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REDUCING BUILDING SURFACE TEMPERATURE AND HEAT TRANSFER BY ADDING PCM LAYER INTO WALL CONFIGURATIONS

BY

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Abstract. This study analyzes the integration of Phase Change Materials (PCMs) into building exterior walls to develop thermal performance and decrease surface temperatures effectively. PCMs are well-known for their capacity to absorb and release substantial heat during phase transitions and stand in as thermal buffers that stabilize temperature fluctuations within buildings. This investigation aims to introduce the optimum PCM position to reduce exterior surface temperature and heat transfer. Experimental findings emphasize the critical role of PCM layer placement in optimizing effectiveness. In scenario 1-PCM, where the PCM was positioned directly to the heat source, surface temperatures rose from 28.43°C to 75.77°C, a notable improvement over the reference wall's increase from 31.01°C to 91.00°C. This configuration facilitated efficient heat absorption, resulting in an average surface temperature of 64.33°C, contrasting with 85.94°C in the reference scenario. Scenario 3-PCM, with the PCM layer between a 2 cm outer and 3 cm inner insulation layer, demonstrated minimal indoor temperature increase, rising from 28.58°C to 29.52°C, compared to the reference wall's rise to 33.11°C. These findings underscore PCM's potential to enhance energy efficiency and indoor comfort, justifying further

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research into durability, climatic adaptability, and cost-effectiveness for sustainable building designs.

Keywords: Phase Change Materials (PCMs), building walls, thermal performance, surface temperature reduction, energy efficiency.

1. Introduction

In the context of rising energy costs and increasing environmental concerns, the quest for more efficient and sustainable building designs has become paramount. One critical aspect of building performance is thermal management, particularly regulating surface temperatures to enhance indoor comfort and reduce energy consumption. While effective, traditional insulation methods often struggle to adapt to the dynamic thermal demands imposed by fluctuating outdoor conditions (Abatzoglou and Williams, 2016). Phase Change Materials (PCMs) present a promising solution to this challenge. PCMs can absorb and release large amounts of latent heat during their phase transition between solid and liquid states (Jarimi *et al*., 2019). This unique property allows PCMs to act as thermal buffers, smoothing out temperature variations and contributing to a more stable indoor environment (Sharshir *et al*., 2023; Kumar *et al*., 2023; Singh *et al*., 2023). When integrated into building walls, PCMs can significantly reduce the surface temperature during periods of high thermal stress, such as peak summer conditions (Nazir *et al*., 2019; Yuan *et al*., 2020; Fan and Khodadadi, 2011; Yang *et al*., 2019).

