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CFD Study of Malaysian Roof Attic with Phase Change Material (PCM26-29) as a Passive Cooling for Buildings Under Malaysian Climate

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ABSTRACT

Malaysia lies near the equator line with hot and humid weather conditions all year round. Thermal comfort inside residential houses becomes a necessity and increasingly important, especially with the recent increase in global warming. Phase Change Material (PCM) offers passive cooling options for buildings, but investigations in Malaysia are still new and scarce. This study investigates the feasibility of using PCM 26–29 in Malaysian roof structures by using a three-dimensional symmetrical Computational Fluid Dynamics (CFD) model. A steady-state condition was solved to simulate the peak temperature when the PCM absorbs the excess heat in the attic. Two cases are proposed based on the thermal performance using different amounts of PCM mass: 12 kg in Case 1 and 24 kg in Case 2. This study shows that the 12 kg PCM integration leads to a 7.8% reduction in indoor temperatures but doubling the PCM mass only results in a diminishing return of another 3.6% reduction in temperature, presumably due to the low thermal conductivity of PCM. These findings confirm the potential of PCM as an efficient passive cooling strategy, but careful designs of the capsule may be needed to increase the surface contact area, particularly if high PCM mass is to be considered. In this way, the dependency on active cooling, such as air conditioning systems, can be reduced. Further experimental work is recommended to confirm the findings. This research offers valuable insights for integrating PCM into buildings. The positive impact of reducing thermal load in indoor areas provides a sustainable solution in residential areas.

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INTRODUCTION

Environmental concerns and global warming issues have led to increased awareness of energy harvesting (Tuapetel et al., 2025; Haryogo et al., 2023; Yayah et al., 2023) and passive cooling techniques (Azimi et al., 2025) as ways to mitigate the side effects of technology development. Passive cooling involves a variety of approaches, and one of the promising techniques is the use of phase change materials (PCMs) (Alam et al., 2017). In building technology, the PCMs absorb excess heat from the buildings during the day and release it at night. After absorption and release of heat with a PCM, there is generally a more stable indoor condition with reduced HVAC energy consumption (Ascione et al., 2019). The PCM material can be broadly classified into three types: organic, inorganic, and eutectic materials. Each of them possesses significant differences in their thermal properties, such as latent heat capacity and temperature of phase change, and is designed for dissimilar applications (Ghamari et al., 2024). Organic PCMs exhibit chemical stability, but their thermal conductivity is low. The inorganic PCMs may have huge heat capacity to overcome supercooling during operation, but studies reported that they experienced phase separation, such as the formation of the anhydrous phases for hydrated salts PCM (Zhi et al., 2023). The separation impacts the performance due to the instability of the PCM. A more careful composition adjustment, the use of composite materials, the microencapsulation technique, and the use of thickening agents have been continuously investigated to minimize the separation effect in inorganic PCM (Yu et al., 2021). In general, a PCM is characterized by its phase-change temperature, thermal conductivity, and cycling stability, which enable its use in building elements like walls and floors over extended periods, thereby providing the necessary efficiency (Ghamari et al., 2024). Organic PCMs, like paraffin waxes, have good stability, are non-corrosive, and present low toxicity, making them safe in residential applications. Encapsulation technology is used to prevent leakage. Materials with high thermal conductivity are used as capsules to compensate for the low thermal conductivity of the PCMs. The latent heat storage capacity and thermal conductivity of inorganic PCMs, like salt hydrates, are significantly larger than those of organic PCMs. Some of these materials bear latent corrosion risks, contributing to the phasing of the salt involved. Eutectic PCMs represent mixtures of organic and inorganic materials targeted to achieve the targeted melting points and are utilized in tuning PCM performance across various climate zones (Abass & Muthulingam, 2025).

