SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V10I12P103

Volume 10 Issue 12, 23-32, December 2023

Original Article

PCM-Enhanced Ceilings in Hot Humid Climates: Experimental and Numerical Analysis of Single and Double-Layer Systems for Energy Savings

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Received: 10 October 2023 Revised: 26 November 2023 Accepted: 11 December 2023 Published: 23 December 2023

Abstract *- In this study, the experimental investigates the potential of Phase Change Materials (PCMs) in enhancing the thermal efficiency of building envelopes in hot and humid climates. The study involves constructing rooms with and without PCM, both in single and double layers and evaluating their thermal behaviour in the extreme heat of Chennai. The chosen commercial organic PCM, with a melting range of 35°C to 40°C, aligns with the temperature variations at the site. Experimental results reveal that the double-layer PCM building envelope exhibits a maximum temperature variation reduction of 8.5°C compared to a single-layer PCM. Validation through experimental and numerical simulations using ANSYS workbench supports the findings. The study considers various PCM temperature ranges, and under free-floating ambient conditions, the PCM-installed room demonstrates a significant drop in indoor air temperature compared to the room without PCM. The percentage of latent heat energy utilized by the PCM to achieve specific temperature differences is also presented, showcasing the effectiveness of PCM integration in mitigating high energy consumption associated with air conditioning in hot climates. The experimental results were validated using experimental and numerical simulation using the ANSYS workbench.*

Keywords *- Phase Change Materials, Single and double layers, Green architecture, Building envelope, Hot humid climate.*

1. Introduction

Building construction consumes around 30% of worldwide energy consumption and contributes to nearly 15% of direct carbon dioxide emissions [1]. The need for energy in buildings is increasing due to several factors. Firstly, developing countries now have better access to energy, leading to increased demand. Additionally, there is a growing need for air cooling at room temperature, as well as heating requirements in continental areas. Furthermore, the widespread use of energy-consuming appliances is contributing to the rise in energy demand [2]. According to estimates, by the year 2050, the combined floor space covered by buildings in India, China, Africa, and North America is projected to reach around 235.5 billion square kilometres [3].

Phase Change Materials (PCMs) are commonly utilized in the building envelope through passive or active means. Despite the economic and technological advantages associated with the passive approach, it is nonetheless plagued by thermal management challenges, including unregulated heat transfer and suboptimal heat charging and discharging processes [4]. Hence, it is imperative to implement a suitable approach for integrating (PCMs) in order to consider the appropriate PCM type, effective PCM position and quantity, and an efficient incorporation method [5]. Researchers often fail to take into account all the aforementioned critical factors that impact the thermal performance of (PCMs) throughout their service life.

Technologies for Thermal Energy Storage (TES) may be able to handle both of these issues successfully [6]. These devices can store and release significant quantities of energy with efficiency thanks to the (PCMs) that are incorporated into them. Materials that shift from one phase to another, including from a solid to a liquid or from a liquid to a gaseous state, are referred to as Phase Change Materials (PCMs) [7]. During this transitory time, (PCMs) have the power to take in or release a considerable amount of energy in the way of latent heat. The energy in question has the potential to be employed in numerous applications related to temperature control, including both heating and cooling procedures [8]. The materials possess the capability to maintain a consistent temperature, allowing them to serve as both insulators and thermal dissipators. As a result, they are employed in clothing engineered explicitly for highly challenging thermal environments, guaranteeing extended thermal satisfaction for humans [9].

Moreover, these materials are utilized in specific electronic equipment for the purpose of regulating thermal conditions and mitigating the occurrence of excessive heat accumulation. Multiple scholars have proposed the adoption of comparable strategies for the addition of (PCMs) in both active and passive cooling, heating, and ventilating systems inside architectural structures [10].

Choosing the suitable raw materials to make a form-stable (PCM) is subject to a number of factors, with the climate of the building being the most important [11]. In the present situation, the phase transition temperature of the (PCM) must correspond with the distinctive ambient temperature of the particular region. Adding waste materials from other processes could also be an excellent way to make a Phase Change Material (PCM) with a stable shape [12].

In the course of our comprehensive investigation, we initially opted for a specific polymer in order to facilitate the development of a form-stable (PCM). This particular polymer exhibits phase transition temperatures that are suitable for climatic locations characterized by moderate to high temperatures, such as Mediterranean regions [13].

However, it is imperative to recognize that the mixing of renewable energy sources, namely wind and solar, into the electrical grid may reduce the system’s resilience because of their inherent volatility [14]. It is projected that worries about energy supply insecurity will increase as a result of the increasing reliance on power to achieve carbon neutrality targets by 2050 [15]. Using energy flexibility is one such tactic for reducing the differences between the supply and demand of power [16]. One potential answer for enhancing grid performance and integrating a significant portion of renewable energy sources is thought to be the energy system’s flexibility [17].

