, and photovoltaic-thermal (PVT) systems that combine electricity and heat production in a single unit [5,6]. However, this system's main challenge is maintaining optimal thermal performance amid dynamic variations in solar intensity. The temperature instability of the working fluid can lead to overheating, which lowers the efficiency of the solar panel and shortens the overall life of the system [7,8].

One of the solutions that is now being developed to overcome this problem is the integration of Phase Change Material (PCM) in thermal collector design [9,10]. PCM stores and releases energy in latent heat during phase change processes, from solid to liquid and vice versa [11,12]. This capability allows the system to absorb excess heat when temperatures are high and release it when they drop, so the collector's working temperature can be controlled passively. PCM integration has also been proven to improve thermal stability, extend optimal operating duration, and reduce extreme temperature fluctuations. This technology is increasingly relevant to PVP systems that require effective heat management without adding mechanical complexity [13,14].

Various studies have shown that applying PCM in solar collectors can significantly improve thermal efficiency and electrical performance [15,16]. Previous research has reported an increase in electrical efficiency of up to 17% and thermal efficiency of more than 60% with various innovations such as PCM container geometry, the use of metal foam, as well as combinations with nanoparticle technology [17,18]. Modification of the structure and material properties of PCM is one of the main focuses to get the best performance according to environmental conditions and application needs [19,20]. In addition to experiments, numerical simulation-based approaches are increasingly used because they can provide in-depth visualization and high accuracy in modeling heat transfer and fluid flow phenomena. Thus, computational methods such as Computational Fluid Dynamics (CFD) become a very potent tool in the exploration and evaluation of PVT-PCM systems [21,22].

Table 1 presents key findings from recent research on innovative approaches to optimizing PCM-based collector systems. These innovations include container geometry experiments, the addition of metal foam structures, efficient mathematical modeling, and the integration of ultrasound and nanoparticle technology. These results open new horizons in understanding how design and material parameters can be optimized to improve overall system performance. However, across these studies, there remain research gaps, especially in comparative performance between PCM types through standardized, systematic numerical simulations. This is important because selecting the correct type of PCM will significantly determine the technology's efficiency and success in the field.

Table 1. State of the art

Reference	Novelty	PCM	Findings
[17]	CFD study of PCM container geometry configuration (trapezoid vs square) and the use of isolation	RT42, RT31, RT25	Electricity efficiency increased by 17%, power output increased by 14.6%; trapezoidal containers are superior in cooling; Insulation increases PCM volume requirements
[23]	2D transient CFD simulation for two organic PCMs with real-time data	Rubitherm 28 and 35 HC	Peak power increased by 10%, total annual energy increased by 3.5%; PCMs with low melting points fail to complete solidification at night
[24]	Direct experiment and simulation of CFD using soybean wax as an environmentally friendly organic PCM	Soybean wax	PV temperature drops from 60.7°C to 54.7°C (at 1100 W/m²); efficiency increased by 0.42% (at 900 W/m²); Cheap price and can be used repeatedly
[4]	PV–PCM integration with solar chimney and fin absorbers, as well as composite PCM	Paraffin/Copper Foam (Pa/CF), Sodium Acetate Trihydrate/Copper Foam (SAT/CF)	Electrical power increased by 16%, ventilation duration increased by 101%; Pa/CF gives a top output of 5.54 kWh
[11]	Numerical simulation of nano-PCM with various nanoparticles and variations of PV tilt angle	RT25HC + MgO, TiO_2, ZnO, CuO	Electrical efficiency 11.6% (horizontal); nano-PCM keeps the panel temperature 4°C lower; The best efficiency occurs when the orientation is horizontal

Based on previous studies, it is evident that there are still limitations in systematically comparing the thermal performance of various PCM configurations, especially in the use of detailed, accurate numerical simulation approaches. To address the research gap, the study focused on the thermal analysis of solar collector systems integrating three PCM container models via CFD simulations. The PCM used is paraffin, selected for its suitable melting point, high thermal stability, and broad applicability in PVP systems. With this approach, this research is expected to make a scientific contribution in determining the most optimal PCM configuration and material, while supporting the development of a more efficient, economical, and sustainable solar collector system design for future energy needs.

