UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

OPTIMIZING ENERGY EFFICIENCY BY INTEGRATING PHASE CHANGE MATERIALS INTO BUILDING ENVELOPES

Booklet of PhD Theses

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1. INTRODUCTION

Globally, buildings are becoming major energy consumers, with heating and cooling alone representing up to 40 % of commercial building energy and as much as 61 % of homes. The International Energy Agency (IEA) identifies the building sector as the largest single user of energy worldwide and warns that if nothing changes, demand for space heating could climb by 12 % and for cooling by 37 % by 2050 [1].

The building envelope (walls, roof, windows, and floors) works as the primary interface between indoor and outdoor environments. It not only protects occupants from the weather, but also governs how much thermal energy enters or escapes. Nearly half of all heating and cooling loads pass directly through the envelope, making its design critical to overall efficiency. Reflecting this, the IEA reports that the greater part of recent investment in the sector has gone toward renovating and constructing higher-performance envelopes, and that building operations plus construction accounted for 39 % of energy-related CO_2 emissions and 36 % of final energy use in buildings in 2018 [2].

To reduce these loads, researchers and practitioners have explored a variety of envelope-focused strategies [3,4]. One of the most promising approaches is embedding phase change materials (PCMs) into building components. By absorbing and releasing latent heat as it melts and solidifies, PCMs can smooth out temperature swings, reducing heating and cooling demands while maintaining thermal comfort [5-11]. Recent studies [12-14] continue to investigate new PCM formulations and ways to integrate them most effectively.

PCMs can absorb and release heat during phase transition (from the solid to liquid state and vice versa) under a constant temperature, as seen in Fig. 1.1. These materials can absorb and release large amounts of heat for a limited unit volume by storing heat during the melting and charging phases and releasing it during the solidification and discharge phases. PCMs may effectively manage energy in a variety of applications. This helps to regulate the required amount of energy. Additionally, PCMs shift peak load to off-peak times, improving buildings' efficiency [18,19].

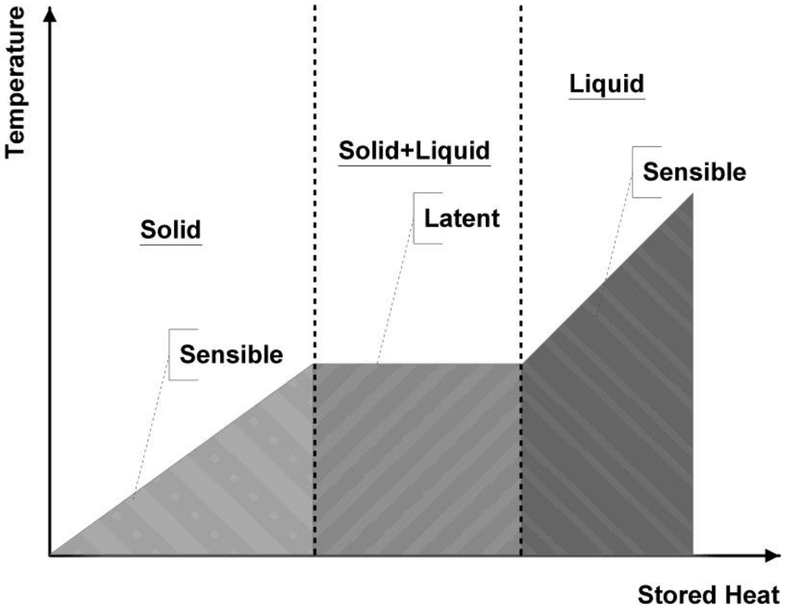

***Fig. 1.1:** Heat transition regions of PCM*

In my research, new insights are presented into the numerical modeling of PCMs for thermal energy storage. By simulating the melting behavior of RT-27 using ANSYS Fluent under realistic convective heating conditions, the uncovers detailed thermal behavior patterns such as the transition from conduction to convection-dominated heat transfer. The results validate the effectiveness of CFD tools in capturing the complex phase change dynamics, offering a precise framework for PCM design in energy-efficient buildings. Original findings emerge from a comprehensive parametric optimization of PCM integration into building envelopes. By evaluating different positions, thicknesses, and melting temperatures of PCM layers, the study identifies optimal configurations that significantly reduce heat transfer. The results not only demonstrate the sensitivity of thermal performance to these parameters, but also establish a practical methodology for customizing PCM use based on local climatic conditions, with a focus on buildings in Miskolc, Hungary, The research breaks new ground by systematically evaluating the thermal impact of various PCM capsule geometries (cuboid, cylindrical, and prismatic) within building materials. The simulations reveal that capsule shape plays a critical role in heat storage and release efficiency. Novel insights are provided into how geometry affects phase transition rates and overall energy performance, guiding the future design of encapsulated PCM systems for optimal building integration. The thesis introduces a novel integration of PCMs into traditional Flemish bond brick walls (architectural method) previously underexplored from a thermal efficiency perspective. The study reveals that Flemish bond structures alone can reduce heat transfer by 6 %, and when combined with PCM, the reduction improves to 21 %. These results highlight a pioneering approach that fuses historical building techniques with cutting-edge energy storage materials, advancing sustainable construction while preserving architectural aesthetics.