In Malaysia, soaring energy consumption due to population growth, urbanization, and a growing demand for user comfort has sparked an awareness of CO_2 emissions originating from electricity generation. The Department of Statistics Malaysia (2024) reported that residential energy consumption is soaring, with a 15% average increase projected between 2020 and 2024. The building sector took about 35% of total electricity usage. Mainly because of a large share of the power usage, which accounts for 45% contribution from air conditioning usage due to the high ambient tropical temperatures (Sadeghifam et al., 2015). This, therefore, fosters the need for energy-efficient designs to mitigate environmental effects and limit the use of active cooling systems. Studies show that the average temperature of Malaysian houses without cooling systems can exceed 30 °C during the daytime, causing very high thermal discomfort to the occupants (Al-Absi et al., 2021). This is where PCM can play its role, where it can greatly reduce indoor temperature with minimal dependence on mechanical cooling systems. Research indicated that PCMs transitioning around the temperature range of 26–29 °C have proven effective cooling material for tropical climates, as it allows the absorption of excess heat at the peak of daytime and subsequently releases it when the atmospheric conditions become cool at night (Al-Absi et al., 2021). Evola et al. (2013) found that passive cooling designs have emerged as a very real alternative, especially with PCM applications, which produced 35% thermal discomfort reduction. The most common PCM application in housing development consists of PCM integration into building materials, wallboards, floors, ceilings, or glazing (Kuznik et al., 2011). PCM-embedded wallboards are amongst the most common due to the ease of installation and efficacy in inducing continual temperature control in indoor environments. PCM-infused gypsum boards were used and proven to be very effective, especially when installed in walls (Tyagi & Buddhi, 2007).

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Recent studies, as tabulated in Table 1, showed the enormous potential of PCM applications for passive cooling in buildings. According to the studies, the results indicated that integrating PCM in roofs, walls, and windows had an effect of reducing indoor temperature levels by 2–4 °C, with cooling energy savings of up to 15%–30%. The heat and flow conditions within the roof, window, and wall envelopes were investigated to understand the potential of passive cooling techniques for buildings. It was reported that the roof accumulates the largest amount of heat, which affects the cooling capacity of the buildings (Rupa et al., 2023). The CFD models provided a good insight into optimizing PCM placement for energy efficiency in residential buildings in tropical and hot climates by accurately modelling heat transfer processes and other phase change behaviors.

Table 1. The associated studies on using PCM for passive cooling in buildings

Author	Layout suggestion	Study Type	Results and Remarks
Abass & Muthulingam (2025)	PCM, OM37 in wall and roof zones	Experimental	PCM with latent heat of 200–250 kJ/kg reduced peak indoor temperature by 3.2 °C
Azimi et al. (2025)	Exterior wall, roof interfaces and window surrounds	Numerical optimization based on Egypt climate	Optimized PCM location reduced cooling load by 11.49% and heating load reduction of 14.89%
Zhang et al. (2025)	Macro- and micro-encapsulated PCM in building materials to handle instability and leakage	Review	Factors to consider are the climate condition, the PCM thermal properties, the encapsulation technique and placement in building wall/ structure. 5 °C temperature reduction in tropical climate building
Baniassadi et al. (2019)	PCM in roof and wall	Numerical	PCM decreased indoor temperature by 3–4 °C
Fadl & Eames (2019)	PCM in vertical/ horizontal enclosures boundary	Numerical	Mushy zone factor 10^5–10^7 affected heat transfer by 15%
Ghafoorian et al. (2025)	PCM in interior wall based on Tehran climate	Numerical	Peak indoor temperature reduced by 4–5 °C
Yang et al. (2023)	PCM on ceiling	Numerical and experimental	Geometry of the enclosure for the encapsulated PCM influence the thermal performance of PCM. Exposure of surface area of capsules help better performance of PCM for passive cooling.
Prakash et al. (2022)	PCM embedded in roof and walls in Chennai	Numerical and experimental	PCM helps reducing indoor temperature especially during summer
Jiao et al. (2024)	PCM27-29 in roof	Review	Reduced indoor temperature by 3–5 °C
Kitagawa et al. (2023)	PCM on radiant floor	Simulation and experiment based on Indonesia Climate	PCM based floor increase thermal comfort period of up to 68.5% a year
Al-Absi et al. (2021)	Organic PCM on walls of apartment building in Malaysia climate	Simulation	PCM 27–26 increase thermal comfort time to 78% throughout a year
Rashid et al. (2023)	PCM imbedded in concrete, 40% integration is optimal	Experimental & Numerical	Thermal reduction of 1.85 °C and 3.76 °C
Zhang et al. (2007)	PCM incorporated in building materials (wall and ceiling)	Experimental & Numerical	Average ambient temperature reduction is 3 °C

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From the perspective of Malaysia, PCM was tested in the walls of a building under Malaysian climate, and it was reported that 100% of the cooling load removal can be achieved with the possibility of 5 times more cooling load reduction when a copper foam encapsulated PCM was incorporated in the wall (Mohd Isa et al., 2010). The study of Al-Absi et al. (2021) reported that the thermal comfort in a building increased as high as 98% when PCM was incorporated in the wall of a residential building in Malaysia. Despite this promising opportunity, there are very few investigations reported for the feasibility of using PCM as a passive cooling method for Malaysian buildings, particularly near the roof under the Malaysian climate. A study in India showed that heat lost during the mild weather of January in Chennai was reduced by approximately 2 °C when a residential roof made of brick and concrete was integrated with a PCM layer. In Malaysia, the roof is usually very hot, and it consists of an attic space for ventilation purposes. The heat flux rate in Malaysia is highest at noon, and 87% of the heat is received from the roof, leading to a hotter ceiling in a building (Morris et al., 2012). Hot ceiling affects temperatures in the living spaces inside the building. Yet there is no record found for the test of PCM as a passive cooling option for the Malaysian roof.