Researchers have gained deep insights into using phase change materials (PCMs). The position of PCMs in building exterior walls has a pivotal role in reducing heat transfer, so Hou *et al*. (2022) employed numerical simulation to investigate the effectiveness of PCMs on the thermal performance of lightweight building walls. They utilized PCM (3 cm) and insulation (10 cm) on the wall at three locations. The results show that the most appropriate place for PCM is the middle of the wall, and the best temperature range for PCM selection is 22-32°C. The efficiency of the PCM contribution decreased significantly by 56.61%, whereas the thermal resistance of the wall increased from 2.0 to 5.0. Kalbasi and Afrand (2022) developed an idea of utilizing PCM and insulation for energy renovation of existing buildings. They determined that PCM was more effective in the summer cooling design. The results also show that the combination of PCM and insulation fosters a medium for reducing the cooling load to zero. Taking advantage of PCM and insulation is beneficial for the annual energy consumption when the PCM proportion is 44% of the insulation share. Javidan *et al*. (2022) worked on a numerical simulation to assess the thermal behavior of brick walls with the cooperation of PCM. The results show that increasing the thickness of phase change material layers leads to enhanced thermal energy storage through melting. Concurrently, this reduces the heat transfer rate. Increasing the paraffin thickness to 20 mm reduced the temperature by 18% on the interior side of the wall. Wang *et al*. (2013) investigated the impacts of water thermal storage walls on the indoor thermal comfort. They designed a passive solar house using TRANSYS software with a specific location in North China. Their outcomes prove that creating a water thermal wall cut down the annual energy consumption by 8.6% compared to traditional walls and enhanced the evaluation index for indoor thermal comfort by 12.9%. Hu *et al*. (2020) introduced a novel water blind-integrated wall (WBTW) and analyzed it numerically and experimentally. According to the results, the WBTW system displayed excellent insulation performance, achieving an average heat transfer coefficient of 0.8 $W/m^2{\cdot}K$. By implementing the WBTW system, the overall thermal load was significantly decreased by 42.6%. Jin *et al*. (2016) used a numerical estimation to find the optimal location of a PCM layer embedded in the wall structure to increase thermal mass and reduce heat fluxes. They found that the PCM layer should be closer to the exterior surface since the heat of fusion of PCM and the PCM melting temperature increased. Lee *et al*. (2015) experimentally integrated phase change materials with building walls to evaluate their performance in terms of heat flux reduction and heat transfer time delay. The PCM thermal shields were installed at various depths, one at a time, within the wall cavities. They found that location 3 (2.54 cm from the wallboard) is the most appropriate placement in the South wall. However, the optimal location in the west wall was 2 (1.27 cm from the wallboard). Meanwhile, the peak heat flux reductions were 51.3% and 29.7% for the south and the west walls, correspondingly.

Various studies consider the applications of PCMs in indoor temperature regulation. However, PCMs can significantly reduce surface temperature, a critical factor in the urban heat island phenomenon. Our investigation highlights the transformative potential of PCMs in modern building design, emphasizing their role in reducing surface temperatures and enhancing occupant comfort. Integrating these advanced materials into traditional construction practices can pave the way for more resilient and sustainable built environments. This study assessed how phase change material and its positions affect the surface. Also, indoor temperatures are analyzed. The results offer valuable insights for architects, engineers, and researchers to optimize building energy efficiency by reducing surface temperature. Ultimately, the findings can contribute to sustainable design practices in building construction.

2. Experimental setup

2.1. Test enclosure and material properties

This research utilizes a laboratory-scale prototype housed within a rectangular cube enclosure. The main enclosure dimensions are 116 cm * 28.5 cm

* 28.5 cm (Fig. 1), constructed by a 1.3 cm gypsum plasterboard. A 10 cm insulation layer surrounds all sides of the enclosure except for the heater side to ensure optimal thermal insulation. The plasterboard box is uniformly covered with joint filler to minimize heat loss from the corners.

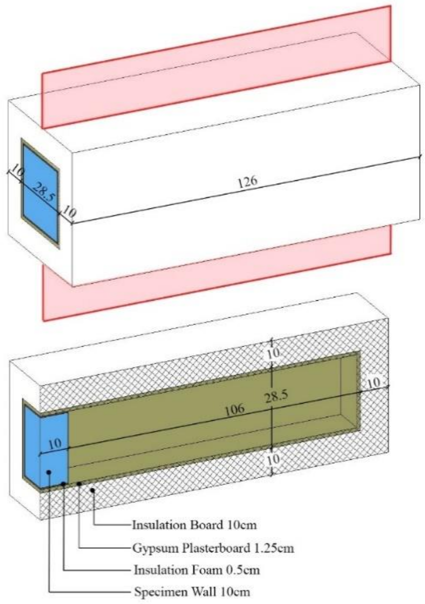


Fig. 1 – The main experiment box details.

The reference wall is constructed with a 10 cm EPS insulation, without any inner and outer finisher, to minimize potential data differences. There are four main categories for wall assembly, including 1: PCM 5 cm, insulation 5 cm, 2: insulation 5 cm, PCM 5 cm, 3: insulation 2 cm, PCM 5 cm, insulation 3 cm, and 4: insulation 3 cm, PCM 5 cm, insulation 2 cm. For all wall classifications, please refer to Fig. 2.

