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Enhancing Thermal Performance and Energy Efficiency in Photovoltaic Thermal-Phase Change Material Systems: A Numerical Investigation of Fin Geometry Variations

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ABSTRACT

Combining Photovoltaic Thermal (PVT) technology with Phase Change Material (PCM) offers an effective solution to improve energy efficiency by simultaneously utilizing electrical energy and solar heat under 33 °C ambient tropical conditions. This study aims to evaluate the effect of fin geometry variation on the thermal performance and electrical efficiency of paraffin-based Photovoltaic Thermal–Phase Change Material (PVT-PCM) systems in tropical conditions, using ANSYS Fluent and Transient Thermal-based numerical simulation approaches. Three geometric configurations were analyzed, namely finless, triangular fin, and trapezoidal fin, with simulations performed at variations in solar radiation intensity between 400 and 1000 W/m². The simulation results showed that the trapezoidal fin shape produced the highest thermal efficiency of 15.42%, while the triangular shape was more effective in maintaining an even temperature distribution. Statistical analysis using the Analysis of Variance (ANOVA) method indicates that the intensity of solar radiation and the geometric design significantly affect thermal efficiency (P-value < 0.05). These findings provide a solid scientific basis for developing PVT-PCM designs that are more efficient and adaptive to tropical environmental conditions, as well as broaden the understanding of the importance of thermal structure optimization in solar energy storage systems.

1. INTRODUCTION

The transition to a sustainable energy system has prompted increased research into more efficient and integrated solar technology. One of the technologies that stands out in this regard is Photovoltaic Thermal (PVT), which is capable of generating electrical energy and heat simultaneously in a single system unit [1-3]. However, one of the main drawbacks to the PVT conventional system is a significant increase in the temperature of the PV module during exposure to solar radiation, which decreases the efficiency of electricity conversion [4-6]. To overcome these problems, researchers began to develop a system, PVT, combined with Phase Change Material (PCM), where this material functions to absorb excess heat in the form of latent energy when a phase change occurs [7, 8]. PCM allows the system to maintain the temperature stability of the panel within the optimal operating range, thereby reducing performance degradation due to overheating [9]. This integration is promising, especially for tropical regions with high solar intensity and large daily thermal fluctuations.

One of the critical aspects in improving system performance, PCM, is the geometric design of the container and its internal structure, in particular, the use of fins (Fins) as a heat dispersing medium [10]. The fins increase the heat transfer area from the PV panel to the PCM material, thereby accelerating the release of energy into the PCM volume [11, 12]. However, the shape, position, and number of fins have a significant influence on the homogeneity of heat distribution and the speed of the melting process [13, 14]. Several previous studies have proven that the geometric design of containers, both in terms of shape and additional insulation, can significantly modify thermal behavior and contribute to an increase in the overall energy efficiency of the system [15]. A summary of these studies can be seen in Table 1, which includes a variety of numerical and experimental simulation approaches with different types of PCMs, enclosure configurations, and different thermal-electrical efficiency results [16]. However, it can be concluded that previous research still leaves gaps, especially in the systematic exploration of fin geometry and its effect on the efficiency of thermal and electrical combinations.

Table 1. Summary of previous studies on Photovoltaic Thermal–Phase Change Material (PVT-PCM) systems

Reference	Originality	PCM Type	Key Outcomes
[17]	CFD analysis comparing trapezoidal and square PCM enclosures, plus thermal insulation integration	RT42	Electrical performance improved by 17%, and power generation rose by 14.6%. Trapezoidal design excels in thermal regulation; Insulation raises the amount of PCM needed
[18]	Time-dependent 2D CFD modeling using real-time profiles for two organic PCM options	Rubitherm 28 and 35 HC	Peak output rose by 10%, yearly energy generation saw a 3.5% uplift; PCMs with lower fusion points don't fully re-solidify overnight
[19]	Combined CFD modeling and lab experiments on sustainable PCM derived from soy wax	Soybean wax	Panel temperature lowered from 60.7 °C to 54.7 °C under 1100 W/m²; Efficiency improved by 0.42% at 900 W/m²; Economical and recyclable option
[8]	Hybrid setup using PV-PCM integration, fins, and solar chimney with composite phase-change materials	Paraffin	Electrical output enhanced by 16%, airflow duration increased by 101%; Pa/CF yielded maximum energy of 5.54 kWh
[20]	Computational modeling on nano-enhanced PCM with various metal oxide additives and tilt angle optimization	RT 25 HC	Maximum electrical efficiency of 11.6% observed on flat PV panels; Nano-PCM maintains panel surface 4 °C cooler; Best performance achieved in horizontal position

In addition to the geometric aspect, the success of the system Photovoltaic Thermal–Phase Change Material (PVT-PCM) is also highly determined by the selection of the right PCM material [21]. Paraffin is one of the most widely used types of PCM in PVT studies due to its abundant availability, good thermal stability, and melting temperature, corresponding to the working range of PV modules in tropical regions. This material has a high heat storage capacity, but it is also known to have low thermal conductivity [22]. Therefore, design solutions such as adding conductive fins are needed so that the distribution of heat energy in paraffin is more even and not locally concentrated [23]. The interaction between fin design and the thermophysical properties of the material becomes a vital combination that affects the system's overall effectiveness. Research that ignores either of these factors risks resulting in systems with suboptimal performance in real applications.

Answering these challenges, this study is designed to evaluate the performance of the system PVT numerically–PCM paraffin-based with variations in fin geometry, using simulation methods Computational Fluid Dynamics (CFD) based on ANSYS Fluent and Transient Thermal. The simulation was carried out to analyze the surface temperature profile, internal heat distribution, and thermal and electrical efficiency in three main geometric configurations, namely, finless, triangle trapezoid [24]. This numerical approach was chosen because it can provide a comprehensive visual and quantitative picture of the behavior of systems in a given time and condition, without direct dependence on expensive experimental resources [25]. This research not only aims to compare the performance of each design but also lays the groundwork for a more efficient thermal design for system development, PVT-PCM in the future. Considering the tropical operational conditions and efficiency limitations of conventional PV systems, the results of this study are expected to significantly contribute to the design of solar energy systems that are more adaptive, efficient, and ready to be implemented in real-world scenarios.

Several recent studies, including Mahdavi et al. [26], Ashouri and Hakkaki-Fard [8], and Ahmad et al. [17]. We have investigated diverse fin-enhancement and PCM modification strategies to improve thermal management in PV systems. Mahdavi et al. [26] introduced unconventional fin shapes such as pin, spring, and Y-shaped fins through experimental validation, but did not systematically explore the influence of geometric variation or implement design parameterization across configurations. Similarly, Ashouri

and Hakkaki-Fard [8] employed an inclined rectangular fin array but confined the analysis to one PCM and fin height under fixed solar conditions, limiting the generalizability of the outcomes. Ahmad et al. [17] focused primarily on nanoparticle-enhanced PCM using a high-concentration nanofluid in a hybrid system, which, although novel in material science, did not consider geometric or structural optimizations of the fin-PCM domain.

The present study aims to bridge this gap by systematically comparing configurations with and without fins and between triangular and trapezoidal fin geometries while maintaining a constant PCM container surface area. This ensures that the observed performance differences stem purely from geometric effects rather than confounding factors such as increased surface contact or material volume. By normalizing these design parameters, the study introduces a controlled framework for evaluating the role of passive fin geometry in enhancing heat transfer and efficiency within PVT-PCM systems. This approach sets the groundwork for more advanced future optimization and responds to previous literature's lack of geometric isolation.