In light of the potential of PCM as a passive cooling option, the current study investigates the feasibility of employing such a technique under Malaysian climate conditions, particularly at the extreme noon condition. A computational fluid dynamics model of the attic area near the roof was used to analyse the potential thermal reduction for the selected domain. The findings show that PCMs have great potential for passive cooling of buildings in Malaysia.

METHODOLOGY

ANSYS Fluent was used to model the effect of PCM integration within building envelopes for passive cooling. In cases that focused on the final performance, a steady-state simulation was reported to be sufficient and could effectively analyze the thermal behavior inside buildings (Wi et al., 2017). Focusing on the peak condition, the current study involves a simulation that was solved using a steady-state laminar model with a coupled solver for pressure-velocity coupling. The solidification-and-melting solver was also used to solve PCM's latent heat property, with a standard value of the mushy zone set as a constant of 1×10^5. A second-order numerical calculation was performed to solve the continuity, momentum, and energy equations. The continuity and momentum equations converged at 1×10^{-3}, while the energy equation converged at 1×10. Fig. 1(a) shows half of the roof structure that was constructed in ANSYS Design Modeler. The computational domain resembles the typical attic and roof style of a Malaysian house. The attic area was chosen because it is the space that accumulates heat during the daytime, and lowering the temperature in the attic area will lead to a reduction in the house's overall temperature. For ease of validation, the dimensions for this model follow exactly the dimensions reported by Morris et al. (2012).

The volume of the attic space is 4 m × 4 m × 3 tan (33º), where 33° is the inclination angle of the roof. Assuming that the heat is distributed evenly due to the symmetrical feature of the roof, the model was then solved as a symmetrical condition, which reduces computational effort. This assumption may not represent the real situation when the heat distribution is not symmetrical, especially when the sun appears at a certain angle to the house. Nevertheless, the symmetrical assumption provides a good starting point for this preliminary study, as the model was only solved for the peak condition where the heat distribution is assumed symmetrical. For cases with PCM, the PCM is hung within the attic area near the roof, around the area where the trusses for the roof structure can be found. Hanging the PCM inside the attic between the roof and the panel could enhance heat transfer throughout the surface of the PCM capsules (Yang et al., 2023). Fig. 1(b) shows the location of the encapsulated PCM near the roof for cases where PCM is installed in the attic space.

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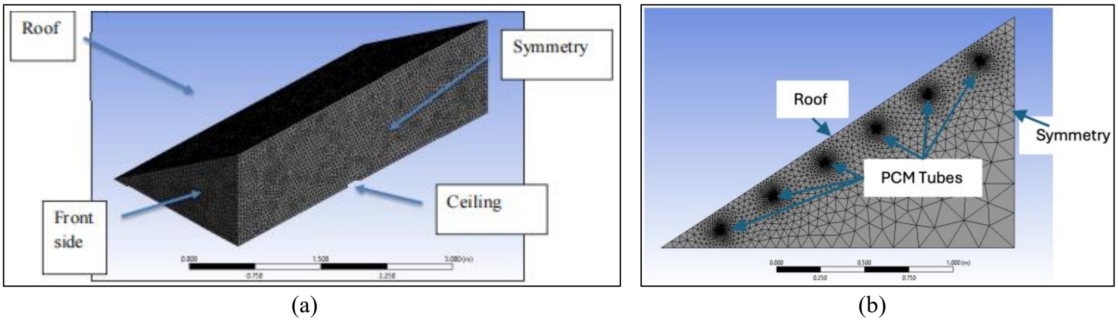

Fig. 1. (a) Boundary conditions on half the attic domain with a symmetry wall and (b) the location of encapsulated PCM near the roof of the computational domain.