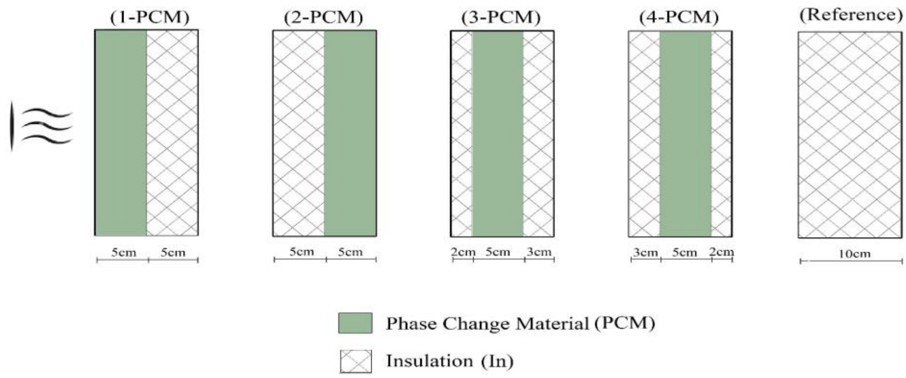


Fig. 2 – Schematic of a wall section showing the locations of insulation and PCM.

Paraffin (RT31) is undertaken as the phase change material (Al-Rashed *et al*., 2021; Ling *et al*., 2021) primarily due to its well-aligned melting and solidification temperatures to building applications in the mediterian region (Table 1). The melting range of the PCM spans from 29°C to 34°C, while its solidification range is from 34°C to 29°C, demonstrating a symmetrical behavior (Kontoleon *et al*., 2007). A case of stainless-steel material (1.5 mm thick) was utilized to preserve thermal storage. Furthermore, the material container featured a cap that prevented leakage of materials during the phase transition and volume expansion resulting from rising inner temperatures.

Table 1
Thermal and physical properties of materials

Property	Unit	RT31 (Kontoleon *et al*., 2007)	Insulation (Shelke *et al*., 2022)
Density of solid	[kg/m³]	880	16
Density of liquid	[kg/m³]	760	–
Specific heat capacity	[J/kg·K]	2000	1200
Thermal conductivity	[W/m·K]	0.2	0.04
Melting temperature	[°C]	29-34	–
Solid temperature	[°C]	34-29	–
Volume coefficient	[1/°C]	0.003	–

2.2. Setup procedure

The experimental setup is arranged within the controlled condition of the mechanical laboratory, ensuring the mitigation of undesired air velocities and extreme temperature fluctuations. This setup core is a solid 1200-watt heater (Shelke *et al*., 2019), selected to provide a consistent and controlled heat flux. For precise temperature measurements, type T thermocouples (Lee *et al*., 2015; Fadl and Eames, 2019; Ho *et al*., 2021) are engaging. These instruments are integrated into the experimental framework, creating a comprehensive network of temperature sensors. Six thermocouples are positioned on the outer side of the wall, mirroring their counterparts on the inner side.

Additionally, two thermocouples are placed inside the main enclosure to monitor the internal temperature (Fig. 3). The data collection process is orchestrated through the utilization of a NI-9213 data collector (Feng *et al*., 2021; Xu *et al*., 2021; Lee *et al*., 2019) from National Instruments company.

Designed with 16 ports, this data collector managed and processed the thermal data gathered from points across the experimental setup. A 3 mm aluminum plate was affixed to the surfaces of the walls to achieve a uniform and efficient heat transfer.

