# Numerical study on the thermal performance of new composite wall with phase change material in a building located in Marrakech

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**Abstract.** Phase change materials (PCMs) hold promise for enhancing building energy efficiency. Smart walls with PCMs effectively control indoor temperatures, reducing heating and cooling energy use. This study examines five PCM configurations within a smart wall, including a reference wall, PCM1 wall, PCM2 wall, a dual PCM wall, and a novel configuration in Marrakech, Morocco. The primary aim is to find the most effective configuration for improving smart wall thermal performance. We employ numerical simulations in the ANSYS CFD environment to analyze the transient thermal behavior of walls with varying melting temperature PCMs.Results show that a novel dual-PCM wall significantly improves temperature stability and reduces energy consumption compared to the reference wall. This configuration excels in thermal energy storage and thermal conductivity. Overall, these findings highlight the effectiveness of a composite layer design for PCM-integrated smart walls. The new wall configuration with PCMs 1 and 2 reduces energy consumption by 89% in winter and 20.46% in summer. Additionally, a wall with two PCMs (1 and 2) in parallel layers reduces energy consumption by 89.5% in winter and 21.76% in the summer.

Keywords— Building; Phase-change materials; CFD simulation; Heating and cooling loads.

## 1. Introduction

Due to the rapid urbanization and increased construction activities, buildings' energy consumption has become a significant contributor to global energy usage and greenhouse gas emissions. In Morocco, the building sector alone accounts for 33% of the country's final energy consumption [1]. Consequently, there is mounting pressure on the construction industry to develop more sustainable and energy-efficient designs. One promising approach to achieving this goal is

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the incorporation of smart materials and technologies. In recent years, the utilization of phase change materials (PCMs) in composite layers of intelligent walls has garnered attention as a means to enhance thermal performance.

PCMs are substances capable of absorbing and releasing substantial amounts of thermal energy (heat) during phase transitions, such as melting or solidification. This property makes them a promising and sustainable solution for active thermal insulation, which involves using energy to control indoor temperature.

Integrating PCMs into building designs not only improves energy efficiency but also enhances thermal comfort for occupants. By stabilizing indoor temperatures, PCMs create a more pleasant and consistent living or working environment, with positive effects on productivity, health, and overall well-being. Moreover, the use of PCMs aligns with the principles of sustainable construction. By reducing reliance on mechanical heating and cooling, buildings can significantly lower their carbon footprint and contribute to global efforts to mitigate climate change. Additionally, PCMs are non-toxic and have a long lifespan, making them environmentally friendly and cost-effective in the long run. As the construction industry continues to prioritize sustainability and energy efficiency, the adoption of PCMs in building materials and designs holds great potential for creating greener and more comfortable spaces. Research and development in this field are crucial for further optimizing the use of PCMs and unlocking their full potential in the quest for sustainable building solutions.

One of the primary advantages of PCMs is their adaptability to climate change. They can dynamically adjust their thermal behavior based on external temperature conditions, which can vary significantly throughout the seasons. For example, in hot weather, PCMs can absorb heat from the surrounding environment and store it as latent heat, effectively reducing indoor temperatures and minimizing the need for air conditioning. Conversely, in cold weather, PCMs can release the stored heat to maintain a comfortable indoor temperature, thus reducing the need for heating.

Zhu and colleagues [2] conducted a study on using PCMs in a Trombe wall to enhance indoor thermal comfort in the climate conditions of Wuhan. The authors employed the TRANSYS heat transfer model and GenOpt optimization tool to determine the optimal values of critical parameters and energy consumption rate. The optimization results indicated that the ideal thickness of the air gap was 0.05 m, the optimal wall thickness was 0.68 m, the optimal vent area was 0.6 $m^2$, and the optimal melting temperatures for the lower and higher temperature PCM layers were 16.5 °C and 27.75 °C, respectively. The optimized PCM-packed Trombe wall reduced the annual building load by 13.52% compared to a conventional Trombe wall.

Louanate et al. [3] conducted a study on the utilization of dual PCMs in buildings in the Mediterranean climatic region using the EnergyPlus software.

In their study, Guo and Zhang [4] investigated the performance of building envelopes packed with PCMs for seasonal fluctuations. They evaluated the PCM layer placed at the center of the envelope using an enthalpy porous model. The results showed that while the application of PCM layer reduced the energy consumption rate, it exhibited varying performance for seasonal fluctuations, with a negative impact in the cold season. The optimal selection of PCMs for different climate conditions was found to depend significantly on the melting point and volume fraction of PCM.

Arici et al. [5] performed a numerical analysis of the impact of PCMs integrated into building walls on their position, thickness, and melting range for the climatic conditions of Turkey.