Recently, there has been a growing focus on using (PCM) in buildings to improve their thermal energy efficiency [18]. (PCMs) can be installed in residential buildings’ walls and ceilings, which provides the dual benefit of lowering indoor temperature fluctuations and lowering the energy consumption associated with HVAC systems. Using latent thermal storage methods in building construction [19]. In the field of thermal energy, researchers frequently utilize diverse approaches during their study investigations [20]. While many academics have shown a predisposition to do experimental studies, there has been a notable increase in interest in numerical methods with finite difference methods, especially in recent years [21]. The (CFD) method, which incorporates both finite difference and finite volume methods, finds wide-ranging applications in industrial contexts, particularly in the domain of thermal investigations [22-23].

Significant research has been done on the optimization of (PCM) quantity and PCM melting temperature, according to the previously mentioned literature. However, there is a lack of academic research that examines the association between energy savings and the melting temperature of (PCMs) and offers a quantitative analysis of this correlation. In order to fill this research gap, the current work optimizes the (PCM) thickness and melting temperature. It performs a quantitative assessment of how sensitive energy savings are to PCM melting temperature.

Thus, the main goal of this work is to close the existing research gap by maximizing the (PCM) melting temperature and carrying out a quantitative analysis to evaluate the effects of various PCM melting temperatures on energy savings. The study of this will be done using Computational Fluid Dynamics (CFD) analysis. The primary objective is to analyze the thermal behavior of rooms with single and double layers of PCM and those without PCM. This helps in understanding how different configurations impact temperature control in building envelopes.

2. Materials and Methods

The experimentation used product materials that were readily available locally; they contained EPS (Expanded Polystyrene) beads as a coarse aggregate, quarry sand as a fine aggregate, and cement as a binding agent. The entire work was mixed and cured using regular water.

Ordinary cement of grade 43, which complies with IS:8112, was utilized. Clean waterway sand from Zone II, which complies with IS 269-1989, was used. The sand of 3.75 mm was sieved; there were no organic contaminants, silt, or clay present. In compliance with IS 2386-1963, the aggregate’s physical conditions, including stage, fineness modulus, specific gravity, and bulk modulus, were tested.

In this investigation, locally accessible crushed stone with a 20 mm and 10 mm downsize was utilized as the coarse aggregate. This experiment used materials and goods that were easily accessible for experimentation. The coarse aggregate is made of expanded polystyrene beads, while the fine aggregate is made of quarry dust. Fly ash, another name for cement serves as this product’s binding ingredient. All of the mixing and curing processes were carried out using regular water. Regular cement of the 43-grade variety that complied with (IS:8112) was the type of cement utilized.

Both the consistency and freshness of the cement were assessed. That was discovered to be lump-free, dry, and pure. The sand was taken from a clean stream in Zone II that complied with IS 269-1989. Three-quarter-millimeter mesh was used to sift the sand. It included none of the organic pollutants, silt, or clay. To ascertain the aggregate's physical requirements, a battery of tests was conducted in compliance with IS: 2386-1963. Gradation, bulk modulus, specific gravity, and fineness modulus were among the tests that were shown. In this particular research topic, the coarse aggregate was locally available crushed stone with a downsize of 10 and 20 mm that was gathered from nearby quarries.

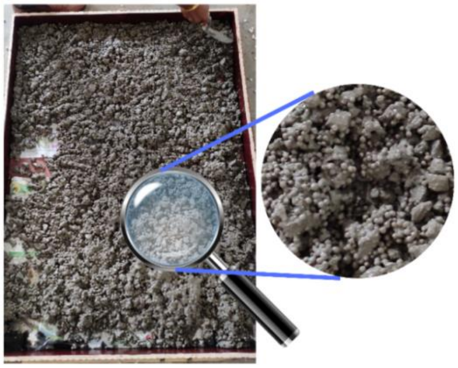


Fig. 1 Mixing of EPS concrete

A study conducted in compliance with the international standard 2386-1963 on the physical properties found that the specific gravity of coarse aggregate was 2.68. A total of 0.25% of the water was absorbed. Figure 1 shows the mixing of EPS balls as a substitute for the standard concrete's aggregate, which is usually crushed stone. For instance, improved thermal and acoustic insulation might be advantageous for conventional concrete. Potable water was necessary for both the concrete's mixing and curing processes to be completed successfully.