2. METHOD

The methodology of this study is systematically designed to evaluate the performance of the PVT system combined with PCM based on numerical simulation and coupled with the ANSYS FLUENT software with thermal transient. The stages of the research are structured in the flowchart in Figure 1, which includes the process from determining design parameters to the final analysis. The initial parameters used include fluid properties such as density, thermal conductivity, viscosity, heat capacity, and PCM melting temperature, in this case, paraffin [27]. The design of the system geometry, including the dimensions and configuration of the fins, as well as the efficiency of the PV panel and environmental data such as ambient temperature and intensity of solar radiation, are also included in the modeling. The simulation used ANSYS software with a CFD approach. After the model validation test was carried out with a Margin of Absolute Percentage Error (MAPE) below 10%, after successful validation, the integration simulation PVT-PCM is carried out to obtain thermal performance output, and evaluation is carried out through the analysis of the main parameters through the Analysis of Variance (ANOVA) [28].
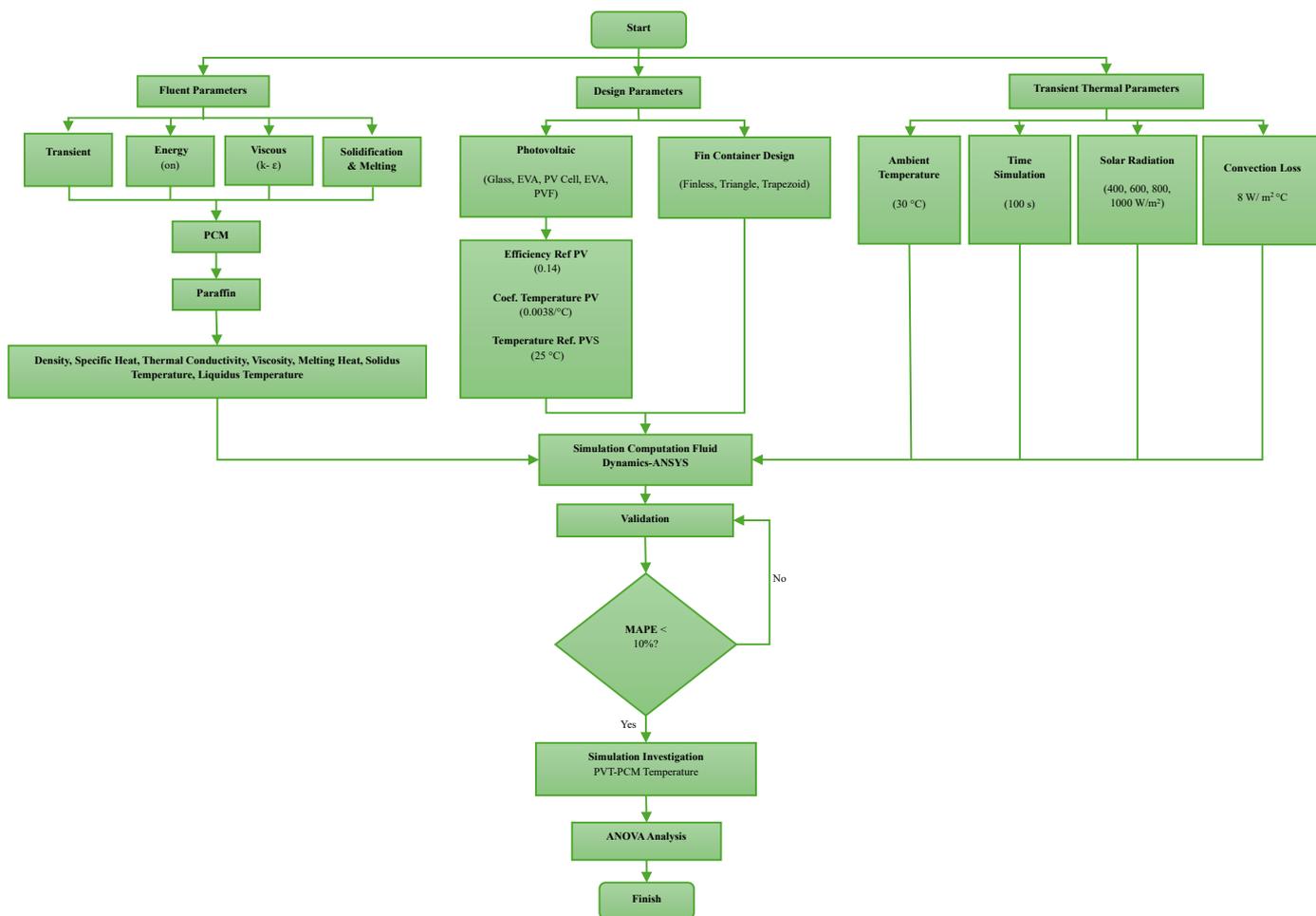
Figure 1. Research flowchart

2.1 Physical structure and composition of Photovoltaic Thermal–Phase Change Material (PVT-PCM) materials

The PVT-PCM model in this study is designed to numerically represent the real conditions of the thermal system. A complete illustration of the system can be seen in Figure 2, which depicts a layered arrangement of the main components, including protective glass, coating ethylene-vinyl acetate (EVA), PV cell, polyvinyl fluoride (PVF), container storage PCM, and PCM in the form of paraffin [29, 30]. The structural dimensions of each layer are shown in Table 2, with uniform length and width measurements (609 mm × 489 mm), but varying thicknesses according to their function. The container has a total thickness of 52 mm, of which 50 mm is explicitly allocated for PCM materials. The design of these dimensions considers heat transfer efficiency, structural stability, and ease of integration with the system's PV. All these geometric parameters are the basis for building the Model numerik before the simulation process.
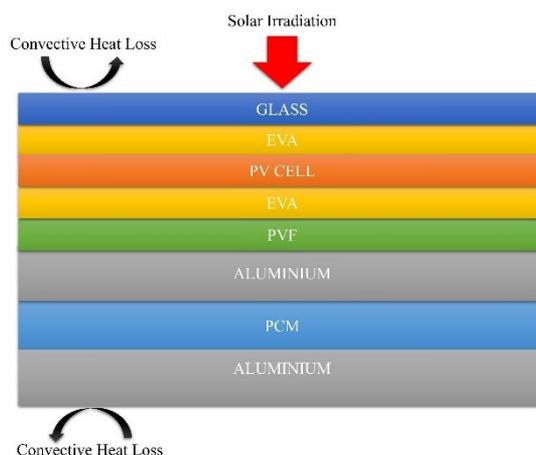

Figure 2. Illustration of the Photovoltaic Thermal–Phase Change Material system

Furthermore, the container's geometry is designed in three different configurations to analyze the influence of fin design on the system's thermal performance, as shown in Figure 3. The three container models used include finless, triangle, and trapezoid designs. The geometric details of the two finned designs are shown further in Figure 4, which shows the position and shape of the fins inside the container. The purpose of this design variation is to evaluate the effectiveness of the fins in improving heat distribution and maximizing the release or storage of latent energy by PCMs. The fins serve as a heat transfer medium from the PV panel to the PCM, so the shape

Table 2. Structural dimensions of Photovoltaic Thermal–Phase Change Material (PVT-PCM) components

Component	Measurements
Glass (mm^2)	609 × 489 × 3.2
EVA (mm^2)	609 × 489 × 0.5
PV Cell (mm^2)	609 × 489 × 0.21
PVF (mm^2)	609 × 489 × 0.3
Container (mm^2)	609 × 489 × 52
PCM thickness (mm)	50

variation dramatically affects the system's efficiency. This modeling allows for an in-depth comparative analysis of the thermal performance of each design.

The thermal and physical characteristics of each system component are listed in Table 3, which includes data such as density, type of heat capacity, thermal conductivity, viscosity, and PCM properties such as melting heat, solidus temperature, and liquidus temperature. This data is essential in modeling because it is the primary input for numerical simulations based on CFD. For example, paraffin used as PCM has a melting heat of 240,800 J/kg, a solidus temperature of 313.6 K, and a liquidus temperature of 317.7 K, which makes it particularly suitable for PVT applications in tropical climates. In addition, aluminum as a container material has a very high thermal conductivity, which is 202.4 W/m-K, which accelerates the heat transfer process. Integrating all these parameters into the model allows simulation analysis close to the actual physical conditions and produces relevant outputs for design performance comparisons.