In their study, Qu et al. [6] used EnergyPlus software to conduct a multi-factor analysis of incorporating PCMs into building envelopes to achieve both thermal comfort and energy savings. The results showed that the PCM envelope type was the most influential parameter affecting energy usage and interior thermal comfort, followed by the PCM layer layout, PCM type, and PCM layer thickness. The authors concluded that selecting appropriate PCMs based on local climatic conditions could result in energy savings ranging from 4.8% to 34.8%.

Li et al. [7] conducted a study on the thermo-economic and environmental analysis of walls loaded with PCMs in rural residences in Northeast China using the EnergyPlus tool. The study examined the impact of PCM layer position, PCM wall orientation, and PCM melting point. The results revealed that PCM filled in the wall near the interior surface achieved an energy saving of 12.9%. Additionally, when compared to the baseline case, the heating load decreased by 12.8% with a PCM-filled wall on the south facade. The optimal melting temperature for PCM was found to be 16°C for an interior design temperature of 18°C. The appropriate use of PCM walls throughout their lifecycle reduced carbon footprints by 52.7 kg/m2.

In this study, we investigate the use of PCMs in composite layers to improve the thermal performance of smart walls in a building located in Marrakech, Morocco. Marrakech has a semi-arid climate with hot summers and mild winters, making it an ideal location for the use of smart walls to reduce cooling loads and lower energy consumption. Our study aims to compare and analyze different composite layer configurations with varying PCM concentrations and melting temperatures to identify the optimal configuration for improving energy efficiency.

We employ numerical simulations using ANSYS Fluent software, which utilizes the finite volume method to solve the governing equations of heat transfer in the walls. Our study focuses on the thermal behavior of the walls with different composite layer configurations, particularly in terms of reducing indoor temperature fluctuations and cooling loads. The findings of this study can contribute to the development of more sustainable and energy-efficient building designs in Morocco and other regions with similar climatic conditions.

In summary, our study addresses the need for more sustainable and energy-efficient building designs by investigating the use of PCMs in composite layers of walls in a building located in Marrakech, Morocco. The use of PCMs in walls has the potential to significantly reduce cooling loads and energy consumption, making it a promising solution for enhancing thermal performance in buildings.

## 2. Description of the configuration

In traditional construction practices in Morocco, buildings are typically constructed using bricks and mortar. However, these conventional structures often face challenges in maintaining thermal comfort during hot summers due to the intense ambient heat. To address this issue, our work focuses on exploring the integration of PCMs to enhance the thermal performance of exterior walls.

In our study, we examine various PCM integration configurations, as depicted in Figure 1. First, we have a reference case (Figure 1a), representing the prevalent construction method in the region. In the second configuration (Figure 1b), we introduce a 2 cm thick layer of PCM1 on the outside of the wall. Similarly, in the third configuration (Figure 1c), we add a 2 cm thick layer of PCM2 on the exterior of the wall. The fourth configuration (Figure 1d) involves the addition of two PCM layers in a new configuration. Finally, the fifth configuration (Figure 1e) entails the addition of two PCM layers in parallel.

To facilitate analysis, we provide the thermal properties of the building wall materials in Table I. These properties are crucial for evaluating the effectiveness of the various PCM integration configurations in improving thermal performance. By investigating these different configurations and their corresponding thermal properties, our goal is to identify the most suitable and efficient PCM integration approach for enhancing the thermal performance of exterior walls.

**TABLE I.** Thermo-physical properties of materials

| **Materials** | **Thermal conductivity (W/m,K)** | **Density (Kg/$m^3$)** | **Specific heat (J/Kg.K)** | **Melting temperature (°C)** | **Latent heat (KJ/Kg)** |
|---|---|---|---|---|---|
| **Brick** | 0.925 | 0.92 | 2100 | - | |
| **Mortar** | 0.97 | 0.84 | 1600 | - | |
| **PCM1** | 0.2 | 870 | 1800 | 28 | 179 |
| **PCM2** | 0.43 | 1515 | 1900 | 13 | 150 |