The model shown in Fig. 1 consists of 35626 nodes and 181263 elements. The selection of the size element was based on the work of Guo et al. (2023). As illustrated in Fig. 2, there is a slight variation in temperature as the mesh size is finer, but the result is approaching a mesh independence state where further refinement of the mesh does not significantly change the result (Mohamad Fauzee et al., 2024). The results indicate that the simulation has reached a mesh independence state at 0.05 m element size, providing an insignificant change in the result as the mesh size changes. Computational time increases significantly as the size of the element decreases. This is a challenge for CFD, where a trade-off must be made between accuracy and computational capability. Details on the mesh check information are provided in the appendix. The size element of 0.05 is found to be sufficient for the current study.

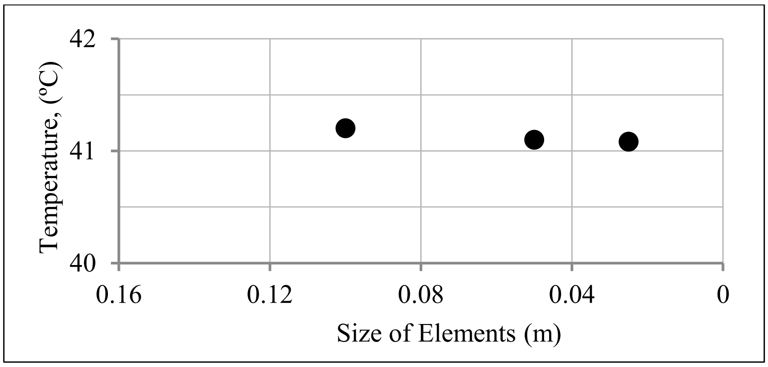

Fig. 2. Grid independence test based on the temperature change with the change of the mesh size.

Once the mesh and geometry were updated in Ansys, the materials were set according to Tables 2 and 3. The solver was determined by monitoring the iteration and convergence until no significant changes were observed in the iteration of the solution (Iten et al., 2018).

For boundary conditions, the roof was set at a static noon temperature of 54.4 °C following the condition stated in the published work of Morris et al. (2012). Morris et al. (2012) numerically solved the heat transfer model of a typical residential house in Malaysia with consideration of the Malaysian climate. The model was used as a benchmark case to mimic the Malaysian roof under Malaysian climate conditions without PCM. Walls of the model are defined as stated in Fig. 1.

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Table 2. Material properties

Material	Density, ρ $[kg/m^3]$	Heat capacity, C_p $[J/kgK]$	Thermal conductivity, k $[W/mK]$	Thickness, t [mm]
Copper (ASTM B-88 Type M)	8970	381	387.6	0.813
Roof tiles	1890	1000	0.836	10
Plaster Ceiling	720	1000	0.108	4.5
Fiberglass	32	670	0.035	100

Table 3. Material properties of PCM26-29

Material	PCM26-29, SP29Eu
Density, ρ_s $[kg/m^3]$ - Solid	1600
Density, ρ_l $[kg/m^3]$ - Liquid	1500
Specific heat, C_p $[J/kgK]$	2000
Thermal conductivity, k $[W/mK]$	0.5
Melting range, T_{melt} [°C]	26–29
Latent heat, L $[J/kg]$	200,000
Max temperature, T_{max} [°C]	60

The ceiling was set to allow for convection to take place. This was done by considering the Rayleigh number, Ra, for the natural convection effect inside the roof and the heat load, Q_{load}, as shown in Equations 1 and 2. The terms L and m represent the latent heat and the mass for PCM 26-29, respectively. The Nusselt, Nu, and Rayleigh, Ra, numbers correlation presented in Equation 2 suits the natural convection within the range of Rayleigh number between 10^4 and 10^7 (Cengel & Ghajar, 2013). This choice is ideal for the Malaysian climate, with temperatures normally ranging between 25 °C and 34 °C (corresponding to Ra of approximately 10^6). The resulting heat transfer coefficient, h, is 3.35 W/m^{2}K. Post-processing is performed to visualize the thermal activity within the domain, including the total temperature, heat flux, and changes in ceiling temperature.

$$Q_{load} = mL \tag{1}$$

$$Nu = \frac{hl}{k} = 0.54Ra^{\frac{1}{4}} \tag{2}$$

The formula for obtaining the approximate mass, m, of the PCM was shown in Equation 1, where the value depends on the heat load, Q_{load}, which is defined based on the temperature and heating conditions of the roof tiles. Based on the calculation, the roof needs to be installed with more than 12 kg of PCM 26-29 to absorb the heat in the attic. The PCM is encapsulated inside a standard off-the-shelf 22.2 mm diameter copper tube. At least 6 rods of 4 m long copper tubes filled with PCM are needed. Based on this evaluation, the study will be conducted for three cases, as defined in Table 4. The benchmarked case is a model without PCM, following the experimental research of Morris et al. (2012).