Consequently, it was found that the water meets all requirements for purity and suitability for use in making the concrete mix. No undesirable organic chemicals or inorganic components from nearby quarries should be present in the mixing water in sufficient amounts. The physical attributes have been established in accordance with IS 2386-1963. It was discovered that coarse aggregate had a specific gravity of 2.68. There was 0.25% water absorption. EPS balls are utilized as an aggregate in place of the crushed stones found in conventional concrete to improve traditional concrete's thermal and acoustic insulation. Both mixing and curing concrete might be done with potable water. Therefore, it was determined to be certain that the water met all the criteria for purity and suitability for use in the concrete mix. Unwanted organic materials or excessive amounts of inorganic elements shouldn't be present in mixing water.

In this experiment, a PCM BhiimTM composed of locally obtainable paraffin wax was purchased from Suvarna Organic Gujarat. This type of PCM Bhiim is a petroleum-based product produced by the dewaxing step of the crude oil refining process. It has a temperature at which it melts in a range of 35°C to 40°C, as indicated in Figure 2, which makes it an ideal option for the temperature change in the site that is being studied and the passive technique that is being utilized. Table 1 has a listing of additional characteristics that are associated with this PCM Bhiim.

The property and its features appear to be pale and yellowish, and the composition consists of 35% oil and 65% wax. 35–40 is the temperature range for melting, expressed in degrees Celsius, and the latent heat kilojoules per kilogram is 189, which applies to both solid and liquid states. Capacity for heat in kilocalories per kilogram at 2.3. 0.22 in terms of watts per meter kelvin for thermal conductivity (solid/liquid).

The density is 925 kg/m^3 for solids and 850 kg/m^3 for liquids. Capacity for heat in kilocalories per kilogram at 2.3. Efficiently capturing Protein-Protein Interaction (PPI) data, this 4-channel recorder is equipped with temperature sensors for monitoring both inside and outside the room temperature.

Table 1. Physical properties of PCM

Property and Its Feature	Unit Value	Properties VALUE
Appearance	-	Light Yellowish in Colour
Composition	%	35 oil + 65 wax
Melting Temperature Range	°C	35°C to 40°C
Latent Heat	kJ/kg	189
Conductivity of Thermal (Solid & Liquid)	W/m.K	0.22
Density (Solid/Liquid)	kg/m^3	925/850
Specific Heat Capacity (Solid/Liquid)	kJ/kg.K	2.3

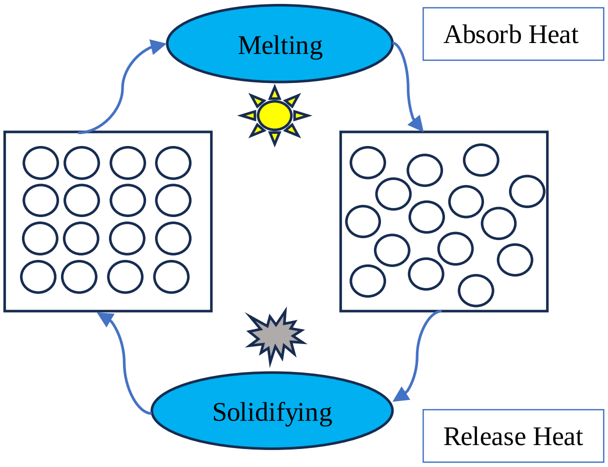
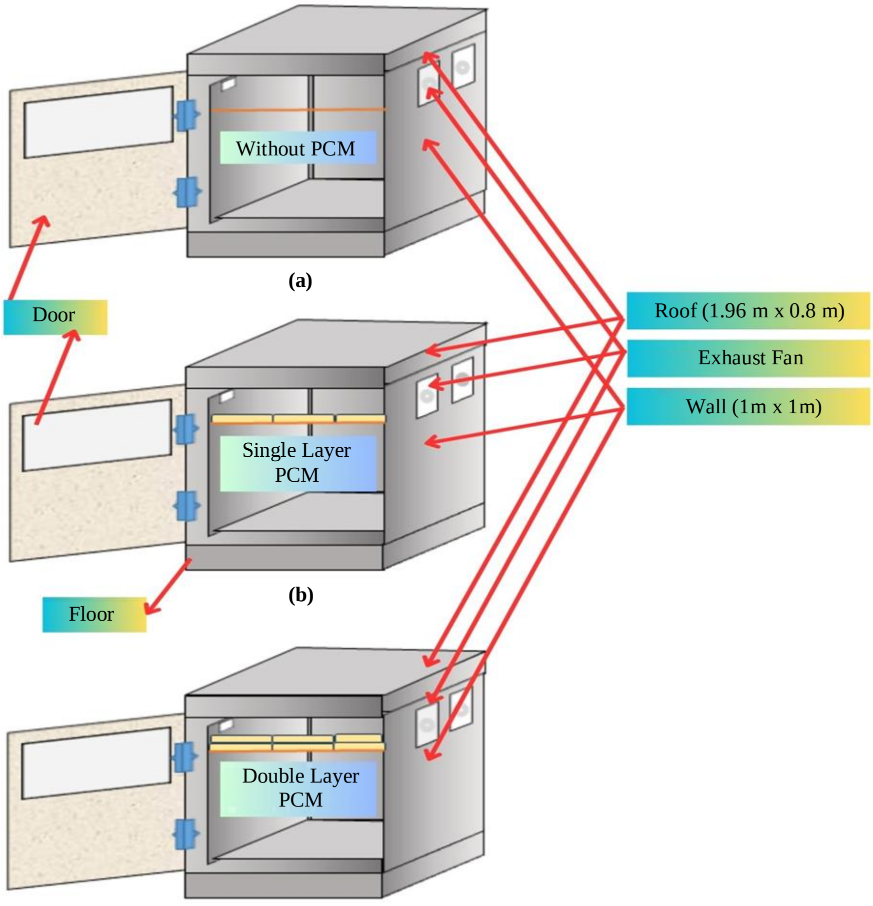