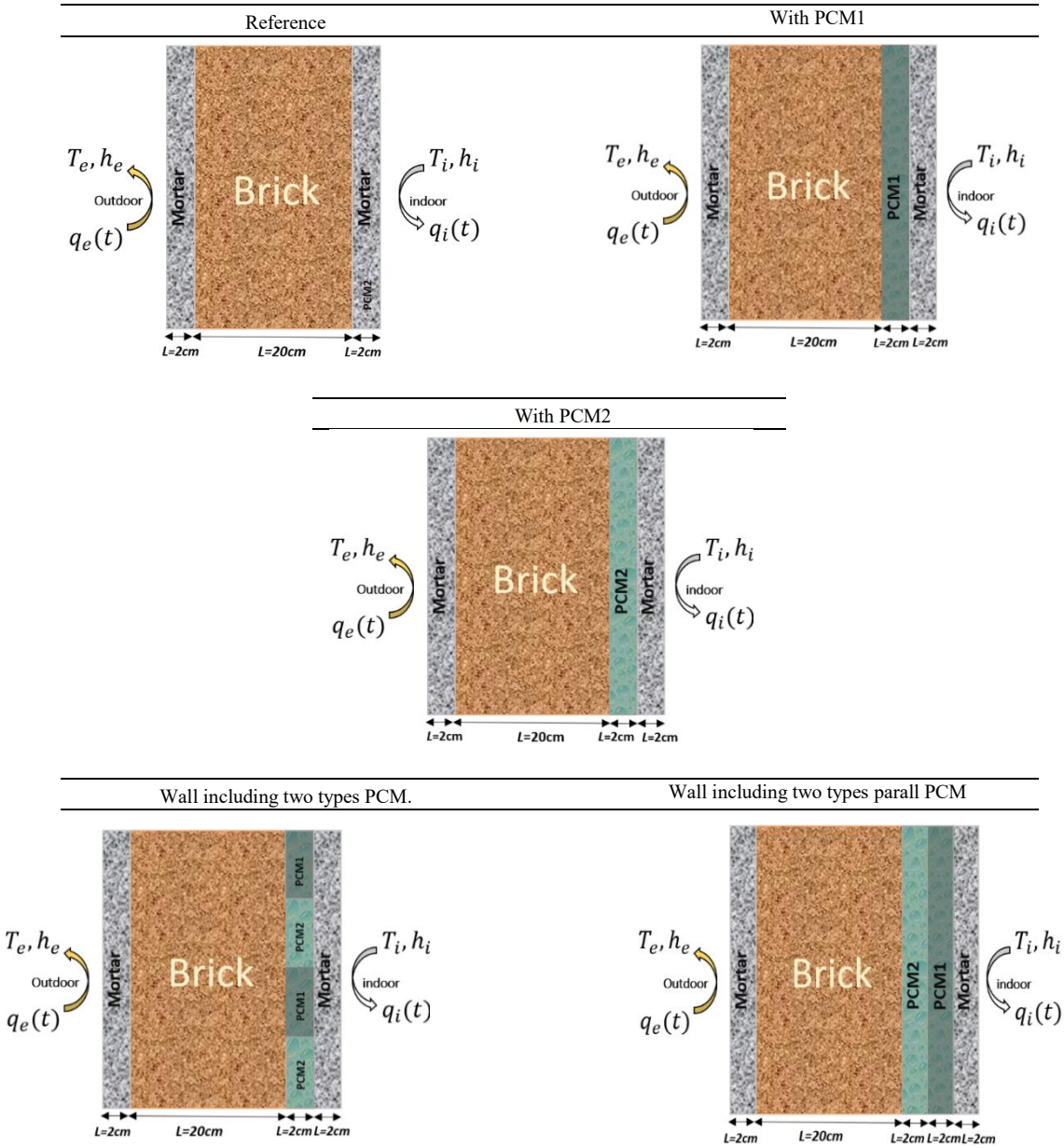


**Fig. 1.** Configuration of the Wall

## 3. Description of meteorology

Marrakech, situated at latitude 31.617 and longitude -8.033, with an elevation of 466 meters above sea level, is located approximately 323 kilometers south of Rabat, Morocco, and about 180 kilometers east of the Atlantic Ocean. The city experiences a dry continental climate characterized by cold winters and hot, dry summers, with significant temperature fluctuations between day and night, often exceeding 20°C. The average annual temperature in Marrakech is around 20°C.

Figure 2 illustrates the climate data for the Marrakech region, sourced from the study's Typical Meteorological Year (TMY2) [8]. The lowest recorded temperature occurs in January (2.5°C), although this month receives slightly more sunshine compared to December. The coldest months, with low solar radiation ranging from 3.5 to 4.2 kWh/m²/day, are January, February, and December. July, as the sunniest month, experiences the highest maximum temperature (45°C) and the corresponding solar radiation (7.8 kWh/m²/day). January exhibits the lowest mean temperature, which rises by 3.3°C in February. August is the hottest month, followed by April, May, June, and June. From April to July, the mean temperature gradually increases by an average of 3 to 4°C before decreasing by 3.3°C in September. Notably, there is a substantial temperature variation between the maximum and minimum values throughout the year, a characteristic feature of the climate in the Marrakech region. The largest temperature difference can reach 27.3°C (in July), while the smallest variation (20°C to 21°C) occurs over the span of three months (June, August, and September).

