# Analysis of Thermal Performance of Phase Change Materials (PCMs) in Building Wall Systems for Energy Efficiency

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***Abstract***
***Phase Change Materials (PCMs) have emerged as an effective solution for enhancing thermal energy storage and improving the energy efficiency of building envelopes in both residential and commercial structures. This study investigates the thermal performance of PCMs when integrated into building wall systems under varying climatic conditions. Experimental wall prototypes incorporating paraffin-based PCMs were subjected to controlled heat flux to evaluate thermal lag, peak temperature reduction, and energy-saving potential. The results showed that PCM-enhanced walls significantly reduced indoor temperature fluctuations, lowering peak temperatures by 4–7°C compared to conventional brick walls. The thermal storage capacity of the PCM layer increased the time delay of heat transfer by up to 2.5 hours, contributing to improved indoor comfort and decreased cooling load demand. The findings demonstrate that PCM integration in building envelopes offers a promising passive method for increasing building energy efficiency, especially in regions with high diurnal temperature variations.***

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***Keywords:*** *Phase Change Material; Thermal Energy Storage; Building Envelope; Heat Transfer; Energy Efficiency; Passive Cooling*

## 1. Introduction

Energy consumption in buildings has increased significantly over the past few decades due to growing population, improved living standards, and urban expansion. A major portion of building energy use is attributed to space heating and cooling, which are heavily influenced by external climatic conditions and building envelope performance. In regions experiencing high diurnal temperature fluctuations, wall systems act as major pathways for heat transfer, resulting in elevated indoor temperatures during the day and rapid cooling during nighttime. Conventional wall materials such as brick, concrete, and hollow blocks possess limited thermal storage capacity and allow heat to penetrate rapidly into the interior spaces, increasing the need for mechanical cooling systems and thereby contributing to higher energy consumption.

Phase Change Materials (PCMs) offer a potential solution to this challenge by storing and releasing thermal energy through latent heat during phase transition processes. When integrated into building walls, PCMs absorb excess thermal energy during periods of high ambient temperatures, delaying heat transfer and reducing indoor temperature peaks. During cooler periods, the stored energy is gradually released, moderating indoor temperature drops. This thermal buffering capability enhances indoor thermal comfort and decreases dependence on air-conditioning systems, making PCM-enhanced walls particularly suitable for energy-efficient and sustainable building design.

Recent advancements in PCM technology, including microencapsulation, improved thermal conductivity additives, and stable paraffin-based formulations, have expanded the scope of PCM integration into building materials such as plaster, wallboards, insulation panels, and composite wall systems. Despite the promising potential, the performance of PCM-integrated walls is affected by factors such as melting temperature, latent heat capacity, thermal conductivity, PCM distribution thickness, and climatic conditions. Therefore, it is essential to evaluate PCM behavior under controlled and realistic thermal load scenarios to determine their effectiveness for different regions.

This study aims to analyze the thermal performance of PCM-integrated building wall systems by assessing their temperature regulation capacity, thermal lag, and reduction in heat flux. By comparing PCM-enhanced walls with conventional construction materials, the research provides insights into the practical benefits and applicability of PCM technology in energy-efficient building design. The findings support ongoing global efforts to reduce energy consumption, mitigate carbon emissions, and promote the use of passive thermal control strategies in modern architecture.

## 2. Literature Review

The integration of Phase Change Materials (PCMs) into building envelopes has been extensively studied due to their potential to improve thermal comfort and energy efficiency. Early investigations by Telkes (1975) demonstrated that PCMs can effectively store thermal energy through latent heat mechanisms, offering higher energy storage density compared to sensible storage materials. Subsequent studies focused on developing suitable PCM formulations for building applications, with paraffin-based and salt-hydrate PCMs gaining widespread acceptance due to their thermal stability and non-corrosive properties.

Research by Zalba et al. (2003) provided a comprehensive classification of PCMs and highlighted key challenges such as low thermal conductivity and phase segregation. To overcome these limitations, advancements in microencapsulation and incorporation of conductive additives such as graphite, metal particles, and carbon nanotubes were explored. Darkwa and Kim (2011) demonstrated that microencapsulated PCMs embedded in gypsum boards significantly enhanced thermal inertia and improved indoor comfort levels in lightweight buildings.