Fig. 2 Paraffin wax-schematic of solid-liquid

3. Experimental Setup

Figure 3 shows the PCM Bhiim of temperature variation of 35°C to 40°C, the integrated building with PCM on the ceiling was analysed and compared to a standard building without PCM, showing the graphical model configuration. In Figures 4(a) without PCM, 4(b) Single Layer PCM, and 4(c) Double Layer PCM, we observed a graphic representation of the experimental setting, which included room dimensions and PCM integration.

Fig. 3 Phase change material



(c)

Fig. 4 Graphical model of the building (a) Without PCM, (b) Single layer PCM, and (c) Double layer PCM.

4. Result and Discussion

The experiments were carried out both with and without PCM (including single and double layers), which were built and assessed in Chennai's intense heat. Commercial organic PCM Bhiim, which has a melting range of 35°C to 40°C, is a suitable material that accounts for the variation in temperature at the site according to investigation and the passive monitoring technique being used.

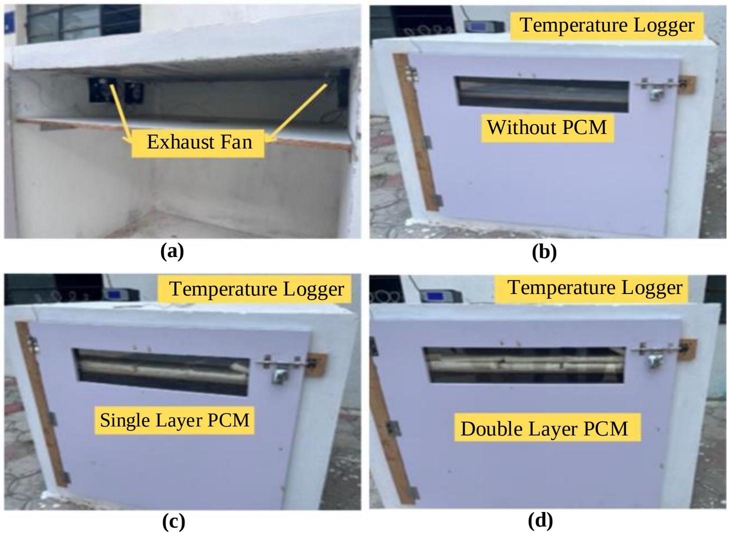
In addition, it has been observed that this temperature trend, according to the circumstance, is discussed in detail. Figure 5 displays the photographic view. (a) Exhaust fan configuration, (b) Without PCM, (c) Single-layer PCM, (d) Double-layer PCM.

Figure 6 shows that the highest difference in temperature existed between the room inside the ceiling and the roof ceiling top during the hours of 8:00 and 17:00 when the temperature difference was in the range of 1.2°C–3.3°C.

Between 12:00 and 13:00, the temperature on the roof ceiling reached its highest point, which was between 38.7°C and 39°C. This temperature gap closes up extremely rapidly after 17:00 as a consequence of the low ambient temperature that occurs during the overnight hours of 1:00 to 2:00, which ranges between 24.9°C and 25.8°C due to the collected heat of all components.

This temperature gap closes up very fast as a result of the low ambient temperature that occurs during the nighttime hours of 1:00 to 2:00. But the temperature gradient of the interior air during daylight was most analogous to that of the upper ceiling roofing.