2. METHODOLOGY OF THE STUDY

2.1. Modeling and Simulation of PCM in Building Envelopes

PCMs are examined for their critical role in thermal energy storage systems. The research focuses on numerical modeling of PCMs, with particular emphasis on using ANSYS Fluent to simulate the melting process. The primary objective is to model the thermal behavior of RT-27 PCM under convective heating conditions using computational fluid dynamics (CFD). The simulation captures the shift from conduction-dominated heat transfer in the early stages to natural convection as the melting progresses. Key variables analyzed include temperature distribution, liquid fraction, density variation, and velocity fields over time. Through this numerical study, the research demonstrates that CFD is a reliable and accurate tool for simulating phase change processes and for optimizing the design of PCM-based thermal energy storage systems in building application. A numerical analysis was performed to investigate the melting behavior of RT-27 within a rectangular domain measuring 10 [mm] in width and 200 [mm] in height. The PCM was subjected to convective heating from the left and right boundaries, while the top and bottom boundaries were treated as adiabatic. This configuration replicates a simplified building envelope condition to observe heat transfer during phase change.

The simulation was conducted over a 360 [min] melting cycle, with results recorded at 30 [min] intervals to track the transient thermal response of the PCM. The findings are presented through contour plots showing the spatial distribution of key physical parameters, including liquid fraction, temperature, density, and velocity, at selected time steps throughout the simulation. The following results, as well as the numerical model conducted for this study, were thoroughly validated through comparison with established numerical and experimental research found in the literature [20-22]. The evolution of the liquid fraction during the melting process is illustrated in Fig. 2.1, where the progression of the phase-change front over time is visible. In these contour plots, red regions represent fully liquid PCM (liquid-fraction f=1), while blue areas indicate fully solid PCM (f=0). The transition zone between these extremes is referred to as the mushy zone, where both solid and liquid phases coexist. This zone represents the moving melting front.