The material properties for the copper tube, ceiling, and roof were tabulated in Table 3. The 22.2 mm copper tube was selected based on the standard measurement of ASTM B-88 type M (KSJ Global Sdn. Bhd., 2026). The PCM26-29 was selected based on the RUBITHERM SP29Eu data sheet, which was reported to give the highest latent heat (200000 J/kg) with a suitable melting point between 26–29 °C, and the properties were as listed in Table 4.

https://doi.org/10.24191/jmeche.v23i2.8934

Table 4. Details of investigated cases

Name of case	Details
Case 0	0 kg PCM (Benchmark case for validation with Morris et al., (2012))
Case 1	12 kg of PCM
Case 2	24 kg of PCM

RESULTS AND DISCUSSION

The simulation for Case 0 provides validation for the model. The results are shown in Fig. 3 and Fig. 4. For Case 0, the lowest temperature of 41.1 °C is shown to be achieved at the bottom surface of the attic space, as indicated in Fig. 3. The bottom surface is the ceiling. In the benchmark case of Morris et al. (2012), it was stated that their simulation work showed a 40 °C temperature at the ceiling when the outdoor temperature is at its peak, which is at noon between 1300 hrs and 1400 hrs. The percentage of temperature difference at the ceiling between the current study and that of Morris et al. (2012) shows an error of 2.75%, which is acceptable considering that the current model is supported by the theoretical calculations of Equations 1 and 2 to account for the ceiling wall conditions that were not reported by the published work. In this model, the ceiling wall was modelled with a heat transfer coefficient that was theoretically calculated based on Nusselt and Rayleigh correlations as presented in Equation 2, as described in the methodology section. The resulting ceiling temperature with a small error of 2.75% shows that the theoretical calculation of the heat transfer coefficient as the boundary condition for the ceiling wall in the model successfully mimics the Malaysian roof condition as reported by Morris et al. (2012).

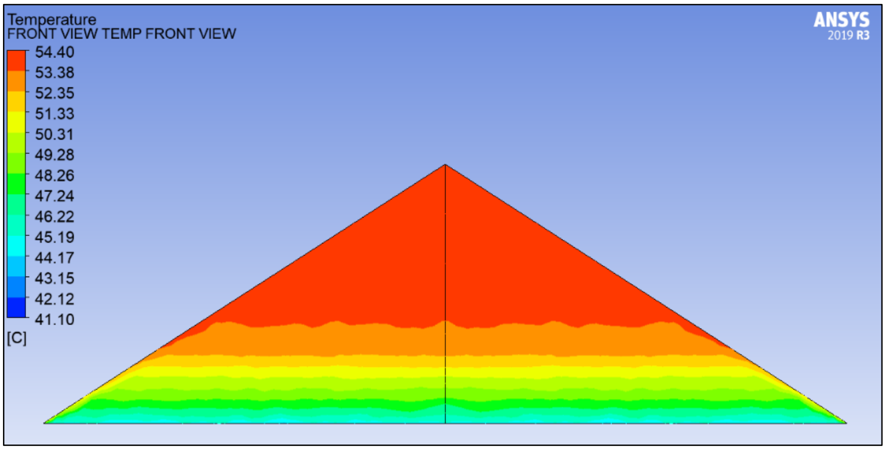

Fig. 3. Temperature contour for the cross-sectional view of the attic space for Case 0.

As mentioned before, two cases of the PCM model were solved in this simulation. Case 1 was embedded with 12 kg of PCM 26-29, resulting in 37.9 °C as the lowest temperature at the ceiling, as shown in Fig. 5. The PCMs that are encapsulated by copper tubes were placed at the location of the truss near the roof, as was illustrated in Fig. 1. It is interesting to note that the use of PCM leads to a 3.2 °C temperature drop for the ceiling (i.e., 7.78% drop compared to the 41.1 °C reported for the benchmark case without PCM). This means that part of the heat in the attic is absorbed by the PCM, and this brings down the temperature at the ceiling.