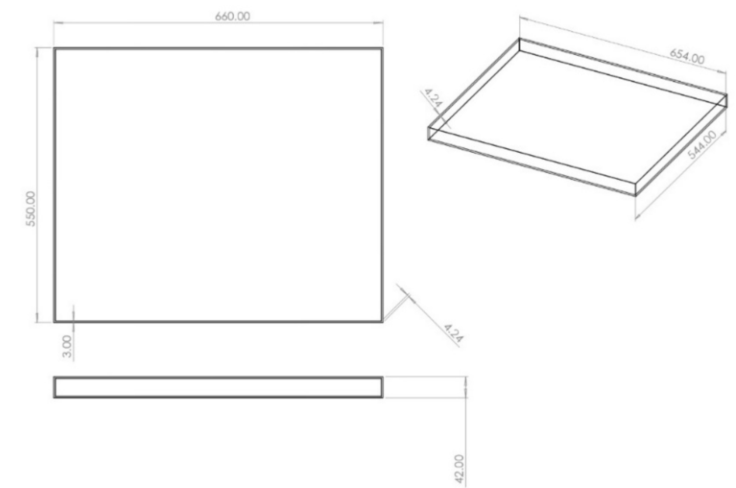
Method

This research used a Computational Fluid Dynamics (CFD) simulation to evaluate the thermal characteristics of a Photovoltaic Thermal (PVT) system integrated with *Phase Change Material* (PCM) as a passive cooling medium. Paraffin was chosen as the PCM material due to its superior thermophysical properties for absorbing and storing energy via a latent heat transfer mechanism, which significantly improves thermal efficiency and stability of photovoltaic cell performance. Heat fluxes of 300 W/m², 600 W/m², 900 W/m², and 1200 W/m² were applied to the panel surface to assess the system's thermal response to varying solar radiation intensities. The system configuration consists of two main layers: a top layer of PV cells and a bottom layer of PCM containers, as shown in Figure 1. The geometric dimensional details of the three numerically analyzed PCM container designs are presented in Table 2 and further visualized in Figure 2.

Fig. 1. Details of the arrangement of layers on the PVT-PCM system.

Table 2. Specification of the geometric size of PCM containers.

Specification	Detail
Material	Aluminum
Total size ($W \times W \times H$)	$660 \times 550 \times 42\ mm$



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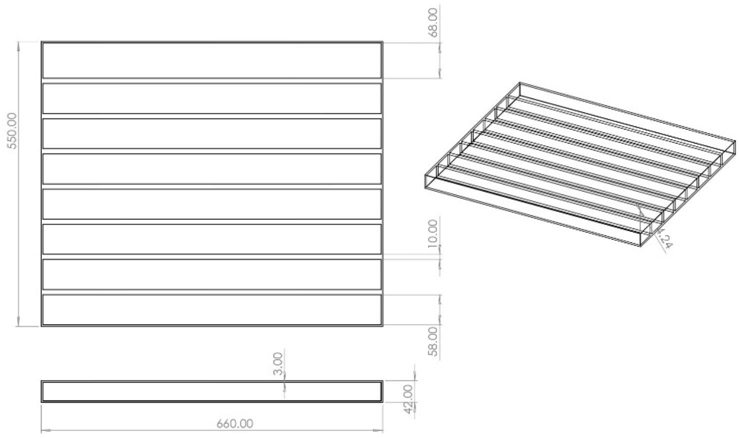

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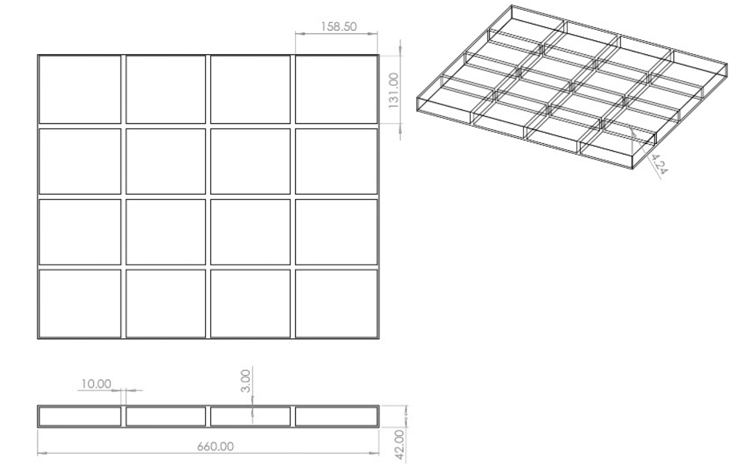


(c)

Fig. 2. Geometric configurations of the three PCM container models: (a) Model 1 without partitions, (b) Model 2 with horizontal partitions, and (c) Model 3 with segmented internal barriers, designed to evaluate the influence of structural variation on heat transfer behavior.