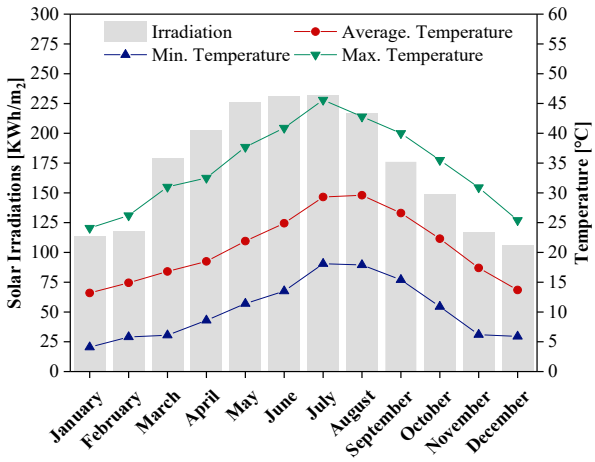


**Fig. 2.** Climate data from the Marrakech region (2022) [8]

## 4. Simulation model

To determine the thermal performance of the four wall configurations, the temperature profile across the configurations is calculated by numerically solving the energy equation using the CFD method (Computational Fluid Dynamics) (Eq 1). The study is carried out for a south-facing wall located in Marrakech (Morocco). The Perez model is used to calculate the solar radiation flux intercepted on the exterior wall.

$$\rho_j C_{pj} \frac{dT_j}{dt} = \lambda_j \frac{\partial^2 T_j}{\partial x^2} + \lambda_j \frac{\partial^2 T_j}{\partial y^2} \quad \text{j is layer number (1, 2,.., N)} \quad (1)$$

Eq (1) is valid for cases of fully solid or liquid materials. However, to fully capture the phase change process (melting or solidification) of the PCM layer, an additional term (Eq 2) must be included.

$$\rho_j C_{pj} \frac{dT_j}{dt} = \lambda_j \frac{\partial^2 T_j}{\partial x^2} + \lambda_j \frac{\partial^2 T_j}{\partial y^2} - \rho_j L_f \frac{\partial f}{\partial t} \quad (2)$$

Where $L_f$ is the latent heat and $f_l$is the liquid fraction of PCM defined as:

$$f_l = \begin{cases} 0 & si\ T < T_{fusion} \\ [0-1] & si\ T = T_{fusion} \\ 1 & si\ T > T_{fusion} \end{cases} \quad (3)$$

Boundary conditions include combined radiative and convective heat transfer outdoors and convective heat transfer indoors and are given by equations (4) and (5) below; so that the other sides of the wall configuration were treated as isolated (Eq. 6).

$$-\lambda_1 \left(\frac{\partial T}{\partial x}\right)_{x=0} = h_e(T_{sa}(t) - T_{x=0}(t)) \quad (4)$$

$$-\lambda_N \left(\frac{\partial T}{\partial x}\right)_{x=L} = h_i(T_{x=L}(t) - T_{in}) \quad (5)$$

$$\frac{\partial T(x,o,t)}{\partial y} = \frac{\partial T(x,l,t)}{\partial y} = 0 \quad (6)$$

Where hi and he represent heat transfer coefficients on the inner and outer surfaces of the wall and are taken to be 9 (W/m2. K) and 22 (W/m2.K), respectively. Tin is the inside temperature, which is set at 20°C in winter and 26°C in summer. Tsa is solar-air temperature that combines the effect of solar radiation and the outside temperature. It can be calculated using Eq (7) according to Yumrutas et al[9];

$$T_{sa}(t) = T_a(t) + \frac{\alpha_s I_s(t)}{h_e} - \frac{\varepsilon\sigma(T_a^4(t) - T_{sky}^4(t))}{h_e} \quad (7)$$

In the context of the meteorological data for the Marrakech climate zone in Morocco, several key parameters are considered to assess the solar-air temperature. These parameters include Ta, representing the outside air temperature, $\alpha_s$ denoting the solar absorption coefficient of the outer surface,$I_s$ indicating the solar radiation on the outer wall surface, ε representing the emissivity of the wall surface, and σ which stands for the Stephan-Boltzmann constant (5.65x10-8 W/m2. K4). The solar-air temperature for the specified period, from 15th July to 17th July, is graphically depicted in Figure 3. This temperature data offers valuable insights into the thermal conditions experienced in the Marrakech climate zone, aiding in the analysis and understanding of solar heating effects on the outer wall surface during this time frame.

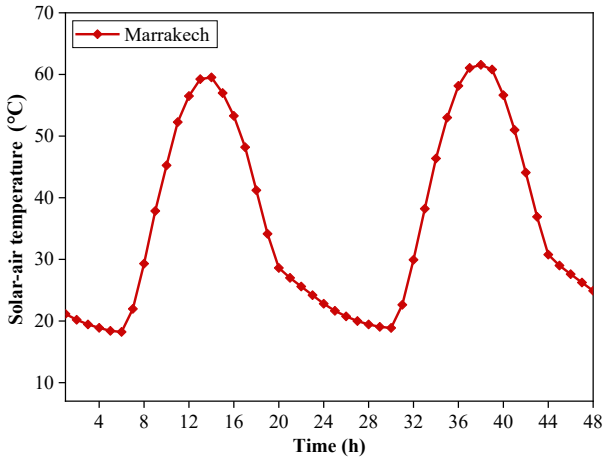


**Fig. 3.** Solar-air temperature profile for different climatic zones.

The governing equation and boundary conditions are discretized by the finite volume method. The size of the grid in space is $7 \times 10^{-3}$ and the time step chosen is Δt=1 hour; this choice is dictated by the solar radiation and temperature data that are available with a time step of one hour. The system of equations is solved iteratively using the Newton-Raphson method.