This suggests that these components have a significant impact on the temperature of the internal environment during the period in which it is at its highest. Without PCM, the temperature was found to vary by 38.5°C at its highest point in the top room and 37.6°C at the inside room temperature.



(a) (b)

(c) (d)

Fig. 5 Photographic view (a) Exhaust fan setup, (b) Without PCM, (c) Single layer PCM, and (d) Double layer PCM.

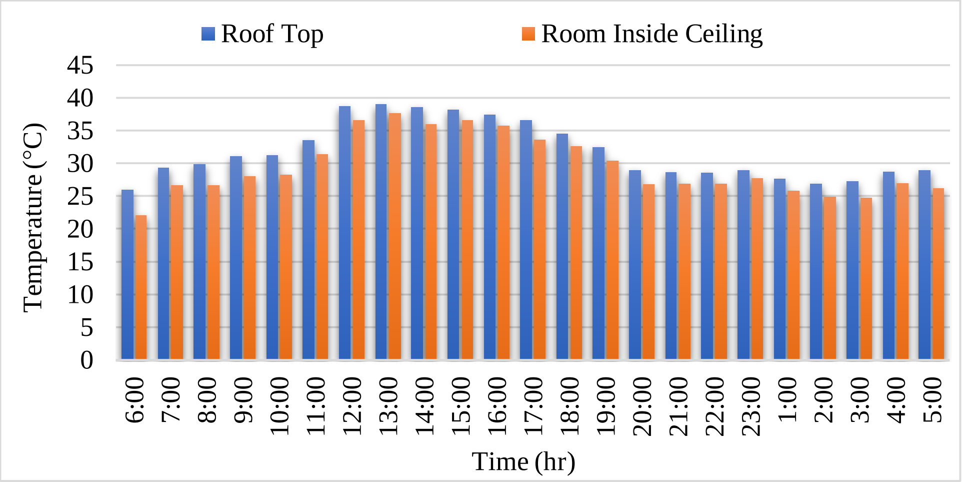


Fig. 6 Changes in room temperature without PCM

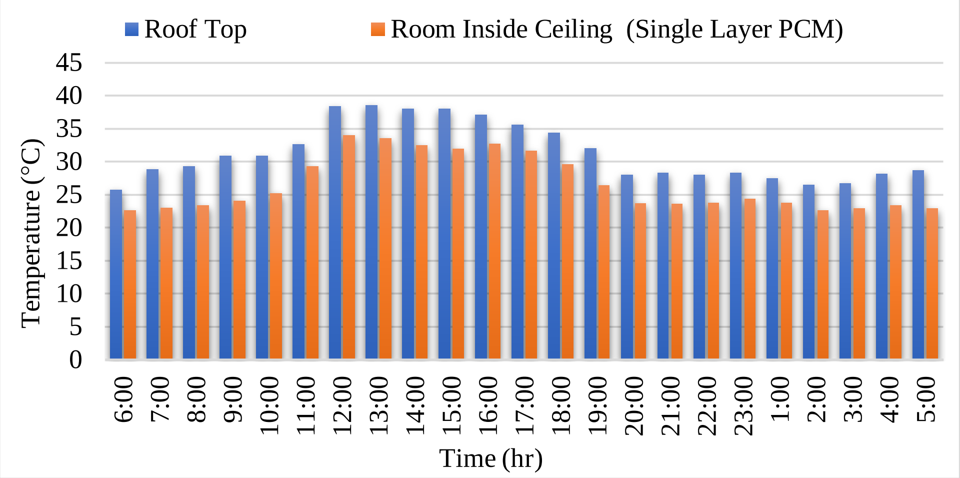


Fig. 7 Changes in room temperature with single layer PCM

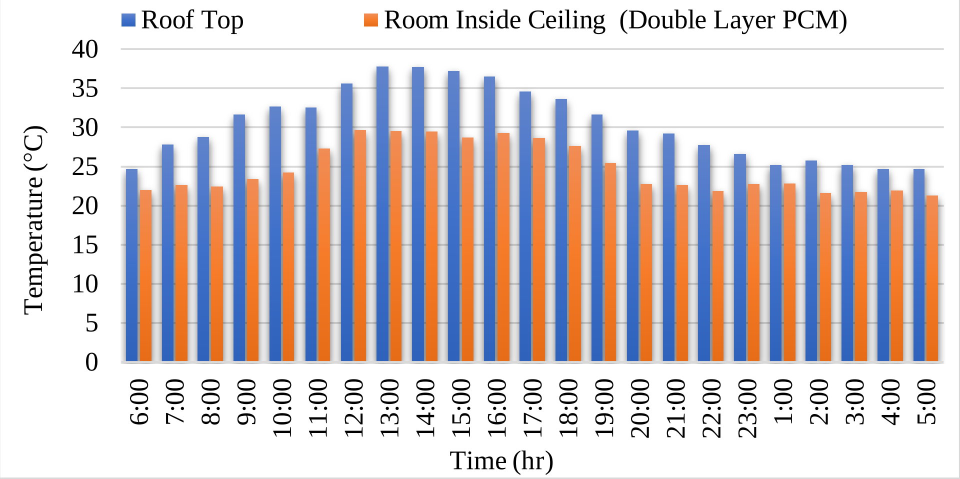


Fig. 8 Changes in room temperature with double layer PCM

Figure 7 illustrates that when a single layer of PCM was installed, the temperature differential between the room below the ceiling and the roof's top was greatest between 8:00 and 17:00. Following the installation of PCM on ceilings, the temperatures of the interior, the walls, and the PCM were regularly measured and recorded every 10 minutes under temporary climatic circumstances. When there was a temperature differential of 3.1°C to 6.8°C. The outside temperature above the roof's ceiling top peaked between 6:00 and 9:00, at a temperature of about 38.5°C.

Due to space limitations and irregular outdoor circumstances, variations in temperature were recorded on an hourly average. The effects of these variations were examined using a single layer of PCM, where the temperature was found to vary by 38.5°C at its highest point in the top room and by 33.6°C at the inside room temperature. These variations were attributed to the