The geometric design of the PV-cell and PCM container systems was developed in SolidWorks, enabling the creation of precise, detailed 3D models. The modeling process was conducted on a laptop equipped with an AMD Ryzen 5 7520U processor with Radeon Graphics, operating at 2.80 GHz, ensuring adequate computational power for the geometry construction and preprocessing stages. The numerical simulation of phase change phenomena in the Phase Change Material (PCM), including melting and solidification processes, was performed using ANSYS Fluent versions 18.2 and 22 under transient conditions. A mesh element size of 12 mm was selected for the final simulation to ensure an accurate representation of flow behavior and temperature distribution within the system domain. With this mesh configuration, the total number of elements generated for the collector model was 27,404 and 45,399 for Model 1, 29,500 and 52,216 for Model 2, and 29,905 and 53,054 for Model 3, respectively. As presented in Figure 3, the variation in maximum PV temperature and thermal efficiency becomes negligible when the mesh size is refined from 12 mm to 8 mm, with deviations below 0.2% for all models. This confirms that the selected 12 mm mesh has achieved grid independence and provides an optimal balance between numerical accuracy and computational cost. All simulations were conducted based on the thermophysical properties of PV cells and PCM materials described in Table 3.

Table 3. Material Characteristics [24–26].

Material	Density (kg/m3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)	Viscousity (kg/m-s)	Pure Solvent Melting Heat (J/kg)	Solidus Temperature (K)	Liquidus Temperature (K)
PV-Cell	2330	667	130	-	-	-	-
Aluminium	2719	871	202.4	-	-	-	-
Paraffin	@800 @790	2150	0.2	0.01	240800	313.6	317.7