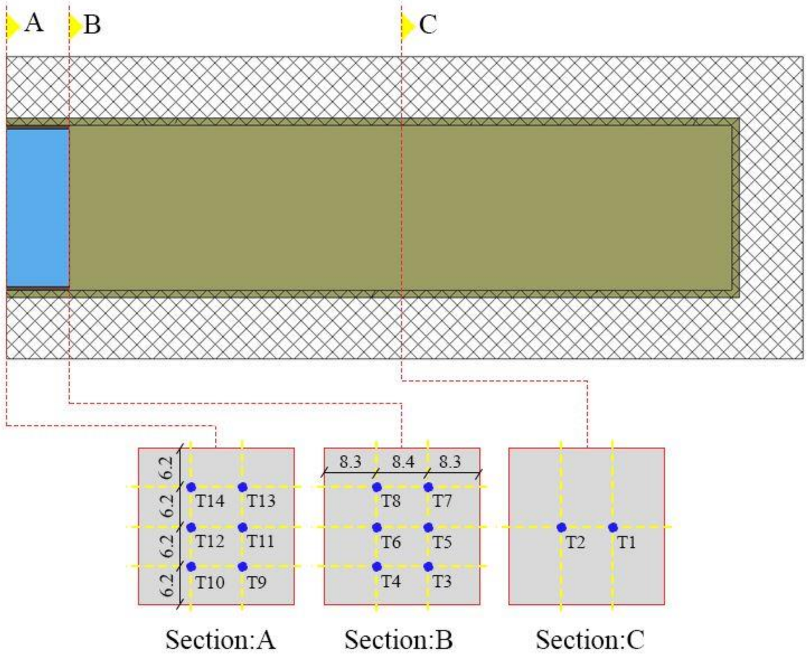


Fig. 3 – The thermocouple design in sections A, B, and C.

2.3. Data Acquisition

The experiment has been carried out on 12 examinations, comparing them with the reference prototype. The thermocouples have been installed by aluminum steak 2*2 cm in a dedicated place. Subsequently, the wall layer compositions were embedded according to the scenarios. A 0.5 cm insulation foam was placed between the conjunction of the gypsum plasterboard (the main box) and the wall materials to prevent thermal conduction and leakage. Screws then fixed the aluminum plate to the enclosure to produce a uniform heat distribution on the entire surface of the wall. The heater is positioned strategically just 25 cm from the prototype wall and efficiently transmits heat.

To begin each experiment, the position of the primary enclosure and heater (Fig. 3) is properly regulated, then turn on the heat resource is continuously for 300 minutes, and the data is collected every minute by thermocouple. When one analysis is finished, the prototype's wall is entirely disassembled to release the stored heat, ready for the next experiment, which is performed a day later. Because of the extended duration of the test period, which lasted 13 days, not all experiments had the same initial temperature, and the materials' initial temperature was the same as the room temperature on the day of the investigation.