properties of PCM. The initial state of PCM was either in a liquid condition or in a transitional stage before becoming liquid PCM because temperature differences were above its phase transition temperature. Even though the PCM's melting temperature was 2.69°C, the average temperature inside the PCM-containing room was discovered to be lower.

Even though the experiment was carried out with and without PCM, Figure 8 shows that when a double layer of PCM is stated, the inside surface temperature improvement achieved by PCM affects the inner temperature of the PCM. In this sense, the heat that was continuously generated by the components within the double-layered PCM space resulted in a significant drop in the indoor air temperature when compared to the reference cases with and without PCM and single-layered PCM.

This illustrates the advantages of PCM over a single-layer PCM building envelope in lowering the temperature to a maximum variation of 8.5°C using double-layer PCM, even in hot external conditions. The inside ambient temperature reached its highest point around 14:00, measuring 29.4°C. As a result, as the outside ambient temperature increased, the double-layer PCM dropped, and more heat passed through the materials because of the solid-liquid state's density to regulate the interior ambient temperature. When accounting for the energy savings for air conditioning consumption and thermal comfort reached, the decrease of such values has a substantial impact on the indoor environment.

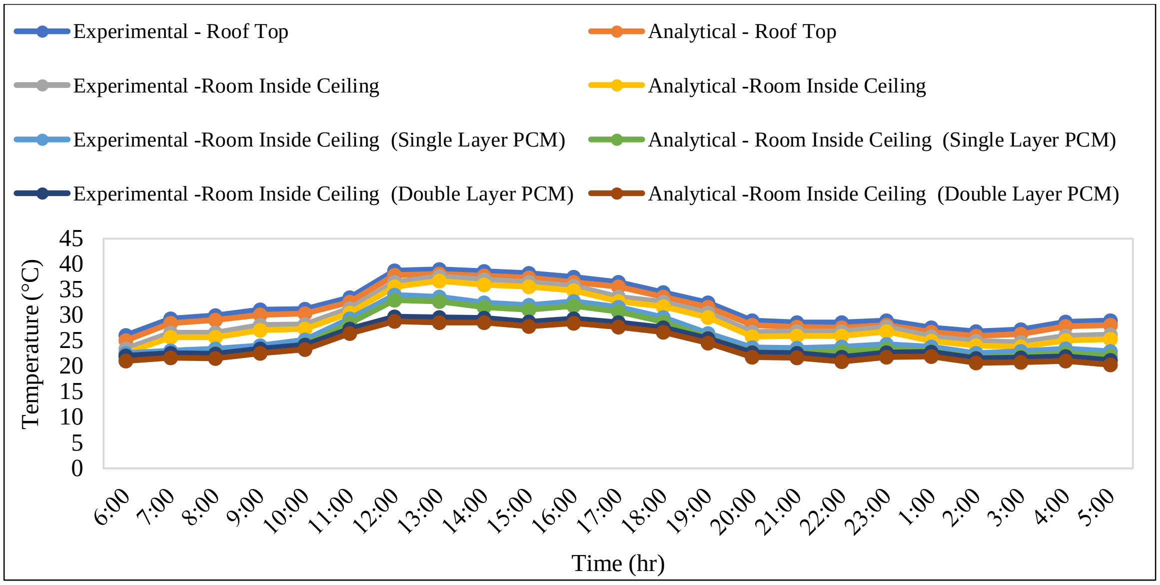


Fig. 9 Building with and without PCM were analyzed numerically and compared to results from experiments