While sensitivity analysis was later used to assess the effect of minor variations in thermal parameters, the selection of paraffin and aluminum as working materials remains highly justified even under ±5% deviation. This is primarily due to the proven thermophysical stability of paraffin in solar energy storage systems, which maintains consistent melting behavior and energy absorption characteristics across varying thermal cycles. The research [31] confirms that paraffin-based PCMs display excellent resilience against thermal conductivity and specific heat variations, with negligible impact on system-level thermal performance. Similarly, aluminum's high intrinsic conductivity and mechanical robustness make it an ideal medium for heat transfer enhancement, even under minor property deviations [32, 33]. Therefore, the materials listed in Table 3 were retained based on their nominal properties and documented stability in dynamic solar-thermal environments.
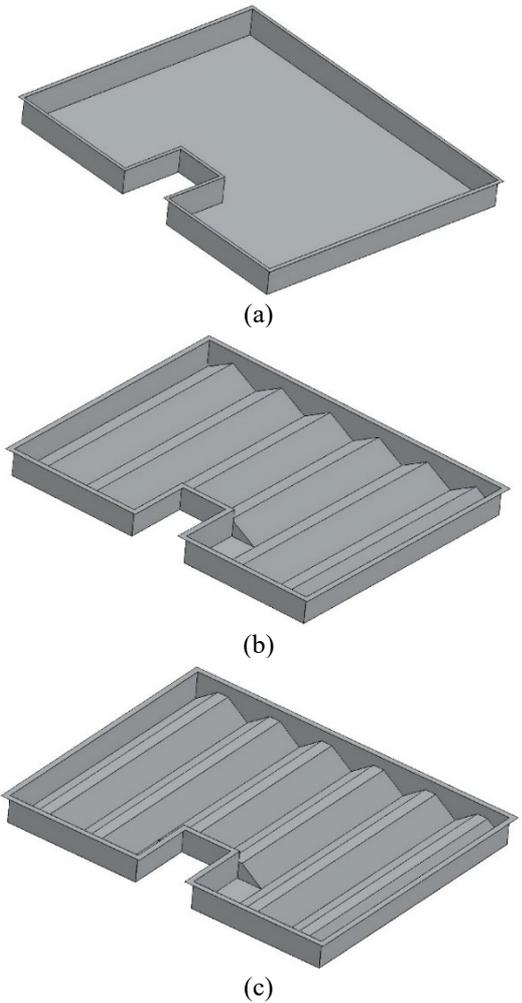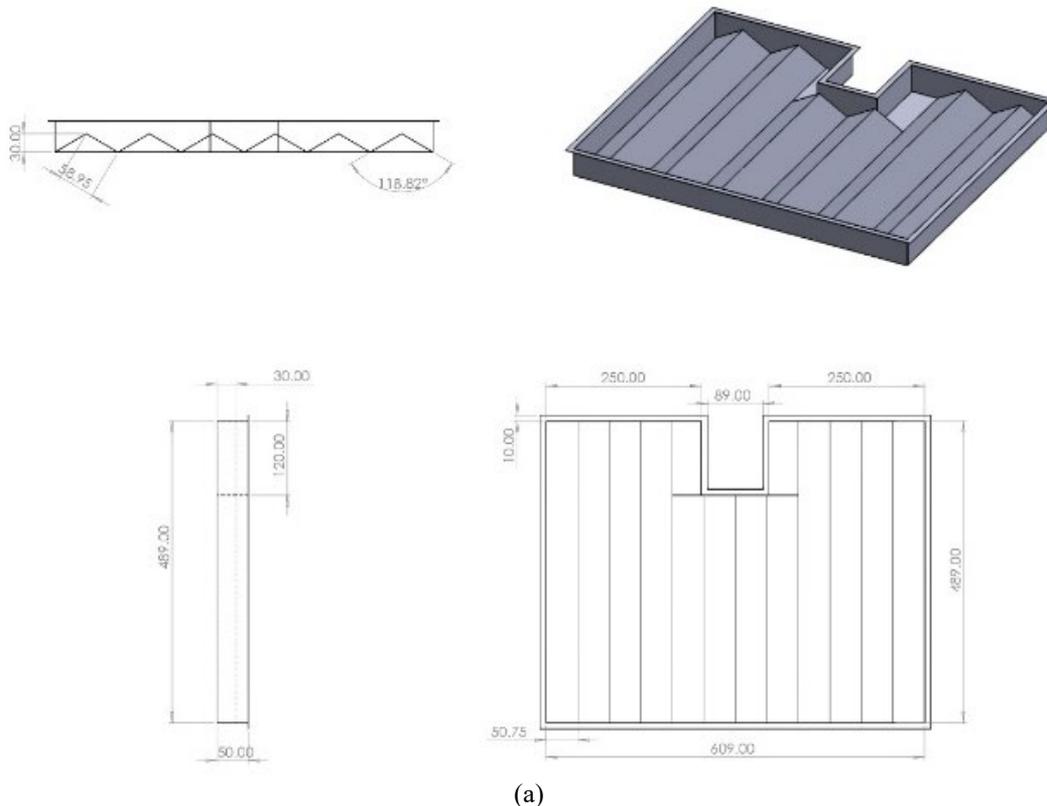
(a)

(b)

(c)

Figure 3. Model of the fin container (a) Finless (b) Triangle (c) Trapezoid
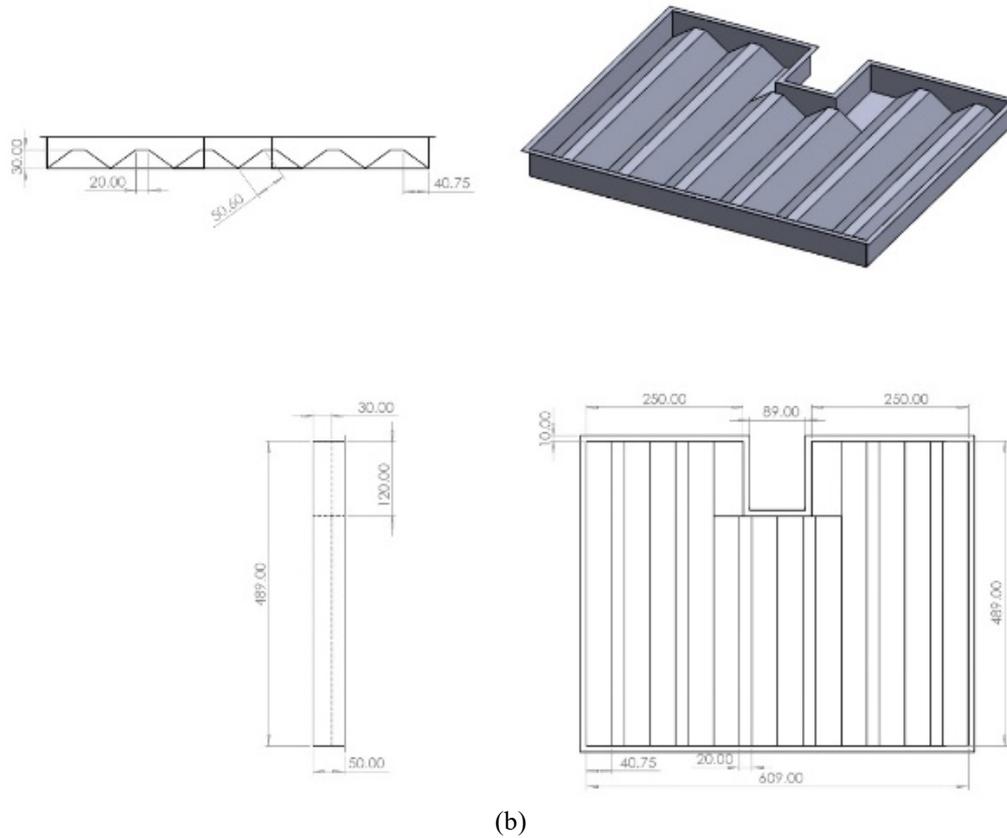
(a)

(b)

Figure 4. Detail geometry fin container of the (a) Triangle (b) Trapezoid

Table 3. Thermal and physical properties of the Photovoltaic Thermal–Phase Change Material system [31, 34, 35]