# 5. Results and discussion

## 5.1. Validation

We note that, as the temperature profile of the inner surface fluctuates and remains superimposed (see fig 4), our numerical results are in good agreement with those of Jin et al.

This section focuses on the validation of the numerical model utilized for the study presented in this work. The accuracy and reliability of the Computational Fluid Dynamics (CFD) model are verified by comparing its results with the numerical findings obtained by Jin et al [10]. In their study, Jin et al investigated the impact of thermal properties on wall performance, specifically analyzing the temperature profile, decrement factor, and time lag. It is essential to highlight that Jin et al employed a different mathematical model from the one utilized in our study to examine the thermal behavior of a brick wall (with thermal conductivity ($\lambda = 0.62\, W/m.K$) , specific heat capacity ($C_p = 840\, J/kg.K$ ; $\rho = 1800\, Kg/m^3$).

Table II presents a comparison of the time lag and decrement factor values calculated by our numerical method and those used by Jin et al. Notably, we observe that our numerical results exhibit good agreement with those obtained by Jin et al, as the temperature profile of the inner surface fluctuates and remains superimposed (see fig 4). This concurrence between the two sets of results strengthens the validation of our numerical model, indicating its accuracy in capturing the thermal behavior of the wall under study.

**TABLE II.** Results of the time lag and decrement factor calculated by our numerical method and those used by Jin et al.

| | **Jin et al (2012)** | **Present study** | **Difference in %.** |
|---|---|---|---|
| **Decrement factor** | 0.1154 | 0.1123 | 2.68 |
| **Time lag (h)** | 10 | 9.85 | 1.5 |

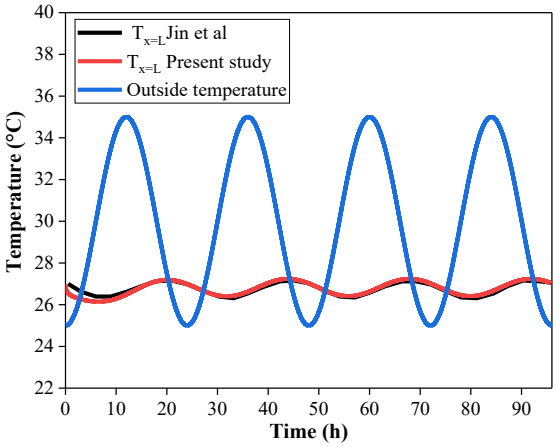


**Fig. 4.** Comparison of numerical results with the results obtained by Jin et al [10].

### 5.2. Analysis of temperature distribution

In this section, we explore different wall configurations, considering both single and double layers of PCM, in conjunction with other passive methods. The study delves into the evaluation of thermal performance in buildings within the Marrakech environment, focusing on four specific configurations. Our objective is to identify the most effective arrangement that ensures optimal thermal comfort during both summer and winter.To achieve this, we maintain steady temperatures of 26°C and 19°C inside the building, corresponding to the desired thermal comfort levels during summer and winter, respectively. Our numerical code simulates two distinct phases during the study. The first phase encompasses the three hottest days of the year, representing the summer months, specifically July 20th, 21st, and 23rd. The second phase covers the coldest period, which is the winter season, including January 15th, 16th, and 17th.Throughout the simulation, we closely monitor the temporal evolution of the temperature at the inner face of the wall for each configuration. In Figures 2 and 3, we present graphical representations of temperature variations during both the summer and winter seasons for the various setups. Now, let's proceed to provide a detailed description of the temperature progression for each configuration.

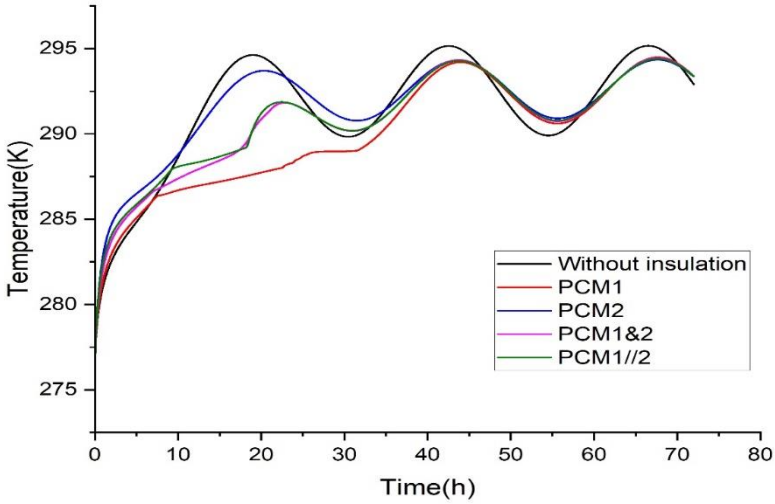


**Fig. 5.** Temperature distribution during the winter period from January 15 to 17 for the different wall configurations.