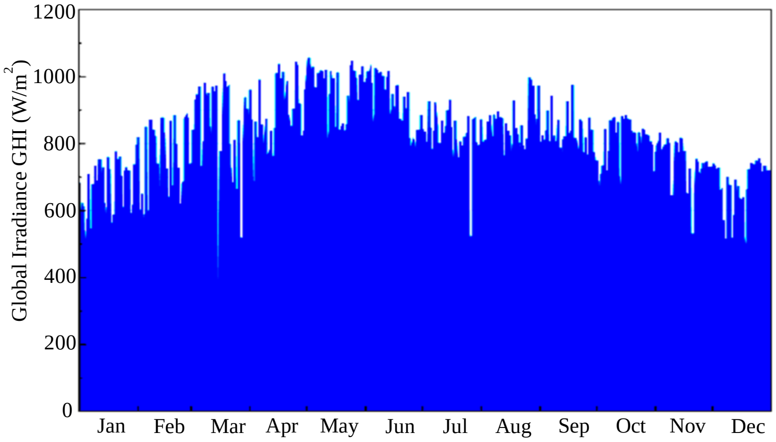


Fig. 10 Solar irradiation pattern

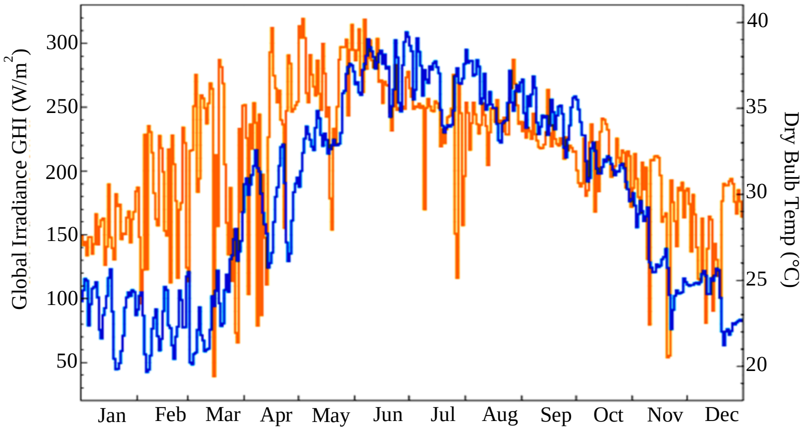


Fig. 11 Solar average irradiation per day

Figures 10 and 11 display the comparison and PCM rooms' solar irradiation patterns as a function of the external ambient temperature. Sunlight in both rooms was less intense than the outside air temperature until about midday, as seen in the figure.

There is a discernible lag between the PCM and the standard room, and it drops as the surface temperatures of the substances within the room rise. In addition, the temperature of the interior air is continuously raised by the heat that accumulates inside the rooms across the experiment because they are not ventilated.

During the day, it was clear that the PCM room had less solar radiation than the reference room. However, this tendency reverted in the evening (after 16:00) and continued until the following day. This is because materials that have PCM integrated into them release energy uncontrollably when the daytime temperature drops below 34°C.

The PCM activation in the PCM rooms' elements was at its peak between 9:20 and 11:30, resulting in a maximum solar radiation differential of 4.6°C at 10:10. Because air conditioning systems in actual buildings in Chennai use the most electricity during this time, it is essential to keep this in mind. Additionally, in order to counteract the rise in interior temperature caused by the PCM heat discharging phase, the rooms needed enough ventilation after daylight.

5. Numerical Simulations are Used to Validate the Experimental Results

Figure 9 shows the temperature difference of the interior space in the building with and without PCM (single and double layer) integration. This information was collected through experimentation and validated using numerically simulated data generated by the ANSYS Workbench. For this, a mathematical model was used to simulate the physical model of the created structures with and without PCM that had dimensions comparable to the experimental buildings in Chennai, India. The mathematical representation includes equations that govern a one-dimensional finite element temperature gradient system to compute heat transport through the building's walls and roof. The structure is subjected to several variation analyses, both with and without PCM.