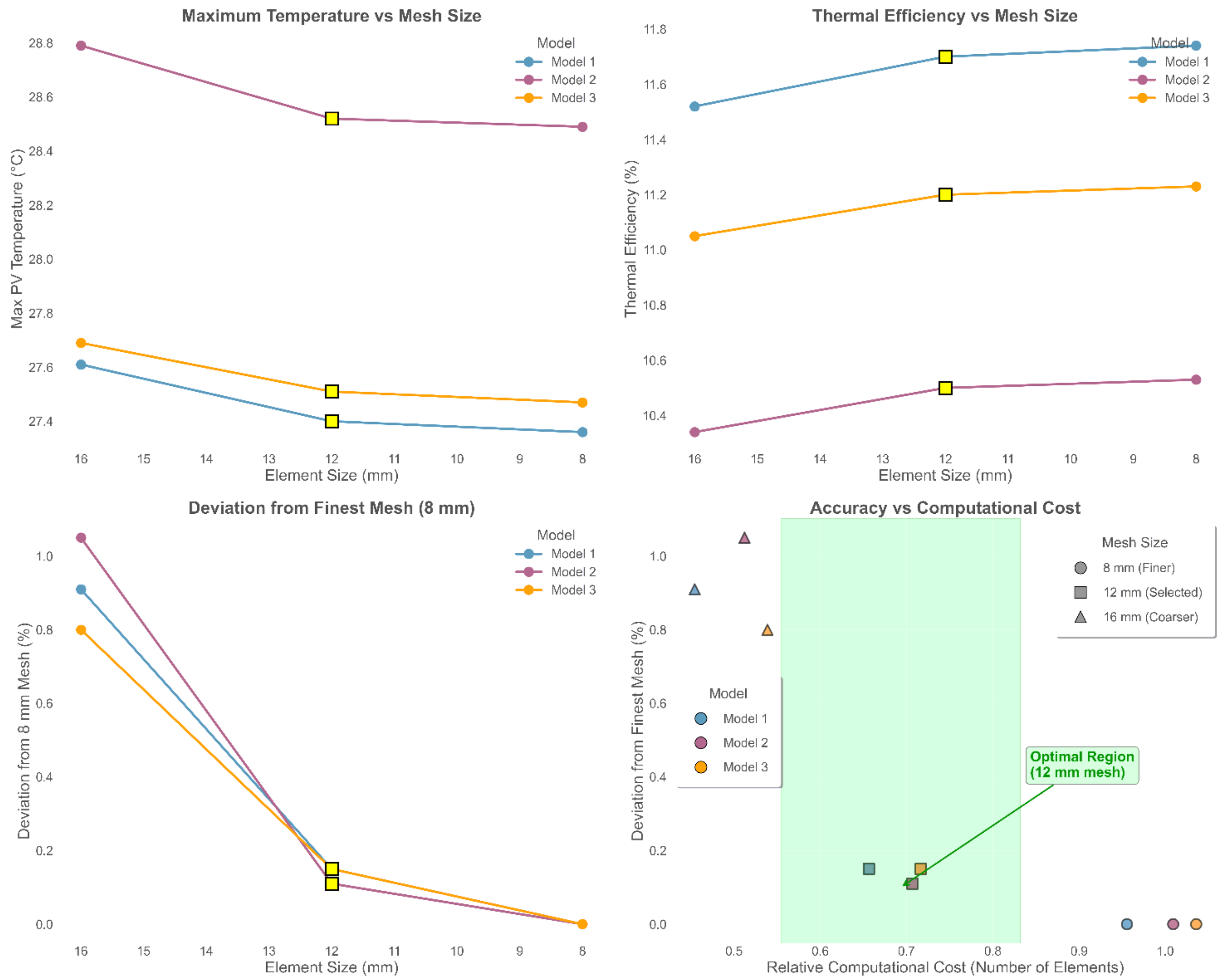


Fig. 3. Mesh sensitivity analysis of the PVT-PCM system showing the maximum PV temperature and thermal efficiency for 16 mm, 12 mm, and 8 mm mesh sizes at 1200 W/m², confirming the grid independence of the selected 12 mm mesh.

Theoretical Foundation & Formulation

Numerical analysis of the PVT-PCM system was carried out using the Energy Conservation approach, where the temperature distribution and heat transfer process were modeled with the following energy equations [27]:

$$\frac{\partial}{\partial t}(\rho_h) + \nabla \times (\rho_{uh}) = \nabla \times (k\nabla T) \tag{1}$$

In systems involving Phase Change Materials (PCM), the enthalpy model describes the total energy accumulation, including sensible and latent energy during phase change. Total enthalpy is formulated as follows [28]:

$$h = C_p(T - T_{ref}) + \Delta H_f \times f_L \tag{2}$$

The liquid fraction of PCM (in the range 0 to 1) is the latent heat of melting, and Cp is the specific heat capacity. The heat transfer process in PCM and PV cells follows the principles of conduction and convection. For heat conduction, Fourier's law is applied $f_L \Delta H_f$[23]:

$$q = -k \times \nabla T \tag{3}$$

Meanwhile, Newton's law explains the heat transfer between the PV surface and the environmental fluid. [29]:

$$q = h_c \times A \times (T_s - T_\infty) \tag{4}$$

To evaluate the thermal performance of the collector system, a thermal efficiency formula based on the increase in PCM temperature is used [30]:

$$\eta_{thermal} = \frac{I_{rad} \times A}{m \times C_p \times \Delta T} \tag{5}$$

To assess the effectiveness of PCM in lowering the temperature of PV [31]:

$$\eta_{pv} = \eta_{ref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \tag{6}$$

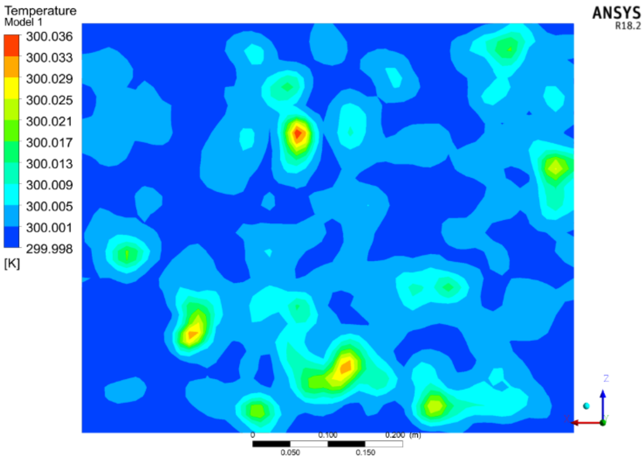
Values are obtained through simulations.T_c

Result & Discussion

The performance of the PVP system was assessed using numerical modeling in ANSYS Fluent. The Solidification and Melting module represents the thermal behavior and phase transition of Phase Change Material (PCM) heat storage materials. PCM is considered a strategic component of heat energy storage and distribution systems due to its ability to absorb and release heat efficiently. Therefore, the simulation is designed to trace the impact of PCM application on improving the overall thermal performance of the system. Computational Fluid Dynamics (CFD) techniques are applied comprehensively to describe the energy transfer process, PCM melting rate, and heat transfer efficiency. The simulation was carried out under transient conditions using ANSYS R18.2 to help students obtain a comprehensive picture of the PVT system's dynamic thermal behavior.