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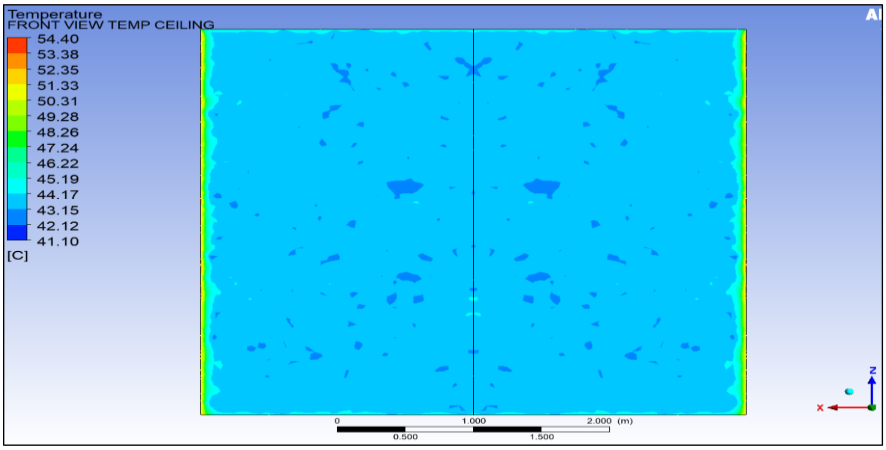

Fig. 4. Ceiling surface temperature distribution for Case 0.

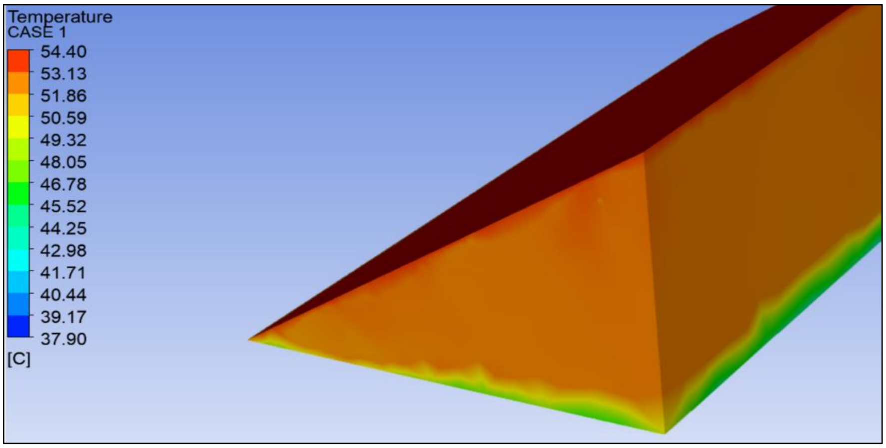

Fig. 5. Temperature contour for half the roof in Case 1.

Fig. 6 shows the central plane distribution of the temperature within the attic space when 24 kg of PCM is placed in the attic. The temperature can be seen to decrease from the roof on top to the ceiling surface at the bottom. The temperature contour for the plane that represents the ceiling (bottom surface) is shown in Fig. 7 for the attic with 12 kg of PCM. The central area of the ceiling shows cold areas with a minimum temperature of 36.4 °C, while the side represents the roof. In general, the temperature change distribution is almost similar to Case 1 but with a different amplitude. The addition of another 12 kg mass of PCM results in a smaller temperature drop at the ceiling, lower than that reported for Case 1. In this case, the minimum temperature T_{min} recorded at the ceiling surface is 36.4 °C. PCM generally possesses small thermal conductivity, which can limit the ability to absorb or release heat (Yang et al., 2023). This means doubling the volume may not lead to a proportional increase in heat transfer rate, leading to a smaller than expected temperature drop (Frank et al., 2023).

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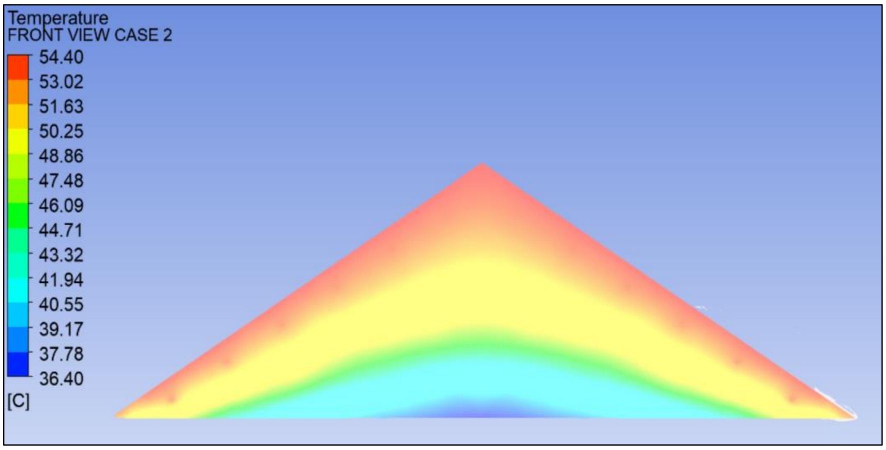

Fig. 6. Temperature contour for the cross-sectional view of the attic in Case 2.