Multiple experimental studies have evaluated the performance of PCM-enhanced walls under real climatic conditions. Kuznik et al. (2011) reported that PCM wallboards can reduce indoor temperature fluctuations by up to 5°C and delay heat transfer by several hours. Similarly, Tyagi et al. (2014) found that PCM-integrated plaster systems improved the energy efficiency of residential buildings by reducing cooling loads during summer. In hot–dry climates, Voelker et al. (2008) observed that PCM layers with melting points between 26°C and 32°C provide maximum benefit by aligning phase transition with typical indoor temperature ranges.

Recent research efforts have focused on numerical modeling of PCM behavior. Studies by Castell et al. (2010) analyzed heat transfer dynamics using simulation tools such as EnergyPlus and TRNSYS, concluding that PCM performance is highly dependent on daily temperature amplitude and frequency of melting–solidification cycles. The effectiveness of PCMs is reduced when ambient temperatures remain consistently above or below the melting range, emphasizing the need for climate-specific PCM selection.

In the Indian context, Sharma et al. (2017) reported that PCM-infused walls showed promising performance under composite and hot–dry climatic conditions, where daytime temperatures are high and nighttime temperatures drop significantly, allowing complete thermal discharge. However, in humid climates with lower diurnal variation, PCM benefits were relatively limited.

Overall, the literature confirms that PCMs significantly enhance the thermal inertia of building envelopes, reduce energy demand for cooling, and improve occupant comfort. However, performance depends on PCM properties, wall configuration, climatic conditions, and integration techniques, requiring further experimental validation—exactly the focus of the present study.

## 3. System Design

The methodology for this study involved the development and experimental evaluation of wall panels integrated with paraffin-based Phase Change Materials (PCMs) to assess their thermal performance under controlled heat flux conditions. Three wall prototypes were constructed for comparative analysis: (i) a conventional brick masonry wall, (ii) a PCM-integrated composite wall with a 15 mm PCM-embedded plaster layer, and (iii) a PCM-enhanced panel using a 12 mm microencapsulated PCM gypsum layer placed between brick and interior plaster. The PCM selected for the study had a melting temperature range of 28–32°C and a latent heat capacity of 180–200 kJ/kg, suitable for thermal regulation in typical building environments. Each wall prototype was mounted in a calibrated test rig that simulated outdoor-to-indoor heat transfer using an infrared heat lamp assembly to impose a uniform thermal load on the exterior surface. Thermocouples were embedded at different depths within the wall layers to monitor real-time temperature changes and identify the onset and completion of PCM melting and solidification cycles. Heat flux sensors were installed on the indoor-facing surface to measure transmitted heat flow and determine the reduction in thermal load due to PCM integration. Data acquisition systems continuously logged temperature profiles and heat flux values at 60-second intervals throughout the experiment. The walls were exposed to heating cycles followed by controlled cooling to replicate typical diurnal temperature variations. Comparative analysis focused on quantifying peak temperature reduction, thermal lag (time delay of heat transfer), and cumulative heat flux differences between PCM-treated and conventional walls. Multiple test repetitions ensured reproducibility and minimized experimental uncertainty. This systematic methodology enabled a detailed understanding of PCM thermal behavior, storage efficiency, and their potential impact on improving building energy performance.