Temperature Distribution Analysis on PCM

Figure 4(a–c) illustrates the temperature distribution of Phase Change Material (PCM) in three different structural configurations. The color in the image corresponds to local temperature, with a gradient from blue (cold) to red (hot) indicating the temperature profile. In Model 1 (Figure 4a), the temperature distribution is relatively homogeneous, with only a few localized hotspots. This shows good heat-conduction efficiency in the PCM, enabling effective thermal diffusion. This model shows that without many internal partitions, the PCM structure can accelerate temperature homogenization, optimizing latent energy storage during the transition phase. In contrast, Model 2 (Figure 4b) shows horizontal partitions that lead to heat accumulation in certain areas. This distribution pattern indicates that lateral (horizontal) heat transfer is impeded, resulting in a sharper temperature gradient between layers. While this barrier can slow overall PCM melting, it can be helpful for applications that require controlled thermal release. Model 3 (Figure 4c) shows a more fragmented heat distribution, with hotspots spread over small areas. This suggests that the additional bulkheads significantly inhibit heat flow, thereby providing greater local thermal insulation. Although heat distribution becomes more uneven, this characteristic helps extend the duration of heat discharge in systems that require long-term thermal stability.



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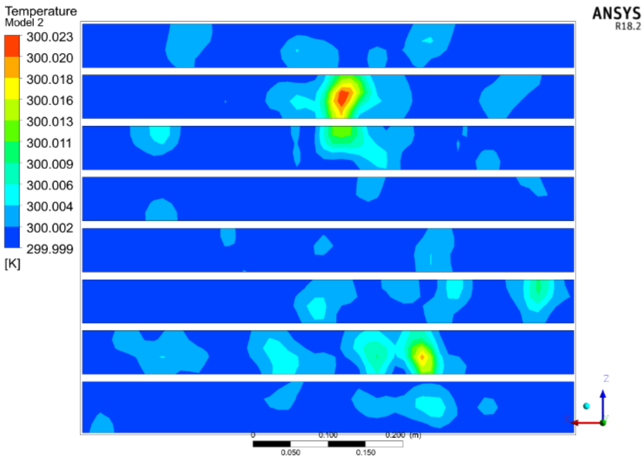

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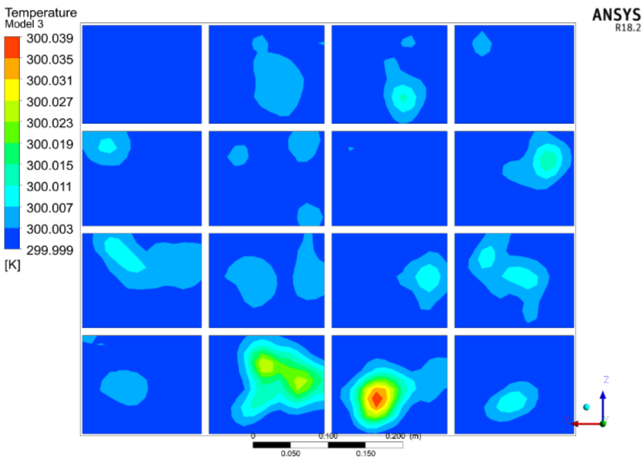

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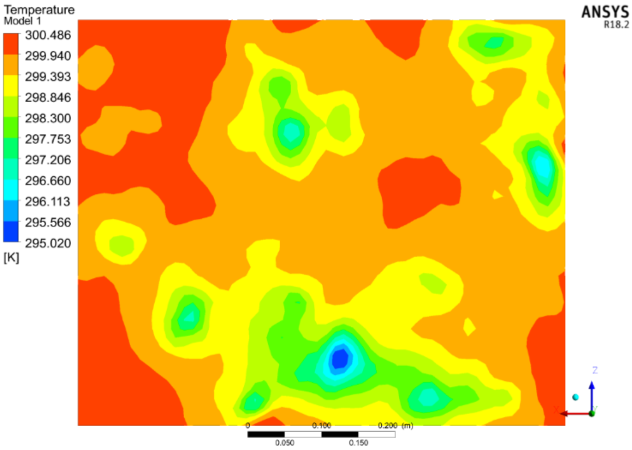
Fig. 4. Numerical visualization of temperature distribution within the PCM domain for (a) Model 1, (b) Model 2, and (c) Model 3 under identical radiation conditions, illustrating differences in heat diffusion and melting behavior.