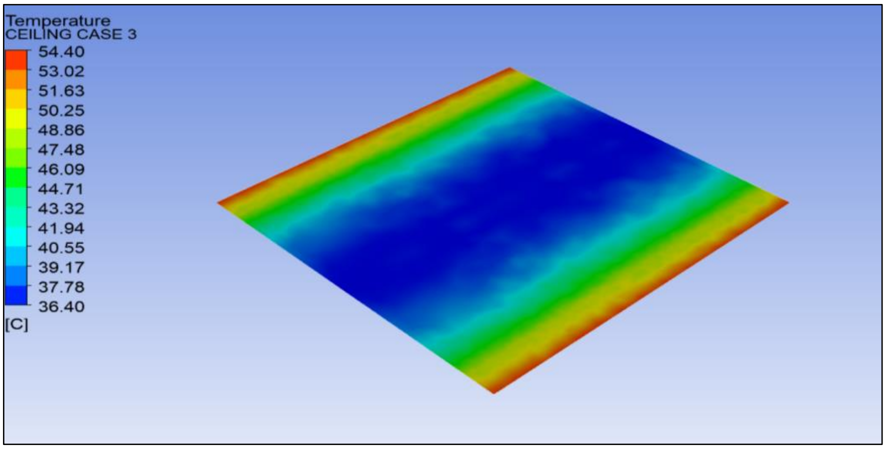

Fig. 7. Temperature contour of the ceiling surface in Case 2.

The data for temperature reduction and minimum temperature at the ceiling surface are tabulated in Table 5. Case 0 does not have any PCM, and the minimum temperature within the attic is 41.1 °C, which represents the ceiling temperature of a base case without PCM in the attic. Once installed with 12 kg PCM, the ceiling temperature drops by 7.78 %. The result also shows that the increase of PCM mass from 12 kg to 24 kg led to a further reduction of 11.43 % in temperature at the ceiling surface compared to the benchmarked case. Even though the mass of PCM is doubled, only 3.65 % of temperature reduction is achieved. This means that increasing the mass of PCM alone could not lead to a bigger drop in temperature, presumably due to the challenging heat transfer dynamics of PCM as reported in many studies (Yang et al., 2023). A better thermal design, such as the addition of fins with several designs within the PCM, may need to be considered to ensure that the PCM can work efficiently.

Fig. 8 provides the plot of temperature difference versus mass of PCM. The temperature difference is calculated as the difference between the temperature of cases with PCM and that of the benchmarked case without PCM. As expected, the temperature difference of Case 0 is null, as Case 0 is the benchmarked case. The implementation of 12 kg of PCM reduces the ceiling temperature by 3.2 °C. Doubling the mass led to

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only a 1.5 °C drop in temperature. This means that doubling the mass of PCM only results in half the drop in temperature. The smaller change in temperature due to the increase in PCM was also reported in other studies related to PCM, where challenges in handling the heat dynamics of the low thermal conductivity PCM were reported as the main contributor (Yang et al., 2023). Hence, further increment of PCM mass may not be necessary in this case.

Table 5. Temperature reduction for all cases

Case number	Mass of PCM, m (kg)	Minimum ceiling temperature, T (°C)	Temperature difference, $[\Delta T = T_{Case\ 0} - T_{Case\ 1,2}]$ (°C)	Temperature reduction $\left[\frac{T_{Case\ 0} - T_{Case\ 1,2}}{T_{Case\ 0}} \times 100\%\right]$ (%)
Case 0	0	41.1	0	0
Case 1	12	37.9	3.2	7.78
Case 2	24	36.4	4.7	11.43