Component	Density (kg/m³)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-F)	Viscousity (kg/m-s)	Pure Solvent Melting Heat (J/kg)	Solidus Temperature (K)	Liquidus Temperature (K)
Glass	2450	790	0.7	-	-	-	-
EVA	960	2090	0.311	-	-	-	-
PV cells	2330	677	130	-	-	-	-
EVA	960	2090	0.311	-	-	-	-
PVF	1200	1250	0.15	-	-	-	-
Paraffin	@800 @790	2150	0.2	0.01	240800	313.6	317.7
Container (aluminium)	2719	871	202.4	-	-	-	-

2.2 Boundary conditions

In this study, numerical modeling was performed using a coupled system incorporating a Green-Gauss cell-based approach for calculating gradients in fluid cell elements. This approach was chosen because it provides high numerical stability in solving energy conservation and momentum equations in multiphase domains such as PVT-PCM. To ensure adequate simulation accuracy, the convergence criteria are set at a residual of 10^{-6} for the energy equation and 10^{-4} for pressure. The PCM used is a paraffin, selected based on its thermal characteristics, and is suitable for solar energy storage applications within the system's operating temperature range. The ambient temperature is set at a constant of 30 °C, representing common tropical conditions. The heat load is given through heat flux as a representation of solar radiation absorbed by the upper surface of the glass layer, with intensity variations of 400, 600, 800, and 1000 W/m², with a simulation time of 100 seconds. In addition, the convective heat loss is set

at 8 W/m² °C and is assumed to occur evenly across the entire surface of the PVT system. The convergence behavior of the simulation is illustrated in Figure 5, where all RMS residuals for energy, pressure, and data transfer steadily decrease below their respective thresholds, confirming the numerical stability and reliability of the coupled model [36, 37].

Three variants are compared for the container geometry configuration: finless, triangle fin, and trapezoid fin. Each model has default mesh elements (11.334 mm) using mesh relevance settings on the center and span angle center in the fine category to ensure optimal geometric precision. The number of nodes and elements used for PCM domains varies, namely (11650, 8888), (11936, 53426), and (12222, 53542) for each model. Meanwhile, for PVP domains, (134080, 36190), (112848, 26151), and (116216, 28073) nodes and elements are used in sequence. This mesh distribution is tailored to balance computational efficiency and spatial accuracy in the CFD simulation process.
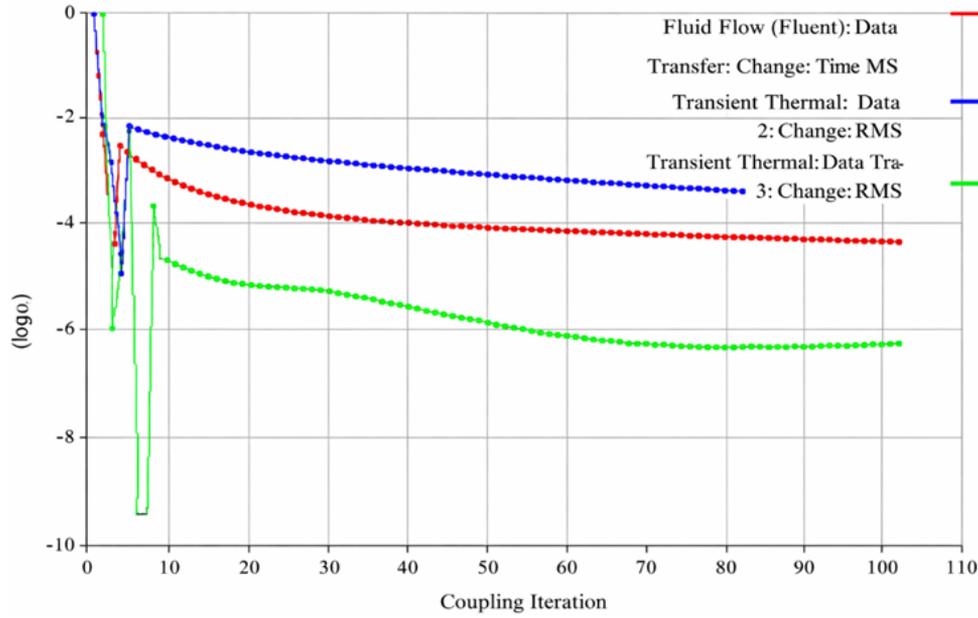
Figure 5. Convergence curve of iterations over simulation time

2.3 Thermal and electrical efficiency formulations

System efficiency analysis PVT-PCM is done by calculating two main parameters, namely thermal efficiency (η_{th}) and electrical efficiency (η_{el}). These two parameters are essential for evaluating the total energy performance of the system, both in terms of heat utilization and the conversion of solar energy into electrical energy. The efficiency calculation approach is based on conventional equations commonly used in thermal and photovoltaic studies, considering key thermal variables such as fluid mass flow rate, type heat capacity, output temperature, and solar radiation intensity. In addition, changes in solar cell performance due to the influence of temperature are also calculated using the reference efficiency parameters and temperature coefficients of the photovoltaic module, $\eta_{th}\eta_{el}$ [38]. Eq. (1) is used to calculate the thermal efficiency (η_{th}) of a system and is written as:

$$\eta_{th} = \frac{\dot{m} \times c_p (T_o - T_{ref})}{\text{IA}} \qquad (1)$$

where, $\dot{m}$ is the mass flow rate (kg/s), c_p is the specific heat capacity of the fluid (J/kg-K), T_o is the output fluid temperature (°C), and T_{ref} is the reference temperature (°C). The value of I represents the intensity of solar radiation (W/m²), while A is the PV panel (m²) area. This equation describes how much heat the fluid successfully absorbs and utilizes from the solar energy hitting the system surface [39]. Furthermore, the electrical efficiency (η_{el}) is calculated using Eq. (2):

$$\eta_{el} = \eta_{ref} \left[1 - \beta_{ref}(T_{ref} - T_o) \right] \qquad (2)$$

This equation considers the decreased PV module efficiency due to the increased operating temperature. In this context, η_{ref} is the reference efficiency of solar cells at a standard temperature (T_{ref}) of 25 °C, which is 0.14 or 14%, and β_{ref}. The PV temperature coefficient is 0.0038/°C. With these two equations, a quantitative description of the performance of the PVT-PCM system in both thermal and electrical terms is obtained, which can be compared between fin configurations as well as against variations in solar radiation intensity [26].

3. VALIDATION

Validation of simulation models is crucial to ensure the accuracy of numerical approaches to actual physical phenomena. In this study, the validation process was carried out by comparing the results of the PV panel temperature simulation obtained from the CFD model with experimental data from previous published studies [17]. Comparisons were made at four variations in the intensity of solar radiation, namely 400, 600, 800, and 1100 W/m². Figure 6 shows that the trend of temperature increase generated by the simulation is in line with the reference data, showing consistency with the thermal behavior of the PV system. The relative error between the simulation results and the reference data remained within an acceptable range, i.e., below 5.5%, which indicates that the numerical model has a reasonable degree of accuracy. Thus, it can be started for further simulation and analysis of the effect of the fin design and use of PCM on the thermal performance and energy conversion efficiency of PVT-PCM systems.

Figure 7 presents the results of the mesh independence test using element sizes ranging from 10 mm to 25 mm for both triangular and trapezoidal fin configurations. The simulation results show that as the mesh element size increases, the average PV temperature also tends to rise due to the lower resolution of thermal gradients in coarser meshes [37]. Furthermore, the smallest error relative to the reference data was achieved at the 15 mm mesh—0.01575 for triangular fins and 0.01375 for trapezoidal fins, while the 10 mm mesh yielded slightly higher errors. All mesh variations produced errors below 10%, indicating numerical stability. Therefore, this study's selected mesh size of 11.334 mm is considered optimal, balancing computational efficiency with simulation accuracy.