Temperature Distribution Analysis in PV-Cell

Figure 5(a–c) presents the temperature distribution on the surface of the PV-cell after integration with the PCM in the same three configurations. In Model 1 (Figure 5a), the heat distribution shows a fairly even pattern across the PV surface. This signifies that PCM effectively controls PV temperatures, keeping surfaces within the optimal operating temperature range. This homogeneity contributes to increased photovoltaic efficiency, as solar cell performance is sensitive to temperature. In Model 2 (Figure 5b), heat accumulates in several limited areas. This condition indicates reduced cooling effectiveness in certain regions due to the bulkhead structure's horizontal thermal resistance. As a result, the potential for PV performance degradation is greater at these hotspots, potentially accelerating PV material aging in the long run. Meanwhile, in Model 3 (Figure 5c), the temperature distribution is more focused on the subsurface. This indicates that the cooling is more concentrated, yet uneven across the PV surface. While this slows the rise in surface temperatures, the uneven heat distribution can still lead to microthermal stress, risking a degradation of PV's long-term efficiency.



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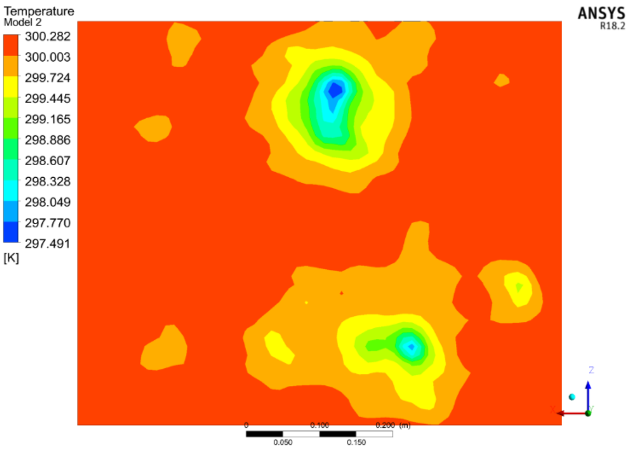

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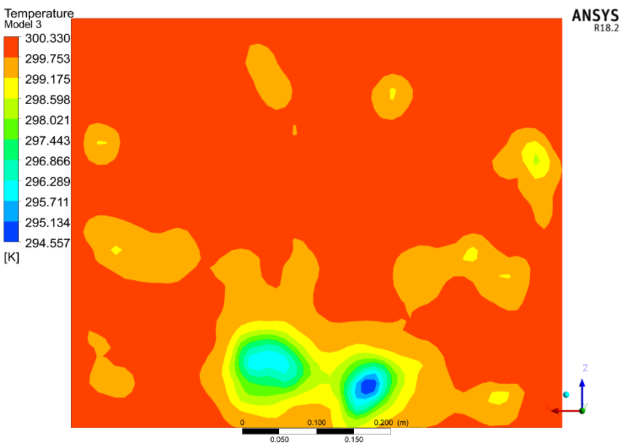

(c)

Fig. 5. Numerical visualization of PV-cell surface temperature distribution for (a) Model 1, (b) Model 2, and (c) Model 3, highlighting the effect of PCM configuration on cooling performance.

Figure 6 illustrates the results of a comparative analysis of PV-cell temperature variations across three paraffin-based PCM container models at light intensities of 300, 600, 900, and 1200 W/m². At an intensity of 300 W/m², Model 2 shows the highest temperature of 27°C, while Model 1 performs best in maintaining the lowest temperature at 26.2°C. When the intensity was raised to 600 W/m², the same trend persisted: the Model 2 recorded 27.3°C, while the Model 1 remained at 26.4°C. At an intensity of 900 W/m², the temperature difference between the three models becomes more pronounced, with Model 2 reaching 28°C. In contrast, the Model 1 and Model 3 maintain lower temperatures in the range of 27°C to 27.3°C, respectively. Finally, at the highest intensity of 1200 W/m², the Model 2 again shows a maximum temperature of 28.5°C, while the Model 1 and Model 3 record 27.4°C and 27.5°C, respectively. Based on this pattern, it can be concluded that Model 1 consistently inhibits PV-cell temperature rise better than Models 2 and 3.