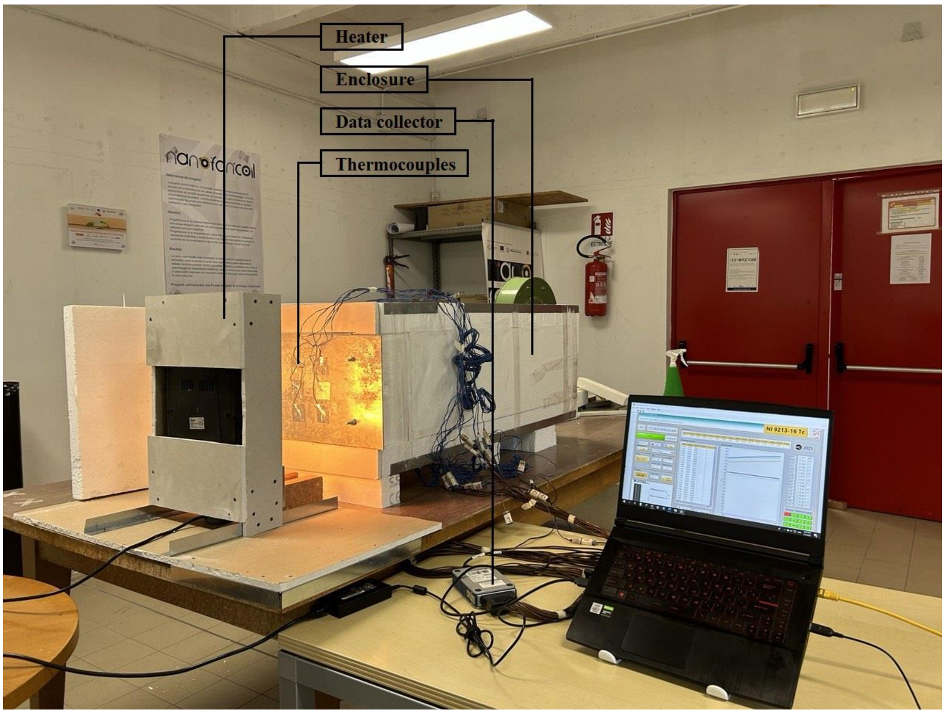


Fig. 4 – Installed instruments and data acquisition in the mechanic laboratory.

3. Results and Discussion

3.1. The Indoor Mean Temperature

The thermal behavior of thermal storage materials depends on the share and attributes of their ingredients. Some substances, such as salts, sodium chloride, and calcium chloride, can enhance the specific heat capacity of water, allowing it to store more thermal energy. In the case of sand, a higher proportion of silica played a pivotal role in the amount of stored energy. In addition, sand grain size influences the heat attribute. The capacity of a PCM to store thermal energy is primarily due to the latent heat of fusion or solidification, which is the amount of heat absorbed or released during phase change at a constant temperature.

The first test was conducted on the reference wall. The main box indoor temperature was 28.58°C at the beginning of the experiment and then gradually rose to 33.11°C after 300 minutes (Fig. 5). The indoor temperature of the chamber remained constant for 25 minutes of the test because the insulation absorbed the heat. Then, the temperature escalated by 4.53°C until the trial was stopped.

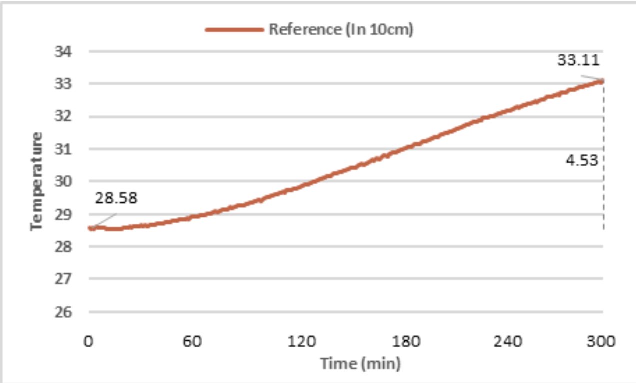
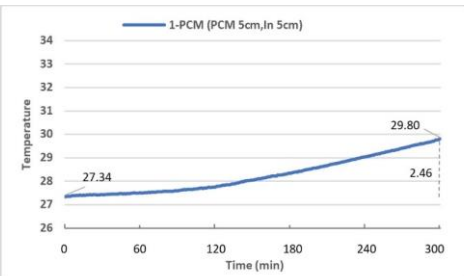
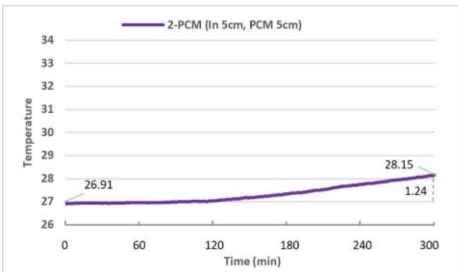


Fig. 5 – The enclosure indoor mean temperature in the reference wall

Concerning PCM performance, a lower indoor mean temperature was observed when the PCM layer was located between two layers of insulations. A minimum ambient temperature was registered in scenario 3-PCM, in which the inner insulation layer is thicker than the outer layer, 3 and 2 cm, correspondingly. The ambient temperature of 3-PCM increased by 0.94°C. It was followed by scheme 2-PCM, which showed a 1.24°C growth. In this composition, the outer insulation layer is 3cm. Generally, positioning the PCM layer adjacent to the interior and outer layer illustrated a higher indoor temperature surge. Therefore, The third largest temperature increase is shown in plan 4-PCM, with 1.49. However, the worst scenario is recorded in design 1-PCM, with a temperature increase of 2.46°C while the PCM layer is exposed to the heat resource. (see Fig. 6). Figure 7 depicts that adding a layer of PCM effectively reduces the mean temperature in contrast with a single insulation layer.