Figure 8 presents the average y+ values calculated in the PCM domain for different mesh sizes. The results show that the average y+ remains in the order of 10^{-10} to 10^{-9}, which is

extremely low. These values suggest that the flow in the PCM region is either fully laminar or extremely weak, corroborating the assumption that latent heat storage in solid–liquid PCM systems does not involve strong turbulent interactions. As such, the near-wall dynamics around the fin surface are governed primarily by conduction and diffusion rather than convective turbulence [31, 40]. This confirms that the numerical model adequately resolves the wall behavior for phase change analysis without requiring advanced turbulence models in the PCM region.
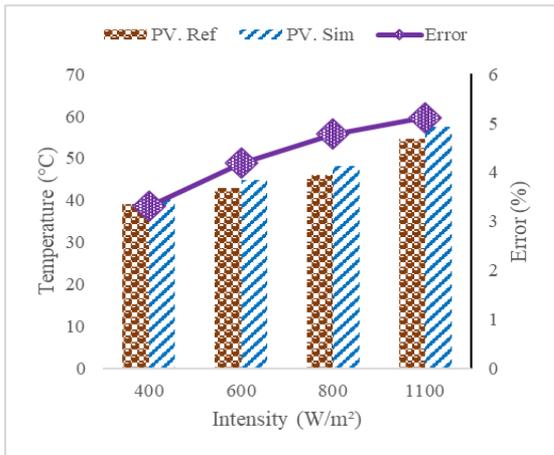

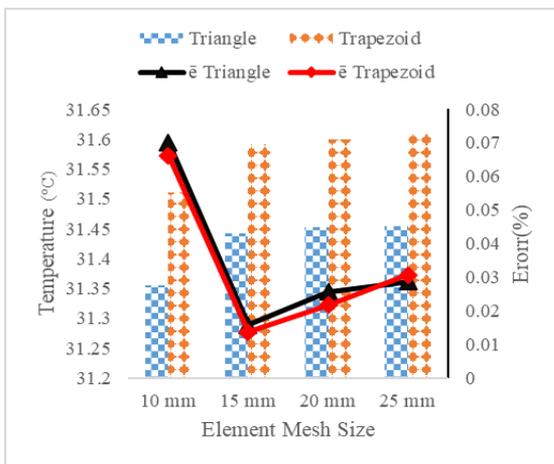**Figure 6.** Validation based on established study [41]
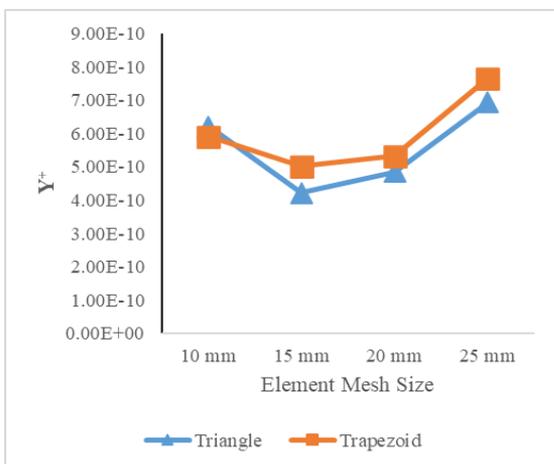

Figure 7. Mesh independence test

Figure 8. Effect of mesh element size on average Y^+ distribution in the PCM domain

4. RESULT AND DISCUSSION

4.1 Simulation result

In the simulation analysis stage, the surface temperature distribution of PV panels is shown in Figure 9 for three system configurations: finless, triangle fin, and trapezoidal fin. The simulation results show that using fins significantly affects the heat distribution on the PV surface. In the finless configuration, the temperature tends to be even but remains higher due to the absence of additional conducting media to aid heat dissipation. In contrast, triangular and trapezoidal fins showed a more distributed heat dispersion pattern, with some areas experiencing better cooling. The dominant colors of blue and green in the configuration with fins indicate a decrease in temperature compared to the red and yellow regions of the finless system. Thus, it can be concluded that fin geometry plays a vital role in modifying the PV system's thermal profile and improving the panels' heat dissipation efficiency.
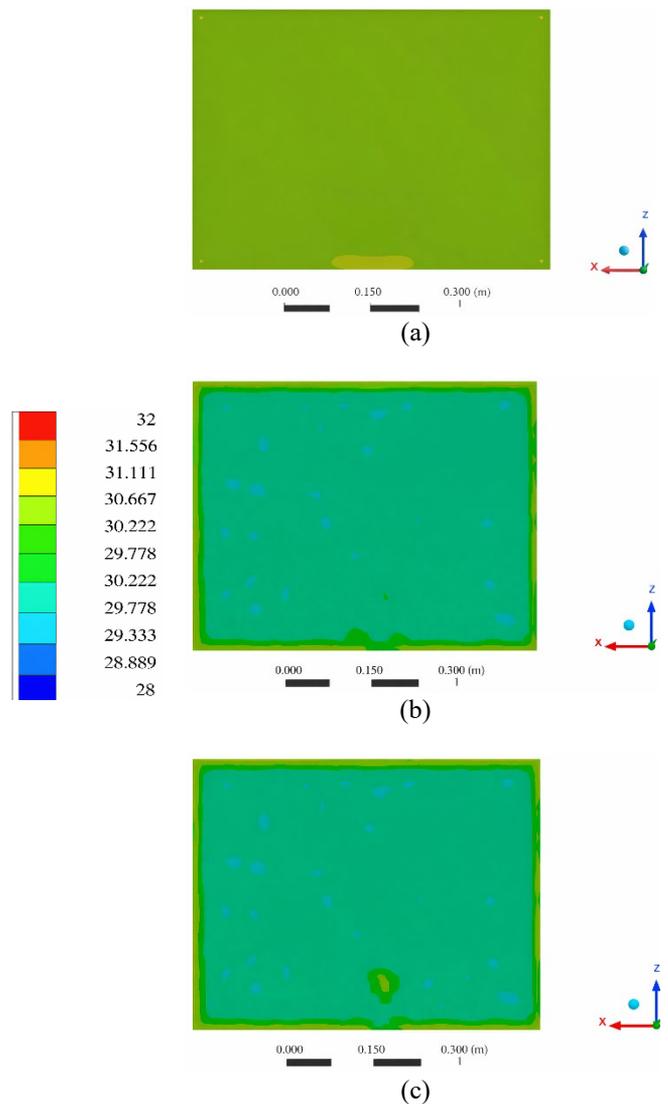

Figure 9. PV temperature distribution (a) Finless (b) Triangle (c) Trapezoid

Figure 10 depicts the temporal progression of the melting liquid fraction in the PCM domain over a 100-second simulation under a radiation intensity of 1000 W/m² for three configurations: finless, triangular fin, and trapezoidal fin. The

results demonstrate that fin geometry plays a significant role in accelerating phase change behavior. At 10 seconds, the liquid fraction in the finless system is just 0.03, while the triangular and trapezoidal fin configurations achieve higher values of 0.07 and 0.10, respectively. This trend continues, and by 50 seconds, the liquid fractions rise to 0.29 (finless), 0.42 (triangular), and 0.56 (trapezoidal), confirming the enhanced thermal response enabled by fin-assisted conduction. Although the trapezoidal fin initially leads the melting rate, the triangular fin maintains a more consistent and stable progression during the latter half of the simulation. By the end of the 100-second interval, the liquid fraction reaches 0.79 for the trapezoidal fin, 0.63 for the triangular fin, and only 0.46 for the finless system. These results highlight that while trapezoidal fins can boost early-stage melting, triangular fins provide more balanced and sustained heat distribution, making them thermally more effective overall in supporting uniform PCM phase transition.
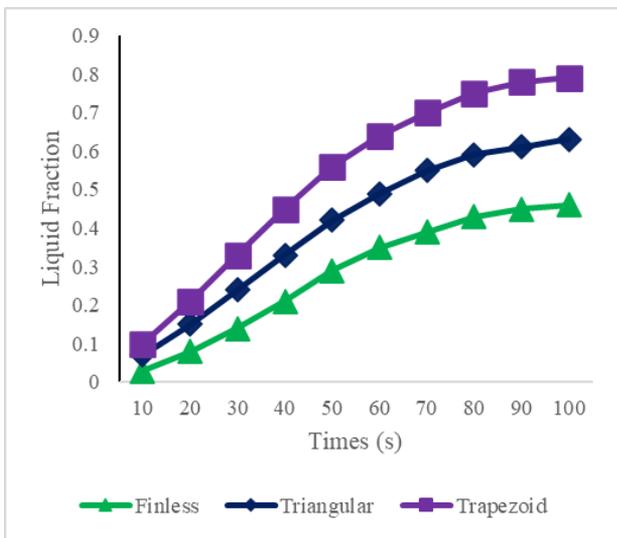