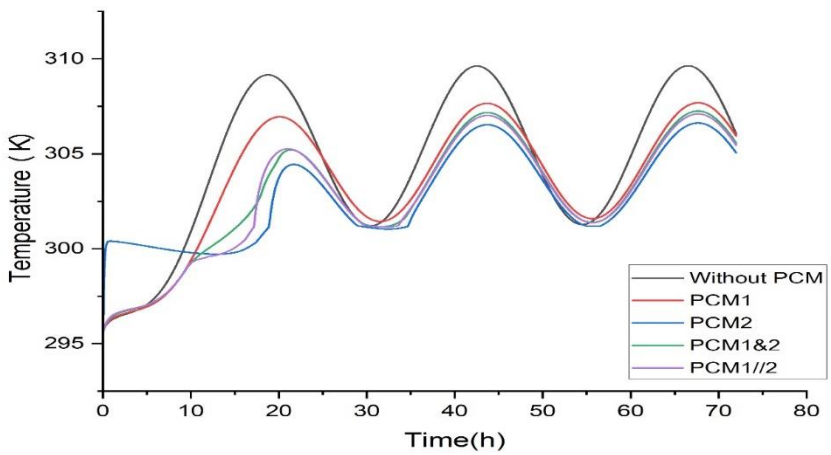


**Fig. 6.** Temperature distribution during the summer period from July 20 to 23 for the different wall configurations.

Integrating PCM1 (Tm = 28 °C) into the wall structure has a significant impact on the temperature profile on the inner side of the wall. During summer, when external temperatures are high, this approach ensures a more consistent and comfortable indoor temperature. When the external interface of PCM1 and the wall's outside face are in direct thermal contact, the wall's external face reaches the PCM's melting temperature, triggering several phenomena. As the PCM melts in response to absorbed heat, it transitions from a solid to a liquid state. This coexistence of solid and liquid phases within the PCM layer stabilizes the temperature at the melting point, resulting in consistent temperature fluctuations at the inner face of the wall. However, during the winter season, PCM1 (Tm = 28 °C) has limited thermal performance in very cold climates like Marrakech, as it remains in a solid state, serving as an insulating layer. This configuration provides minor improvements during winter but significantly enhances thermal comfort in summer, stabilizing the internal temperature at around 30 °C.

On the other hand, incorporating PCM2 (Tm = 13 °C) into the wall structure influences the temperature profile on the inner side of the wall. PCM2 helps stabilize the internal temperature during the winter season, mitigating external temperature fluctuations and providing more consistent indoor conditions. However, PCM1 (Tm = 28 °C) outperforms PCM2 during the winter, especially in high-temperature climates like Marrakech, where PCM2 fully transforms into a liquid state (f = 1), acting as an insulating layer. This configuration has limited impact during the summer but improves thermal comfort during the winter, stabilizing the internal temperature at approximately 20 °C.

To enhance thermal comfort year-round, our research explored configurations with two distinct PCMs: PCM1 (Tm = 28 °C) and PCM2 (Tm = 13 °C), each selected for their specific roles in addressing seasonal concerns. PCM1 targets summer comfort, while PCM2 focuses on winter comfort. Figures 5 and 6 highlight the effectiveness of these dual PCM configurations. During the summer, introducing a second PCM2 (Tm = 13 °C) has minimal impact on energy performance, as outside temperatures remain above the melting point of PCM2. In winter, the combination of two PCMs significantly improves thermal comfort, stabilizing the inner wall temperature at around 19 °C in winter and 26 °C in summer. This stability results from PCM1 (Tm = 28 °C) serving as an insulating layer and PCM2 (Tm = 13 °C) partially melting to buffer temperature between the interior and exterior. Combining PCM1 and PCM2 optimizes temperature stabilization and offers energy-efficient solutions for buildings, promoting sustainable and comfortable living environments year-round.

### 5.3. Energy performance

Assessing heating and cooling requirements, we maintained a consistent indoor air temperature in accordance with Moroccan standard NM ISO 7730, ensuring comfort standards were met. Specifically, we set the indoor air temperature at 26°C during the summer and 20°C during the winter. Figure 4 illustrates energy usage in the summer, while Figure 5 displays energy consumption in the winter.

Our modeling results revealed that the fourth wall, which incorporated both PCM1 and PCM2, achieved a remarkable 89% reduction in energy usage during the winter and a significant 20.46% reduction during the summer. Similarly, the fifth wall, featuring parallel layers of PCM1 and PCM2, delivered outstanding energy savings with a reduction of 89.5% in the winter and 21.76% in the summer.