A



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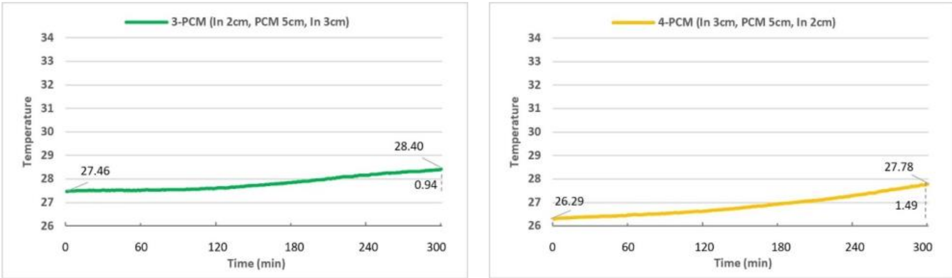

C D

Fig. 6 – The enclosure indoor mean temperature (ºC) in PCM scenarios; A: 1-PCM, B: 2-PCM, C: 3-PCM, D: 4-PCM.

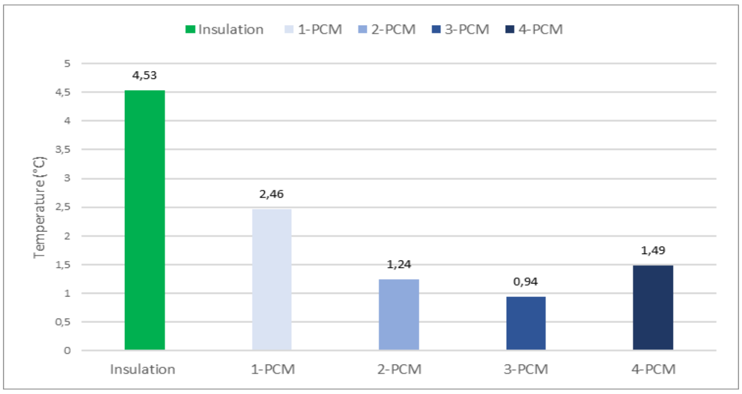

Fig. 7 – Comparing the indoor mean temperature of reference and PCM walls.

3.2. Surface temperature

The properties of materials, such as thermal conductivity, density, and heat capacity, significantly impact the exterior wall's surface temperature. It is difficult to determine which feature of materials has the most significant impact on elevating surface temperature since the mentioned features influence each other thermal performance (Radhi *et al.*, 2014; Berdahl and Bretz, 1997). Generally, materials with lower thermal conductivity transfer heat slowly through the wall and ramp up surface temperature. Higher-density materials have a higher thermal mass, enabling them to absorb and retain heat for longer hours. The density results in a slower temperature alteration and can drive higher surface temperatures (Berardi and Naldi, 2017). Materials with lower heat capacity cannot store heat effectively, which can escalate surface temperatures during peak temperatures.

The surface temperature of the reference wall illustrated how lower thermal conductivity and density can accelerate the surface temperature, so the temperature of the reference wall surged by 59.99°C from 31.01 to 91.00 after 300 minutes of heat. It also had the highest average temperature of 85.94°C (Fig. 8).

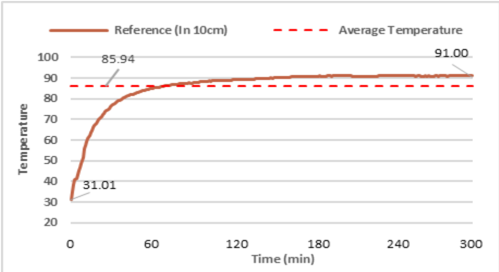

Fig. 8 – Surface temperature in the reference wall.