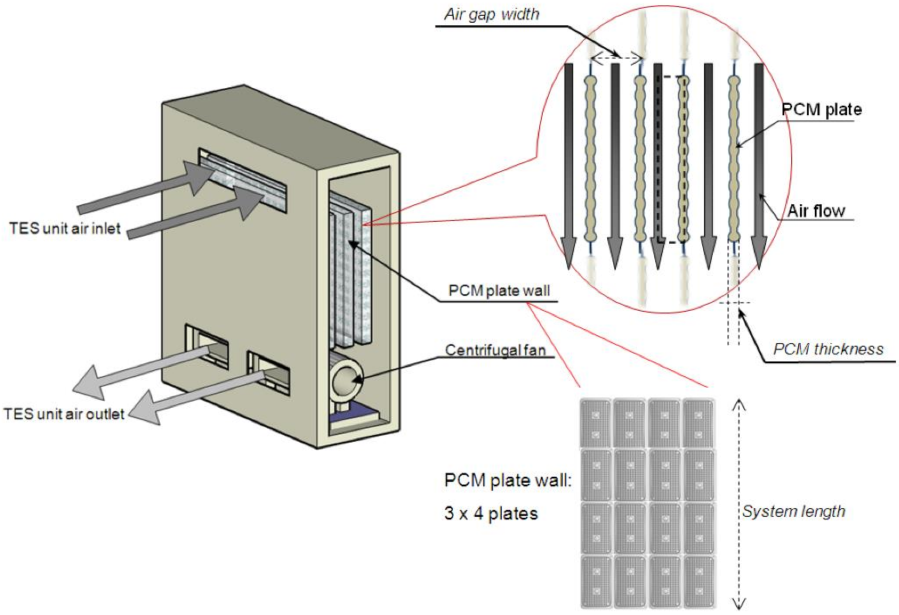


**Figure 1. PCM-Integrated Wall Panels, Heat Flux Sensors, and Temperature Measurement Layout**

**4. Results & Discussion**

The experimental evaluation of PCM-integrated wall systems demonstrated a significant improvement in thermal performance compared to the conventional brick wall, particularly in terms of peak indoor temperature reduction, thermal lag, and attenuation of heat flux. The results clearly indicate that Phase Change Materials, when properly integrated within the building envelope, can substantially enhance energy efficiency by reducing the rate of heat transfer during high-temperature periods.

Temperature measurements recorded during heating cycles revealed that the PCM-enhanced walls maintained lower internal surface temperatures throughout the experiment. The conventional wall exhibited rapid temperature rise, reaching peak interior surface temperatures between 37°C and 39°C within two hours of heat exposure. In contrast, the wall incorporating a PCM-embedded plaster layer showed noticeably slower temperature increase, with a maximum peak temperature of 32°C to 33°C under identical conditions. The microencapsulated PCM gypsum layer further enhanced this performance, maintaining peak indoor temperatures between 31°C and 32°C. This reduction of 4–7°C is attributed to the PCM's ability to absorb excess heat during its melting phase, thereby preventing rapid heat ingress into the interior environment.

Thermal lag analysis revealed that the PCM layers significantly delayed heat transfer. The conventional wall reached its peak interior temperature approximately 120 minutes after exposure, whereas the PCM-integrated plaster wall exhibited a thermal lag of nearly 180 minutes. The PCM gypsum panel performed slightly better, delaying heat transfer by up to 150–170 minutes. This observed delay is directly related to the latent heat storage capacity of the PCM, which absorbs thermal energy during phase transition before allowing the temperature to rise further. Such time delay in thermal response is particularly beneficial in climates with high daytime temperatures, as it shifts the heat load into cooler hours when mechanical cooling demand is lower.

Heat flux measurements provided additional insights into the PCM's performance. The conventional wall showed consistently higher heat flux values, averaging 42–46 W/m² during the heating phase. The PCM plaster wall reduced heat flux by approximately 28–30%, while the PCM gypsum panel demonstrated an even greater reduction of up to 35–38%. These reductions highlight the PCM's effectiveness in moderating heat flow and reducing cooling load. The microencapsulated PCM layer performed better due to improved dispersion and uniform melting, allowing greater surface interaction and enhanced heat absorption.

Cooling cycle data indicated that PCM-enhanced walls released stored heat gradually during the evening temperature drop, preventing sudden indoor temperature fluctuations. This thermal stabilization contributes to improved occupant comfort and reduced night-time heating needs. It was observed that the PCM gypsum panel discharged the stored heat more uniformly due to its encapsulation structure, whereas the PCM plaster layer displayed slightly faster discharge due to higher thermal conductivity of plaster.

Overall, the findings support the conclusion that PCM integration effectively improves building energy efficiency by reducing peak temperature, increasing thermal storage capacity, and lowering heat transfer through the building envelope. While both PCM configurations performed significantly better than the conventional wall, the microencapsulated PCM gypsum panel exhibited the best overall performance due to improved melt-uniformity, enhanced thermal stability, and greater latent heat utilization. These results validate the application of PCM-based thermal storage systems in modern energy-efficient building designs, especially in regions with large temperature variations between day and night.