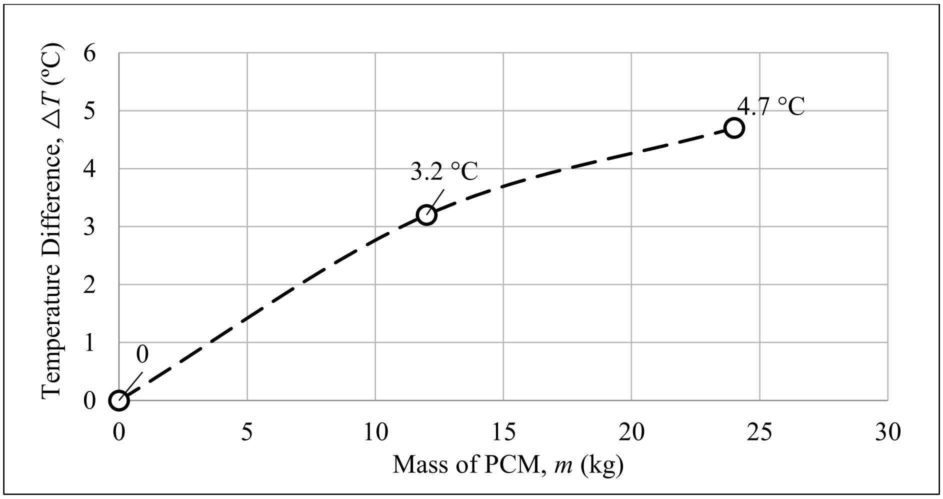

Fig. 8. Thermal reduction at the ceiling presented as temperature difference, ΔT, for cases based on mass, m, of PCM.

CONCLUSION

In conclusion, the potential of implementing encapsulated PCM for passive cooling in the Malaysian roof of a residential building is shown, where a temperature drop in the building can be achieved when a 12 kg and a 24 kg PCM are installed in the attic space. This observation is limited to the peak condition, which is simulated based on the assumption of a steady-state, symmetrical model. The result shows a 7.78 % reduction in the ceiling surface temperature when 12 kg of PCM 26-29 encapsulated in copper tubes are installed along the truss near the roof. A further reduction of 3.65 % was achieved when 24 kg of PCM was used. The diminishing reduction of ceiling temperature with an increase of PCM mass indicates the need for better design of the capsules to enhance surface contact area for better heat transfer in PCM. This calls for a transient model investigation to capture the effect of the dynamic temperature changes at the roof and the resulting solidification and melting of the PCM, especially when the roof is exposed to temperature fluctuations during the day and night of different seasons. Other factors, such as the role of humidity, which was excluded in the current study when modelling the air in the attic, may also need to be considered in the future. Experimental studies are also needed to confirm the insights reported in this paper.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Sadradin, M. A. A., Mohd Saat, F. A. Z.; data collection: Sadradin, M. A. A.; analysis and interpretation of results: Sadradin, M. A. A., Mohd Saat, F. A. Z.; manuscript preparation and editing: Sadradin, M. A. A., Mohd Saat, F. A. Z., Koyunoğlu, C., Herawan, S. G.

DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Grammarly for grammar and style enhancement. ScopusAI and NotebookLM were used to help organize and structure content in the literature review. After using these tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

DATA AVAILABILITY/ SUPPLEMENTARY MATERIALS

The datasets generated during the current study are available in the Zenodo repository, https://zenodo.org/records/17084039

ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknikal Malaysia Melaka.

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APPENDIX

The meshing style used for the attic model in this study is known as the Patch Conforming Method, as the method was reported to produce accurate results by capturing heat transfer phenomena near wall layers (Iten et al., 2018). The body and face were named specifically for boundary conditions that were set in the solver. The average element size is 0.05 m. The model consists of 35626 nodes and 181263 elements. The selection of the size element was based on the work of Guo et al. (2023). The key metrics that are used to assess mesh quality are the Orthogonal Quality and the Skewness Quality. High-quality mesh is crucial for the accuracy and stability of numerical simulations.

Orthogonal Quality measures the alignment between the mesh cell face and the vector connecting the cell centres. The value should be in the range of 0.7 and 1.0. Skewness is defined as the deviation of cell angles from their ideal values, for example, 90° for hexahedral cells and 60° for tetrahedral cells. Skewness is a strong indicator of mesh distortion. Values below 0.25 are considered excellent, values up to 0.5 are acceptable, and values above 0.85 are generally unacceptable as they can introduce significant interpolation errors and affect solution fidelity. Table A1 breaks down the effect of mesh sizes on the accuracy of the results.

Table A1. Minimum temperature at ceiling for mesh independence test

Element Size	Total Number of Elements	Mesh Nodes	Orthogonal Quality	Skewness Quality	Minimum Temperature [°C]	Computer Time [hours]
0.1	6862	32586	0.9	0.116	41.203	0.5
0.05	35626	181263	0.768	0.118	41.1	1
0.025	184070	971650	0.68	0.121	41.082	3.5

The finer the mesh size, the higher the number of elements and nodes. The increase in the number of elements and nodes is typical in mesh refinement, and the case with finer meshes results in higher computational resolution. The size element of 0.05 is found to be sufficient for the current study.

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