As Fig. 9 illustrates, adding a layer of phase change material reduced the average surface temperature of the wall, especially when the material was placed near the heat source. The lowest surface temperature accounted for scenario 1-PCM; the temperature was ramped up from 28.43 to 75.77ºC, and its average surface temperature was 64.33ºC over five hours of heating. In this scheme, the PCM material considerably reduces surface temperature due to direct heat resource exposure. Reverse to scheme 1-PCM. The remaining components performed almost similarly in temperature reduction. So, the surface temperatures were registered at 81.96, 79.27, and 78.91ºC for 2-PCM, 3-PCM, and 4-PCM, respectively. Their average surface temperature ranged between 74 and 78, approximately 15% more than in the first scenario. Comparing the surface temperature result of PCM compositions and the insulation layer demonstrated that PCM can effectively reduce the wall exterior temperature (Fig. 10).

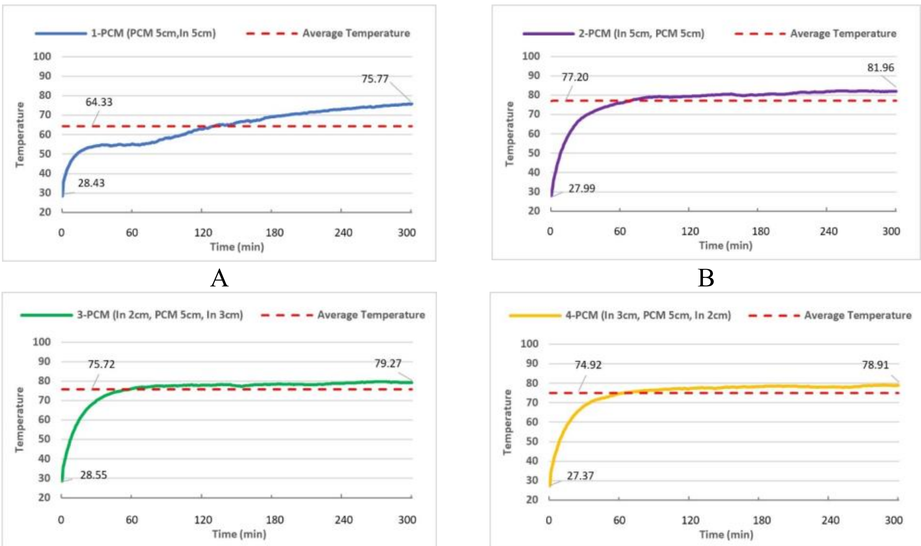

Fig. 9 – Surface temperature in PCM scenarios; A: 1-PCM, B: 2-PCM, C: 3-PCM, D: 4-PCM.

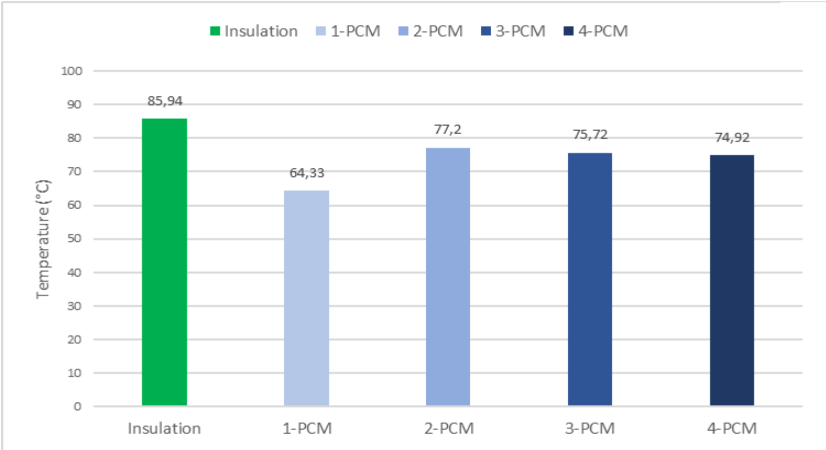

Fig. 10 – Comparing the mean surface temperature of reference and PCM walls.