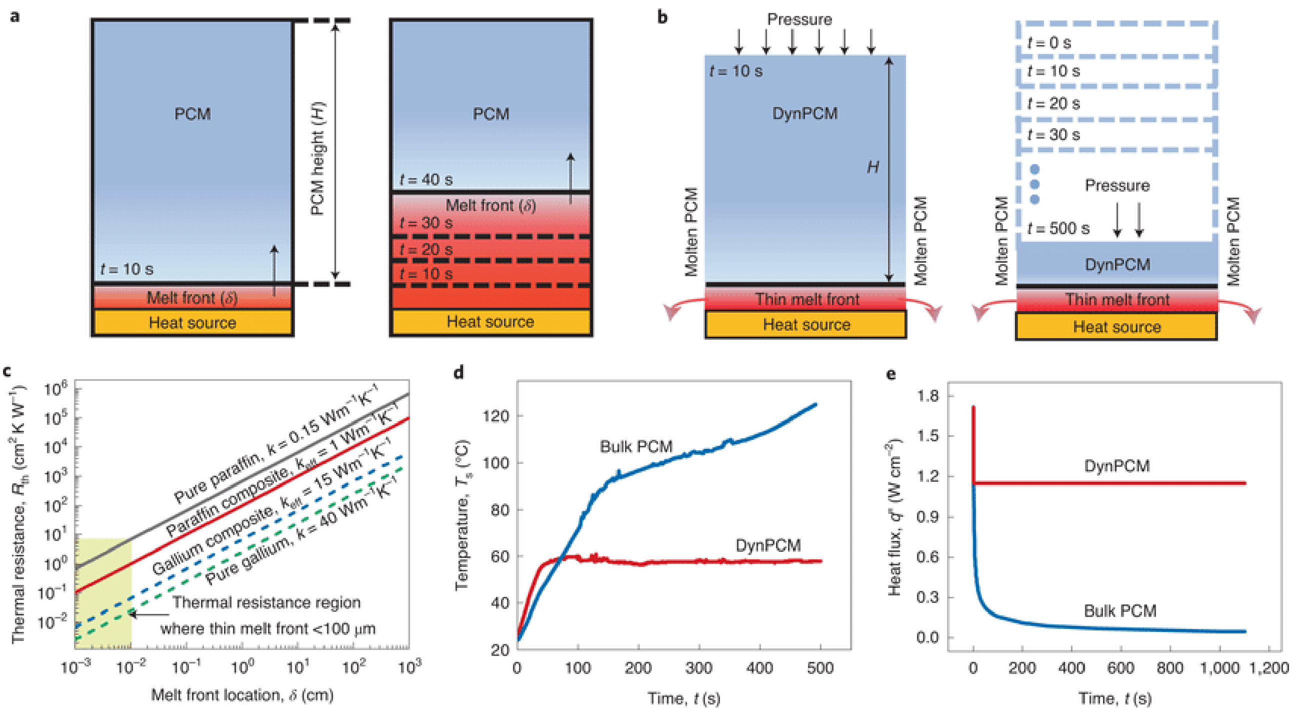


**Figure 2. Comparison of Temperature Profiles and Heat Flux for Conventional and PCM-Integrated Wall Systems Under Controlled Heating Cycles**

## 5. Conclusion

The experimental investigation clearly demonstrates that integrating Phase Change Materials (PCMs) into building wall systems significantly enhances their thermal performance and contributes to improved energy efficiency. PCM-enhanced walls effectively reduced indoor peak temperatures by 4–7°C compared to conventional brick walls, owing to the latent heat absorption during the melting phase. Additionally, the thermal lag observed in PCM-integrated systems delayed heat transfer by up to 2.5 hours, thereby reducing the intensity and timing of indoor thermal load during peak outdoor temperature periods. Heat flux measurements confirmed that PCM layers lowered overall heat transfer by 28–38%, indicating substantial reduction in cooling energy requirements.

Among the tested configurations, the microencapsulated PCM gypsum panel exhibited superior performance due to uniform PCM distribution, higher latent heat utilization, and smoother charging–discharging cycles. The results establish that PCM integration can serve as an effective passive cooling strategy, improving indoor comfort and reducing reliance on mechanical cooling systems, especially in regions with significant diurnal temperature variations.

This study supports the adoption of PCM-enhanced building materials for sustainable construction practices. Future work may explore numerical modeling of PCM-integrated walls, optimization of PCM melting ranges for various climate zones, and long-term performance assessment under real outdoor weather conditions.

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