Figure 10. Temporal evolution of the melting liquid fraction at 1000 W/m²

Figure 11 shows the average temperature distribution of PVT systems for three container geometry modes: finless, triangle, and trapezoid, at radiation intensity variations of 400, 600, 800, and 1000 W/m². Numerically, at an intensity of 400 W/m², the average temperature of the finless system was recorded at 30.7 °C, the triangle at 31.3 °C, and the trapezoid at 31.5 °C. This difference continues to increase at higher intensities: at 1000 W/m², the finless reaches 32.6 °C, the triangle 32.9 °C, and the trapezoid reaches its highest at 33.1 °C. Thus, the temperature difference between the finless and trapezoid configurations can be about 0.7 °C–1.0 °C, depending on the radiation intensity level. Although these values may seem small, in the context of PVT systems, such a slight temperature rise can significantly impact the decrease in photovoltaic efficiency due to the sensitivity of the panels to temperature. This analysis shows that the triangle geometry can maintain a more even and efficient heat distribution than the trapezoidal fin, which tends to lead to local thermal accumulation. The linear regression analysis of average temperature versus radiation intensity confirms this behavior. The finless system shows the steepest temperature rise, with a regression equation of y = 0.6443x + 30.082 (R² = 0.976), followed by the trapezoidal fin at y = 0.5648x + 30.57 (R² = 0.9457), and the triangular fin with the lowest slope at y =

0.5441x + 30.803 (R² = 0.9271). A lower slope value indicates that the triangular configuration responds more gradually to increasing solar intensity, signifying a more stable and uniform thermal distribution.
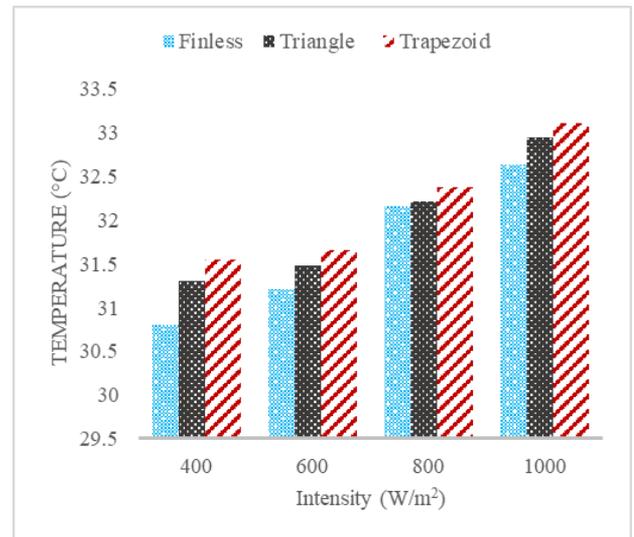

Figure 11. Mean temperature distribution in the PVT system

4.2 Thermal and electrical efficiency analysis

Thermal efficiency and electrical efficiency are two key parameters in evaluating the performance of PVT systems, especially when paired with heat storage materials such as PCM. Figure 12 and Figure 13 present comparative data on the thermal and electrical efficiency performance of PVT-PCM system configurations with finless shapes: finless, triangle, and trapezoid, against variations in solar radiation intensity ranging from 400 to 1000 W/m². Data shows that the shape of the fins plays an essential role in increasing heat transfer from the PV module to the PCM, thus having a direct impact on the thermal efficiency of the system. The higher the intensity of solar radiation, the greater the thermal efficiency achieved by the system, with trapezoidal configurations consistently showing the most optimal results. On the other hand, electrical efficiency tends to increase marginally with the increase in radiation intensity, which is mainly influenced by the more controlled working temperature of the PV module due to the role of PCM and fin design. The decrease in the working temperature of the PV module contributes to the increase in electrical efficiency, as calculated through a thermal correction to reference efficiency.

Numerically, the PVT-PCM system with trapezoidal fins exhibits the highest thermal efficiency compared to other configurations. At a radiation intensity of 1000 W/m², the system's thermal efficiency increased from 14.17% (finless) to 14.97% (triangle) and reached 15.42% for trapezoidal fins. A similar trend is also seen in electrical efficiency, albeit with minor variations, ranging from 14.3% to 14.43%. This suggests that although the role of fin shape on electrical efficiency is not as strong as on thermal efficiency, there is still a significant improvement, especially in the long term of use. The difference in efficiency values scientifically indicates that a more even and efficient heat distribution by the trapezoidal fin geometry can maintain the stability of the PV working temperature within the optimal range. Thus, optimizing the design of the fin geometry is crucial for improving thermal efficiency and positively impacts the overall efficiency of

electrical energy conversion.

The statistical analysis of thermal efficiency in the PVT system was conducted using the ANOVA method to examine the influence of two primary factors: solar radiation intensity and fin geometry. As shown in Table 4, solar radiation intensity significantly affects thermal efficiency, with an F-value of 134.65, dramatically exceeding the critical F-value (F crit) of 4.76. The corresponding P-value is 6.82×10^{-6}, far below the 0.05 threshold, indicating an extreme statistical significance. This confirms that different solar radiation levels significantly influence the thermal performance of the PVT-PCM system. In addition, the effect of fin geometry is also statistically significant, with an F-value of 16.22, exceeding the F crit of 5.14, and a P-value of 0.0038. These results demonstrate that the structural design of fins—whether finless, triangular, or trapezoidal—plays a critical role in thermal performance enhancement. Therefore, environmental (radiation intensity) and design (geometry) factors are proven to contribute significantly to the thermal optimization of the system.

Meanwhile, the ANOVA results for electrical efficiency, as detailed in Table 5, reveal a comparable trend, albeit with a much smaller magnitude of variation. The influence of solar radiation remains dominant, with an F-value of 117.03, exceeding the F crit of 4.76, and a P-value of 1.03×10^{-5}, confirming its statistical significance. Similarly, fin geometry also exhibits a statistically significant effect on electrical efficiency, supported by an F-value of 16.42 and a P-value of 0.0037, surpassing the threshold for significance. However, the Sum of Squares (SS) for both radiation and geometry in the electrical analysis is considerably lower than that in the thermal analysis, suggesting that the actual impact of these variables on electrical output is less practical despite being statistically significant. This is likely due to the inherently narrow range of variation in electrical efficiency across different configurations. In summary, while radiation and geometry affect electrical performance, their influence is far more pronounced and practically relevant in thermal behavior, reinforcing the importance of fin design in thermal

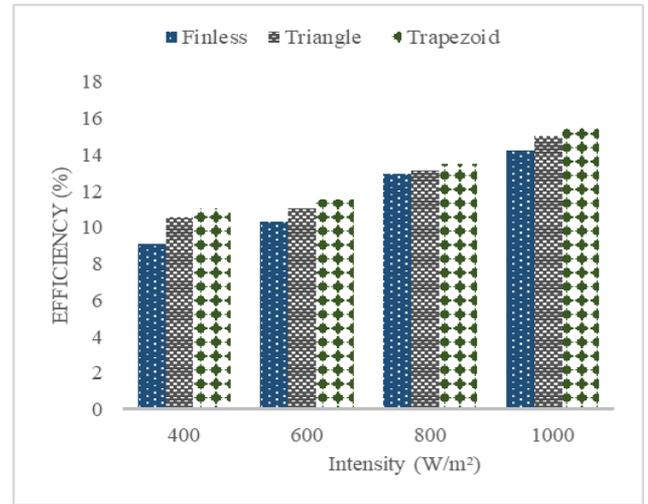management strategies for PVT-PCM systems.