The apparent heat capacity approach was utilized to simulate the PCM phase change process. For the hours observed, the simulation ran for 24 hours with an average step size of every 10 minutes. The following governing equation, which was solved using an explicit finite heat transfer analysis approximation, is used to simulate the heat transfer through the building's walls and roof. Figure 12 (a-c) displays the results of the simulation analysis. A numerical simulation was also run and compared to the experimental findings; the simulations agreed with the experimental data's value.

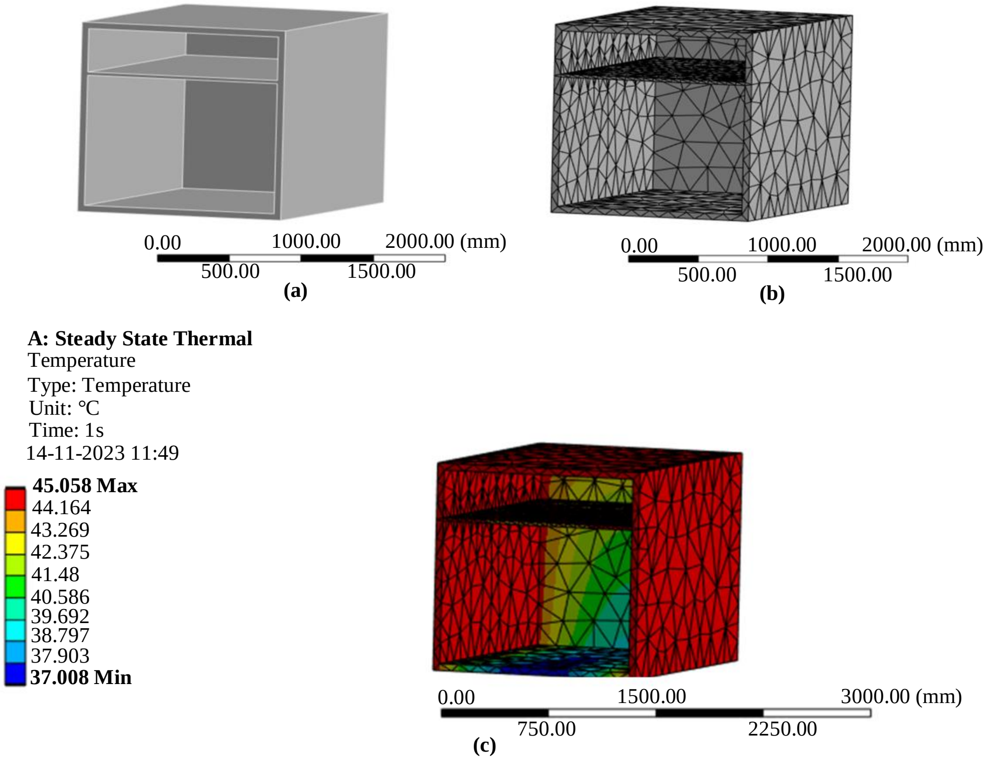


Fig. 12 Simulation analysis (a) CFD model, (b) Meshing, and (c) Temperature analysis.

6. Conclusion

An investigation was conducted into the impact of PCM (single and double layer) on the ceiling of a building by comparing buildings without PCM to those with varying PCM temperatures relative to the ambient temperature.

An ANSYS workbench simulation of a thermal transient has been performed, and the results have been verified against experimental data. Conclusions derived from the observation are listed below.

- In the observation without PCM, the maximum temperature recorded on the roof ceiling was between 38.7°C and 39°C. The rapid closure of this temperature gap after 17:00 is due to the exceptionally low ambient temperature that occurs from 1:00 to 2:00 during the night, which ranges from 24.9°C to 25.8°C as a result of the heat accumulated by all components.
- The absence of PCM resulted in a temperature variation of 38.5°C at the uppermost point of the room and 37.6°C at the interior temperature.
- By analyzing the impacts of these fluctuations on a single-layer PCM, it was determined that the temperature fluctuated by 38.5°C at its maximum point on the roof surface and 33.6°C at the room inside temperature.
- Approximately 29.4°C was the minimum interior ambient temperature for double-layer PCM. In contrast to a single-layer PCM building envelope, the utilization of double-layer PCM results in a reduction of the maximum temperature variation by 8.5°C.
- The temperature variation within the interior space of the building was investigated experimentally, both with and without the integration of PCM (in the form of single and double layers). The ANSYS workbench was utilized to validate the experimental and numerical simulations that were conducted.

Acknowledgments

The Vinayaka Missions Research Foundation provided funding for this endeavour under the Researchers Supporting seed money research grand File No. VMRF/Seed Money/Aug 2021/AVIT-Kanchi/5.

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