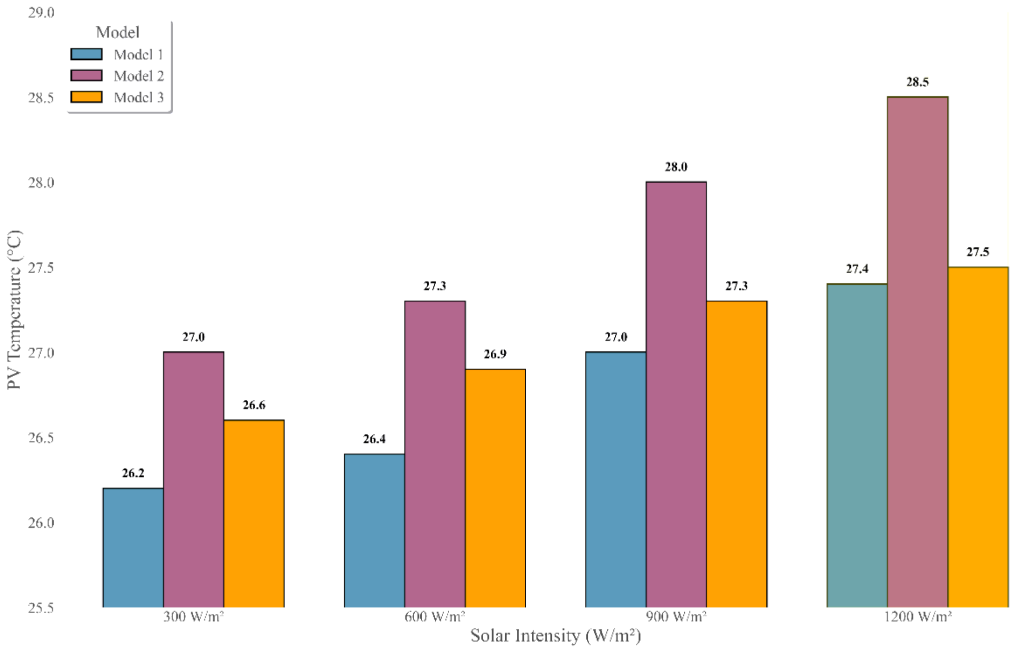

Fig. 6. Comparative analysis of maximum PV-cell temperature under solar radiation intensities of 300–1200 W/m² for the three PCM models.

Analysis of Thermal Regulation Efficiency in PV-Cells

Figure 7 shows a comparative analysis of the variation in energy conversion efficiency in PV-cells based on three PCM usage models at various solar radiation intensities (300, 600, 900, and 1200 W/m²). The data showed that PV-cell efficiency increased with increasing radiation intensity across all models, but there was a difference in efficiency performance among the three models. At low intensity (300 W/m²), Model 1 recorded the highest efficiency of 5.3%, followed by Model 3 at 5.1% and Model 2 at 5.0%. An increase in intensity of up to 600 W/m² shows a similar trend, with Model 1 maintaining better performance (7.3%) than Model 2 (6.5%) and Model 3 (6.8%). At 900 W/m², Model 1's efficiency remained higher at 9.5%, followed by Model 3 (9.1%) and Model 2 (8.8%). At its highest intensity, 1200 W/m², the Model 1 maintains its advantage, with an efficiency of 11.7%, compared to the Model 2 at 10.5% and the Model 3 at 11.2%.