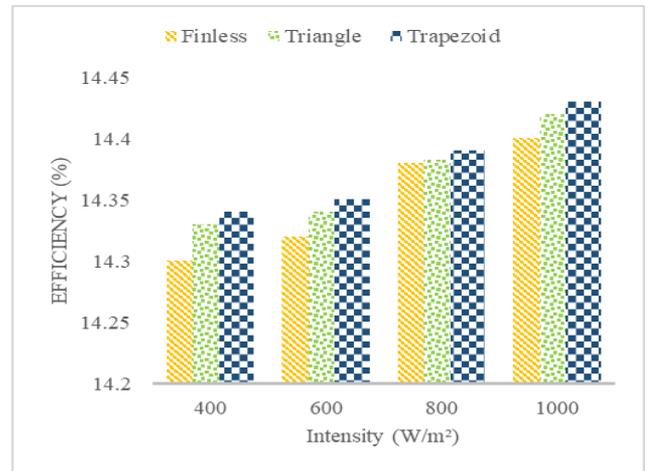**Figure 12.** Thermal efficiency performance of PVT system

Figure 13. Electrical efficiency performance of PVT system

Table 4. Evaluation of thermal efficiency using ANOVA for Combining Photovoltaic Thermal system

Source of Variation	SS	df	MS	F	P-Value	F Crit
Solar Radiation	40.38727	3	13.46242	134.6504	6.82E-06	4.757063
Geometry	3.243117	2	1.621558	16.21874	0.003804	5.143253
Error	0.599883	6	0.099981			
Total	44.23027	11				

Table 5. Evaluation of electrical efficiency using ANOVA for Combining Photovoltaic Thermal system

Source of Variation	SS	df	MS	F	P-Value	F Crit
Solar Radiation	0.016746	3	0.005582	117.0338	1.03E-05	4.757063
Geometry	0.001566	2	0.000783	16.42225	0.003685	5.143253
Error	0.000286	6	4.77E-05			
Total	0.018598	11				

Table 6. Post-Hoc Tukey HSD analysis for thermal efficiency comparisons

Comparison	Absolute Difference	Critical Value	Significantly? (Yes or No)
Finless-Triangle	0.8025	0.396147463	Yes
Finless-Trapezoid	1.2575	0.396147463	Yes
Triangle-Trapezoid	0.455	0.396147463	Yes

Table 7. Post-Hoc Tukey HSD analysis for electrical efficiency comparisons

Comparison	Absolute Difference	Critical Value	Significantly? (Yes or No)
Finless-Triangle	0.01825	0.008652832	Yes
Finless-Trapezoid	0.0275	0.008652832	Yes
Triangle-Trapezoid	0.00925	0.008652832	Yes

The Tukey HSD post-hoc test results for thermal efficiency, as shown in Table 6, indicate that all pairwise comparisons between fin geometries exhibit statistically significant differences. The comparison between the finless and triangle configurations shows an absolute mean difference of 0.8025, greater than the Tukey critical value of 0.3961. This confirms a significant improvement in thermal performance when triangle fins are used. Similarly, the finless versus trapezoid comparison yields an even larger difference of 1.2575, far exceeding the same critical threshold, highlighting that the trapezoidal design substantially enhances thermal efficiency compared to having no fins. Notably, even the triangle versus trapezoid comparison results in a difference of 0.455, surpassing the critical value, and is therefore statistically significant. This suggests that, although both triangle and trapezoid fin designs are superior to the finless configuration, the trapezoid fin geometry provides a significantly higher thermal efficiency than the triangle. These findings reinforce the earlier ANOVA results and quantitatively confirm the hierarchy of thermal performance: trapezoid > triangle > finless.
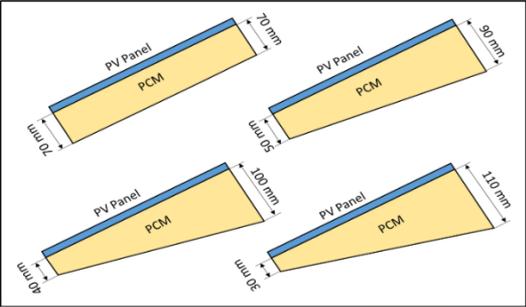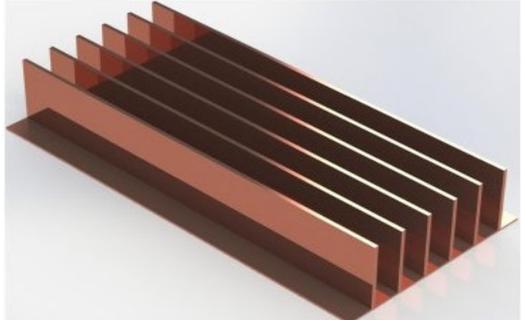
In contrast, the Tukey HSD results for electrical efficiency, presented in Table 7, also reveal statistically significant differences among all geometric configurations, although the magnitude of the differences is numerically small. The difference between finless and triangle is 0.01825, greater than the critical Tukey value of 0.00865. This indicates that even a triangle fin configuration leads to a measurable and statistically valid improvement in electrical output. The comparison between finless and trapezoid shows a slightly larger difference of 0.0275, further reinforcing the improved heat management's positive impact on electrical performance. Interestingly, even the triangle versus trapezoid comparison results in a statistically significant difference of 0.00925, slightly exceeding the Tukey threshold. Although these differences may appear minimal from a practical energy output perspective—ranging between 0.01 and 0.03 absolute efficiency points—they remain statistically valid within the confidence level of the analysis. Therefore, the data suggest that changes in fin geometry, while more impactful on thermal efficiency, also contribute meaningfully and significantly to the stability and enhancement of electrical efficiency in PVT-PCM systems.

4.3 Comparison with previous research

To contextualize the contribution of this study, a comparative analysis with prior research on PVT-PCM systems is presented in Table 8. Previous studies have mainly focused on enhancing system performance through material innovation—such as using different types of PCM (e.g., RT42, RT35HC) or nano-enhanced PCMs—and optimizing fin parameters like height and arrangement. While these approaches have led to notable improvements in electrical efficiency, ranging from 1.6% to 17%, most did not isolate the geometric effect of fin shape under consistent thermal and boundary conditions. As a result, it is difficult to determine how much of the performance gain stems purely from geometry rather than combined variables like material type, volume, or insulation configuration.

Table 8. Comparison of research findings with previous literature

Reference	Fin Design	Photovoltaic Thermal–Phase Change Material System-Phase Change Material Type	Result
[17]		TR42, RT31, and RT25	Electrical efficiency ↑ **17%**, power ↑ **14.6%**
[8]		RT50	Power output ↑ **16%**; Ventilation duration ↑ **101%**
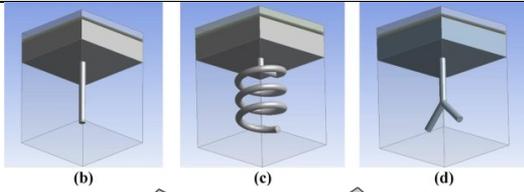
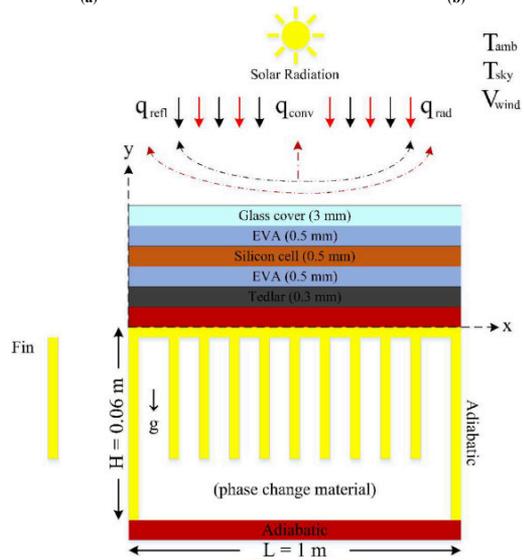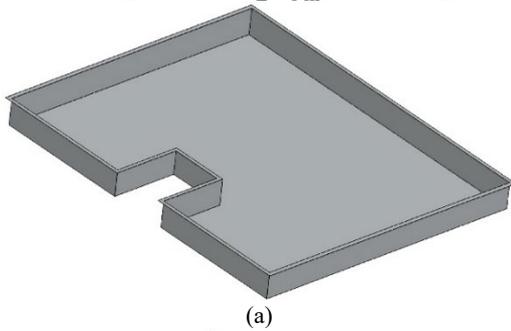| [26] | | RT35-HC | Temp ↓ 9 °C → Electrical efficiency ↑ **4%**, VOC ↑ 0.8 V |