4. Conclusion

This study investigated the integration of Phase Change Materials (PCMs) into building walls to improve thermal performance and reduce surface temperatures. PCMs, known for their capability to absorb and release significant amounts of heat during phase transitions, act as thermal buffers, stabilizing building temperature fluctuations. The experimental results highlighted that the placement of the PCM layer plays a crucial role in its effectiveness. In the optimal configuration (scenario 1-PCM), where the PCM was directly exposed to the heat source, the surface temperature rose from 28.43°C to 75.77°C. This is a significant reduction compared to the reference wall, which increased from 31.01°C to 91.00°C. This placement allowed the PCM to absorb and mitigate the heat most effectively, resulting in a lower average surface temperature of 64.33°C compared to the 85.94°C observed in the reference wall.

Concerning indoor temperature results, the most effective scenario was 3-PCM, where the PCM layer was placed between a 2 cm outer insulation layer and a 3 cm inner insulation layer. This configuration resulted in the smallest indoor temperature increase of just 0.94°C, starting from 28.58°C and peaking at 29.52°C after 300 minutes of heating. This contrasted sharply with the reference wall, which exhibited a more substantial increase from 28.58°C to 33.11°C. The other configurations, while still beneficial, did not perform as effectively as the 1-PCM and 3-PCM setups. For instance, scenario 2-PCM saw a rise to 81.96°C on the surface, and scenario 4-PCM led to an indoor temperature increase of 1.49°C. These results demonstrate that strategically placing PCMs can significantly stabilize indoor temperatures and reduce the energy needed for cooling. Incorporating PCMs into building walls, particularly in configurations that optimize their heat absorption and release capabilities, can achieve greater energy efficiency and enhance occupant comfort. Future research should focus on the long-term durability and climatic adaptability of PCMs, as well as a comprehensive cost-benefit analysis to validate their practical applications in sustainable building designs.

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REDUCEREA TEMPERATURII SUPRAFAȚEI CONSTRUCȚII ȘI A TRANSFERULUI DE CĂLDURĂ PRIN ADĂUGAREA STRATULUI PCM ÎN CONFIGURAȚILE PEREȚILOR

(Rezumat)

Acest studiu analizează integrarea materialelor cu schimbare de fază (PCM) în pereții exteriori ai clădirii pentru a le crește performanța termică și pentru a reduce în mod eficient temperaturile de la suprafață. PCM-urile sunt bine-cunoscute pentru capacitatea lor de a absorbi și elibera căldură substanțială în timpul tranzițiilor de fază și sunt ca un tampon termic care stabilizează fluctuațiile de temperatură în interiorul clădirilor. În acest studiu ne-am propus să introducem poziția optimă PCM pentru a reduce temperatura suprafeței exterioare și transferul de căldură. Descoperirile experimentale subliniază rolul critic al plasării stratului PCM în optimizarea eficacității. În scenariul 1-PCM, în care PCM a fost poziționat direct pe sursa de căldură, temperaturile suprafeței au crescut de la 28,43°C la 75,77°C, o îmbunătățire notabilă față de creșterea peretelui de referință de la 31,01°C la 91,00°C. Această configurație a facilitat absorbția eficientă a căldurii, rezultând o temperatură medie a suprafeței de 64,33°C, în contrast cu 85,94°C în configurația de referință. Configurația 3-PCM, cu stratul PCM între un strat de izolație exterior de 2 cm și 3 cm interior, a demonstrat o creștere minimă a temperaturii interioare, crescând de la 28,58°C la 29,52°C, comparativ cu creșterea peretelui de referință la 33,11°C. Aceste descoperiri subliniază potențialul PCM-urilor de a îmbunătăți eficiența energetică și confortul interior, justificând cercetări suplimentare privind durabilitatea, adaptabilitatea climatică și rentabilitatea pentru proiectele de clădiri durabile.