These substantial energy savings were made possible by utilizing the combined capacity of PCM1 and PCM2 to absorb and store thermal energy during the day. This process effectively lowered indoor temperatures, reducing the need for cooling during the summer.

In summary, the integration of PCM1 and PCM2 in the wall structures demonstrated an exceptional ability to reduce energy consumption, particularly during winter months, achieving significant savings of up to 89%. Additionally, during hot summer periods, the combined effect of these two PCMs led to significant energy reductions, enhancing the overall energy performance of the walls by up to 21.76%. This research underscores the promising potential of PCM integration in creating more energy-efficient buildings and contributing to sustainable energy practices.

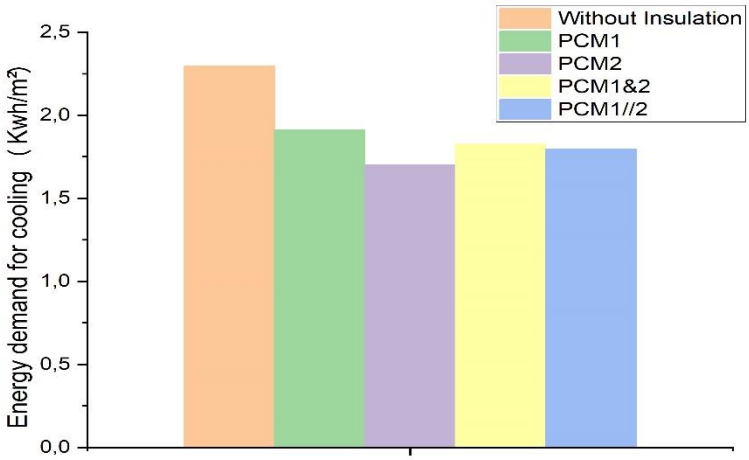


**Fig. 7.** Demand for heating for four configurations.

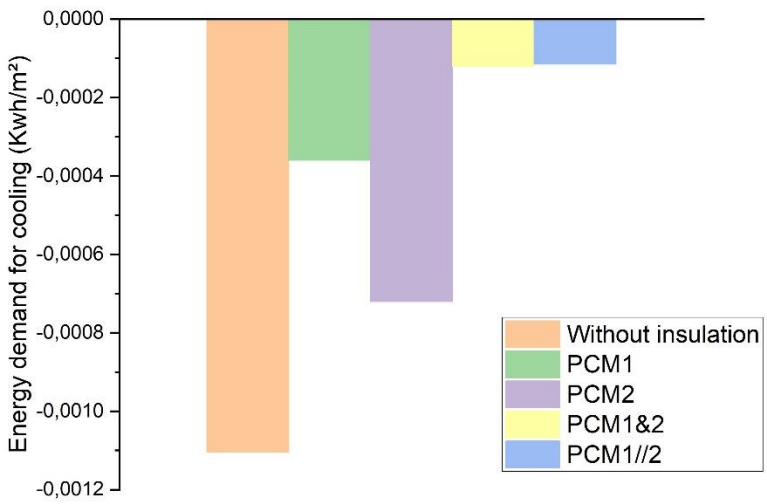


**Fig. 8.** Demand for cooling for four configurations.

# 6. Conclusion

In conclusion, this study explored the efficacy of various phase change material (PCM) configurations in smart walls, aiming to enhance the thermal performance and energy efficiency of buildings. The findings underscore the substantial potential of PCMs as a promising passive technology for moderating indoor temperatures and reducing energy consumption for both heating and cooling needs.

Through numerical simulations conducted using the ANSYS CFD environment, we scrutinized the transient thermal behavior of walls equipped with PCMs of differing melting temperatures. Our comparative analysis of five configurations, encompassing a reference wall, PCM1, PCM2, two PCMs, and an innovative design, situated in the climate of Marrakech, Morocco, furnished us with valuable insights.

The numerical simulations convincingly showed that incorporating PCMs into smart walls can dramatically reduce temperature fluctuations and energy consumption when contrasted with conventional wall structures. The novel configuration featuring parallel layers of PCM1 and PCM2 exhibited exceptional thermal energy storage and thermal conductivity. The outcomes emphasize the significance of judiciously selecting and designing PCM configurations within building structures to optimize their performance. Notably, the dual PCM configuration displayed remarkable energy savings, with an 89% reduction in winter and a 20.46% reduction in summer. Similarly, the wall employing separate layers of PCM1 and PCM2 achieved energy reductions of 89.5% in winter and 21.76% in summer.

This study contributes numerous advantages and benefits to the domain of building design and construction. Firstly, it demonstrates the compelling potential of PCMs in advancing energy efficiency. The incorporation of PCMs into smart walls markedly reduces energy consumption for heating and cooling, yielding cost savings and fostering a more sustainable approach to building operations. Secondly, the adoption of smart walls with PCMs elevates thermal comfort by effectively stabilizing indoor temperatures and curbing temperature fluctuations, with the potential to enhance productivity, occupant well-being, and overall satisfaction.