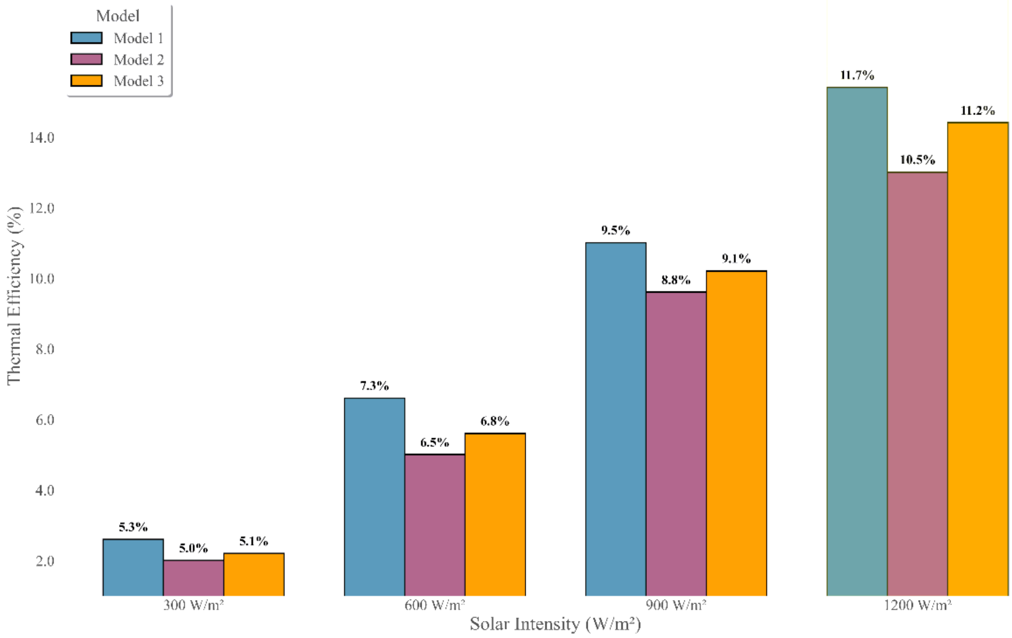

Fig. 7. Comparative analysis of PV-cell electrical efficiency under solar radiation intensities of 300–1200 W/m² for the three PCM models.

The consistently higher efficiency of Model 1 across intensity variations demonstrates the significant role of the PCM's characteristics. The effectiveness of PCM in absorbing heat during phase change contributes to temperature control of PV cells. By maintaining a lower and stable PV-cell operating temperature, the PCM on Model 1 can reduce the thermal energy losses that typically occur at high temperatures, thereby improving the efficiency of electrical energy conversion. This phenomenon is consistent with the thermal theory, which predicts that PV-cell efficiency decreases as cell temperature increases. Optimal PCM acts as a latent heat storage medium, absorbing excess heat without causing a drastic rise in temperature and releasing it gradually as the intensity decreases. Thus, the PCM used in Model 1 is more effective at slowing the degradation of efficiency due to temperature fluctuations than the PCM used in Models 2 and 3. This is because model 1 can absorb excess heat energy without causing temperature spikes, thanks to a latent heat storage mechanism, and then release energy gradually as the radiation intensity decreases. The Model 1's design, which does not use partitions, allows for more even and efficient heat distribution compared to the Model 2 and Model 3, which use internal dividers. Uniform heat distribution accelerates the process of heat absorption by PCM, reduces internal temperature gradients, and slows down the rate of efficiency degradation due to local heat accumulation (*hot spots*) [32,33].

Conclusion

This study has conducted numerical modeling and analysis of the Photovoltaic Thermal (PVT) system integrated with paraffin-based Phase Change Material (PCM) using three different container configurations. Simulations based on Computational Fluid Dynamics (CFD) were conducted to evaluate the characteristics of the temperature distribution and PV-cell efficiency variations in response to changes in solar radiation intensity from 300 to 1200 W/m². Each PCM container model exhibits a unique thermal distribution pattern, which directly impacts cooling performance and PV-cell surface temperature stability. The results of the temperature distribution analysis showed that Model 1, with its unpartitioned container structure, produced a more homogeneous and more effective heat distribution, inhibiting temperature rise and controlling the PV-cell surface temperature more stably and at lower levels than in Model 2 and Model 3. Model 1 consistently recorded the lowest PV-cell operating temperature, with a maximum value of 27.4°C at an intensity of 1200 W/m², while Model 2 and Model 3 reached 28.5°C and 27.5°C, respectively.

Analysis of PV-cell efficiency also showed that Model 1 performed best across all radiation intensities, achieving 11.7% at the highest intensity, compared to 10.5% for Model 2 and 11.2% for Model 3. This performance is directly attributed to the PCM's ability to effectively absorb and release heat through a latent heat storage mechanism, which slows down the rise in PV-cell temperature and maintains the efficiency of electrical energy conversion. Based on all simulation results, Model 1 is the best configuration for PVT-PCM system applications, as integrating paraffin-based PCM within a container structure without additional bulkheads provides an optimal balance of thermal stability, homogeneous heat distribution, and energy efficiency. Therefore, Model 1 is recommended as a flagship design to improve thermal efficiency, maintain PV-cell electrical performance, and extend the operational life of integrated solar collector systems.

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