(b)   (c)   (d)
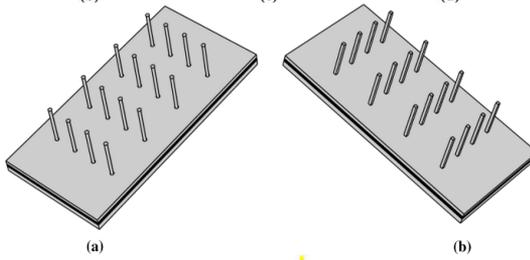
| [42] | | RT25HC | Electrical efficiency ↑ **11.6%** (flat panel, horizontal mount) |

(a)   (b)

| [14] | | RT35HC | Optimal fin height = 3 cm; electrical efficiency ↑ **~1.6%** |

Solar Radiation

T_{amb}
T_{sky}
V_{wind}

q_{refl} ↓ ↓ ↓ ↓ q_{conv} ↓ ↓ ↓ ↓ q_{rad}

Glass cover (3 mm)
EVA (0.5 mm)
Silicon cell (0.5 mm)
EVA (0.5 mm)
Tedlar (0.3 mm)

Fin

$H = 0.06$ m

↓ g

Adiabatic

(phase change material)

Adiabatic

$L = 1$ m
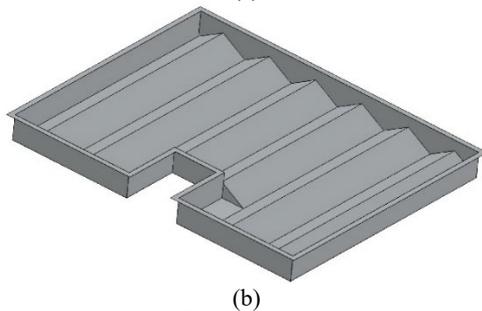
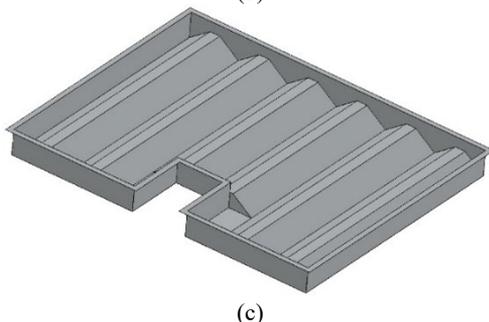| This Study | | Paraffin | Thermal efficiency up to **15.42%** and Electrical Efficiency **14.43%**; triangular fins ↑ uniformity |

(a)

(b)

(c)

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In contrast, the present study offers a novel and structured contribution by focusing exclusively on the effect of fin geometry within a controlled numerical framework. By standardizing the PCM type (paraffin), container surface area, and operating environment, the research isolates fin shape—specifically, finless, triangular, and trapezoidal configurations—as the only varying parameter. This methodological isolation reveals that trapezoidal fins yield the highest thermal efficiency (15.42%). In contrast, triangular fins provide more uniform heat distribution, essential for minimizing thermal stress and maintaining PV performance. The systematic comparison and clear separation of geometric influence make this study one of the few that rigorously evaluate passive design optimization in PVT-PCM systems, particularly for tropical climate applications.

4.4 Research scope constraints

The scope of this study is limited to modeling PVT-PCM systems with simplified environmental conditions to represent static tropical climates. The entire analysis only considers the heat flux imposed on the upper surface of the system without considering changes in direction or radiation intensity due to the sun's daily movement. The model does not include the interaction between natural wind and external convective cooling, so its effect on panel cooling is not represented. In addition, modeling is carried out with thermophysical properties that are assumed to remain constant during the phase process, whereas in real conditions, these values can change nonlinearly. This limitation means that the simulation results cannot fully represent the system's behavior in a long-term dynamic scenario.

Modeling includes only three basic geometric shapes of fin containers without systematically considering fin number, position, or thickness variations. This approach limits exploration to the potential for more complex or innovative thermal design optimization. In addition, no sensitivity analysis was carried out on material parameters such as the thermal conductivity of the container, the density of the PCM, or the thermal characteristics of the PV coating material, which could affect the accuracy of the system's prediction. The simulations also did not include the effects of material aging or thermal degradation due to repeated freeze–liquid cycles, which are essential in assessing the system's long-term reliability. As such, the model is predictive in a limited parameter space and needs further development for comprehensive practical applications and experimental tests.

5. CONCLUSIONS

This study successfully evaluated the performance of the PVT system combined with paraffin PCM through a numerical simulation approach based on ANSYS Fluent and Transient Thermal. The simulation results show that fin geometry plays a vital role in regulating the temperature distribution as well as the energy efficiency of the system. At the highest radiation intensity (1000 W/m²), the system's average temperature reaches 32.6 °C for the finless configuration, 32.9 °C for the triangle, and 33.1 °C for the trapezoid. Regarding thermal efficiency, the trapezoid configuration produced the highest value of 15.42%, followed by the triangle at 14.97%, and the finless at 14.17%. Meanwhile, the electrical efficiency experienced only minor variations, from 14.3% in finless

systems to 14.43% in systems with trapezoidal fins, suggesting that the effects of thermal enhancement contribute to the stability of electrical efficiency within certain limits.

ANOVA analysis confirmed that solar radiation intensity was the most influential factor for thermal efficiency, with an F value of 134.65 and a P-value of 6.82×10^{-6}. Fin geometry also showed a statistically significant effect, with an F value of 16.22 and a P-value of 0.0038. For electrical efficiency, solar radiation remained dominant (F = 117.03; P = 1.03×10^{-5}), while fin geometry also had a significant impact (F = 16.42; P = 0.0037). While both factors affect performance, geometry has a more substantial effect on thermal outcomes. A Tukey HSD post-hoc test was conducted to validate these findings further, revealing that all pairwise comparisons between fin configurations were statistically significant. Notably, thermal efficiency differences between finless–triangle (0.8025), finless–trapezoid (1.2575), and triangle–trapezoid (0.455) all exceeded the critical value of 0.3961. Similarly, electrical efficiency comparisons showed differences as slight as 0.00925, yet all exceeded the critical value of 0.0086, confirming that fin design has a measurable and statistically valid influence on system performance.

However, this study remains limited to simplified environmental assumptions, a short simulation time of 100 seconds, and constant thermophysical properties of materials. Moreover, the fin geometry was only tested in three basic forms, which do not fully capture the potential of more advanced thermal designs. The current modeling did not include long-term thermal cycling, material aging, and environmental factors such as wind and humidity. Future research should include experimental validation, more complex fin variations, and real-world integration scenarios of PVT-PCM systems. The application of advanced statistical tools, such as Tukey HSD, proved useful in differentiating the performance of each geometry and should be incorporated in future design optimization efforts. Additionally, future studies should implement uncertainty and sensitivity analysis techniques like Monte Carlo simulation and Latin Hypercube Sampling (LHS) to better assess the effect of material and environmental variability on long-term system reliability. With these directions, the PVT-PCM system holds great potential to be optimized as an efficient and practical renewable energy solution, particularly for tropical climates.

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