Furthermore, the study provides invaluable insights into the optimal design of PCM configurations in smart walls. By comparing and assessing various setups, it offers guidance to designers and engineers for optimizing PCM integration into building structures, facilitating informed and efficient use of PCM technologies.

Additionally, the research adds to the scientific understanding of PCMs and their influence on thermal performance. Specific to the Marrakech region, the study generates empirical data confirming the effectiveness of PCMs in reducing energy consumption and temperature fluctuations, contributing to the body of knowledge in the field and informing future research.

Lastly, the study's findings hold practical applicability, focusing on a specific location with a unique climate and environmental context. As such, the results can be directly translated into real-world applications within local building practices and policies, providing tangible benefits and guiding stakeholders in energy-efficient and comfortable building design decisions.

In conclusion, this study's merits encompass contributions to energy efficiency, improved thermal comfort, optimized design strategies, scientific knowledge advancement, and applicability to real-world scenarios. These advantages have the potential to drive sustainable and comfortable building practices, reduce energy consumption, and enable well-informed decision-making in the realm of building design and construction.

The study opens up several avenues for further research and practical application in the field of building design and energy efficiency. Future studies could expand their scope to encompass a

broader range of building types and climate zones, fostering a more comprehensive understanding of the effectiveness of PCM-based smart walls in various contexts and enabling tailored solutions for specific regions and building categories.

Moreover, the study's findings could be extended to evaluate the economic feasibility and cost-effectiveness of implementing PCM-based smart walls in real-world building projects. Life-cycle cost analyses, incorporating factors such as material costs, installation expenses, and potential energy savings, would furnish stakeholders and decision-makers with valuable insights.

Lastly, field experiments and monitoring studies could validate the findings of numerical simulations and assess the real-world performance of PCM-based smart walls. Measuring energy consumption, indoor temperatures, and occupant comfort in actual buildings would provide more precise data, reinforcing the reliability of the study's conclusions.

In summary, future perspectives for this research encompass broadening the scope of the investigation, evaluating economic viability, conducting field experiments, and exploring synergies with other energy-efficient technologies. These research directions are poised to advance and apply PCM-based smart walls, furthering the pursuit of sustainable and energy-efficient buildings.

## References

[1] « AMEE | Adhérons à un avenir énergétique durable ». https://www.amee.ma/fr/home (consulté le 21 juillet 2023).

[2] D. Zhou, G. S. F. Shire, et Y. Tian, « Parametric analysis of influencing factors in Phase Change Material Wallboard (PCMW) », *Applied Energy*, vol. 119, p. 33-42, avr. 2014, doi: 10.1016/j.apenergy.2013.12.059.

[3] A. Louanate, R. E. Otmani, K. Kandoussi, et M. Boutaous, « Dynamic modeling and performance assessment of single and double phase change material layer–integrated buildings in Mediterranean climate zone », *Journal of Building Physics*, vol. 44, nº 5, p. 461-478, mars 2021, doi: 10.1177/1744259120945361.

[4] J. Guo et G. Zhang, « Investigating the performance of the PCM-integrated building envelope on a seasonal basis », *Journal of the Taiwan Institute of Chemical Engineers*, vol. 124, p. 91-97, juill. 2021, doi: 10.1016/j.jtice.2021.04.066.

[5] M. Arıcı, F. Bilgin, S. Nižetić, et H. Karabay, « PCM integrated to external building walls: An optimization study on maximum activation of latent heat », *Applied Thermal Engineering*, vol. 165, p. 114560, janv. 2020, doi: 10.1016/j.applthermaleng.2019.114560.

[6] Y. Qu, D. Zhou, F. Xue, et L. Cui, « Multi-factor analysis on thermal comfort and energy saving potential for PCM-integrated buildings in summer », *Energy and Buildings*, vol. 241, p. 110966, juin 2021, doi: 10.1016/j.enbuild.2021.110966.

[7] J. Lei, J. Yang, et E.-H. Yang, « Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore », *Applied Energy*, vol. 162, p. 207-217, janv. 2016, doi: 10.1016/j.apenergy.2015.10.031.

[8] « intro - Meteonorm (de) », *Meteonorm (en)*. https://meteonorm.com/en (consulté le 21 juillet 2023).

[9] R. Yumrutaş, M. Ünsal, et M. Kanoğlu, « Periodic solution of transient heat flow through multilayer walls and flat roofs by complex finite Fourier transform technique », *Building and Environment*, vol. 40, nº 8, p. 1117-1125, août 2005, doi: 10.1016/j.buildenv.2004.09.005.

[10] X. Jin, X. Zhang, Y. Cao, et G. Wang, « Thermal performance evaluation of the wall using heat flux time lag and decrement factor », *Energy and Buildings*, vol. 47, p. 369-374, avr. 2012, doi: 10.1016/j.enbuild.2011.12.010.