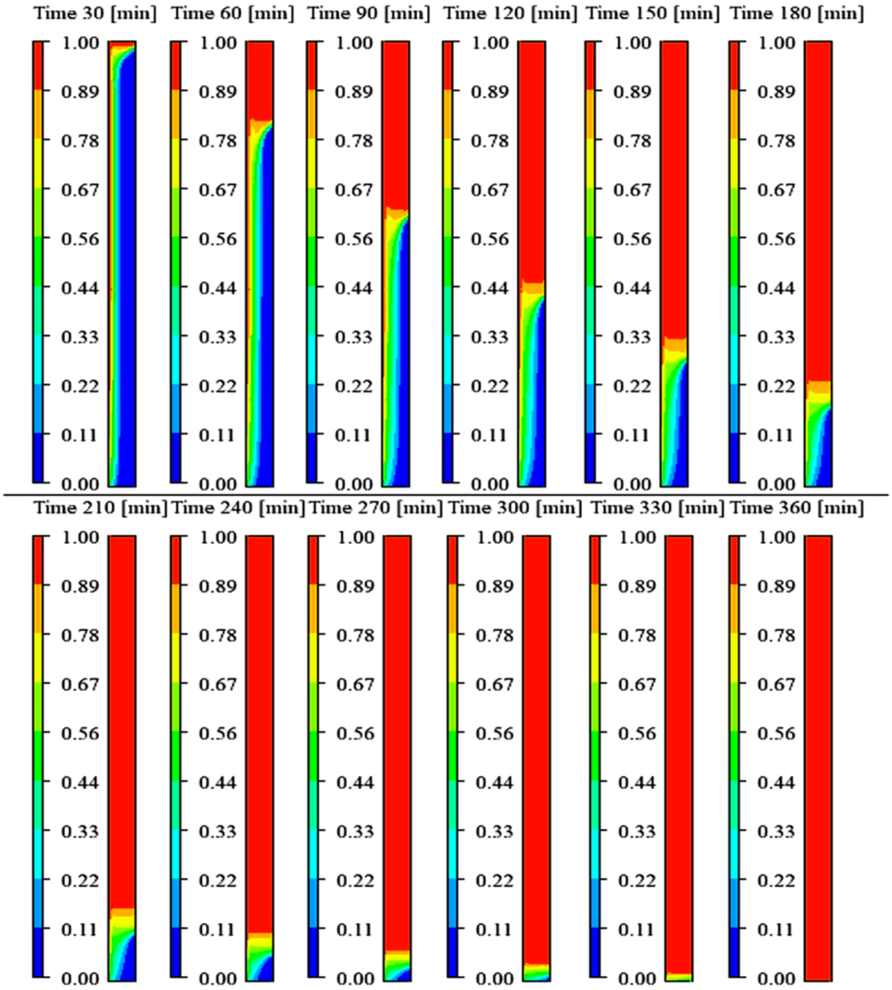

***Fig. 2.1:** Liquid-fraction contours*

The evolution of density contours within the PCM domain over time is illustrated in Fig. 2.2, with results displayed at 30 [min] intervals throughout the melting process. As PCM undergoes heating, its density decreases with rising temperature, reflecting the inherent temperature-dependent behavior of the material. As a result, the less dense, warmer PCM tends to rise toward the upper region of the domain due to buoyancy forces, creating a distinct zone of low-density fluid, which is represented in blue in the contour plots. This vertical density stratification becomes more pronounced as the phase transition progresses, with continuous circulation reinforcing the accumulation of lower-density PCM in the upper layers. Toward the end of the melting process, the entire PCM domain reaches a thermally uniform liquid state, and the density distribution.

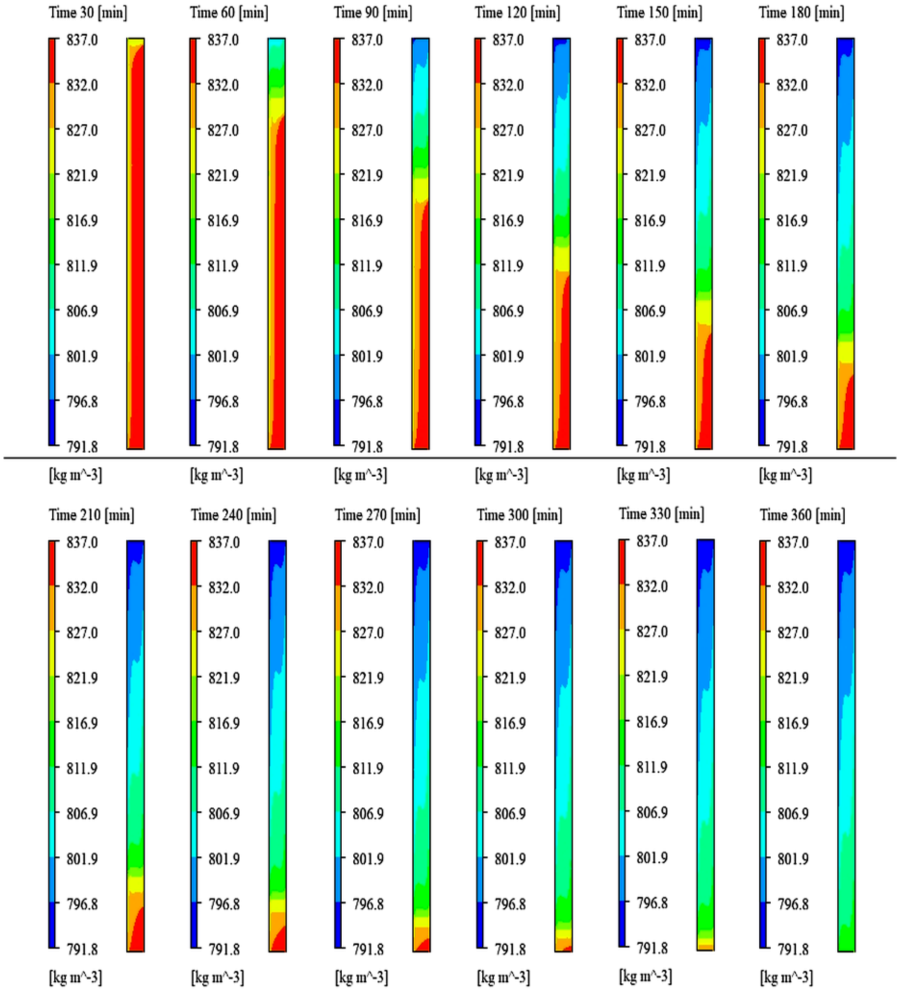

Fig. 2.2: *Density contours*

The study employed fine meshing and carefully selected time steps to ensure numerical stability, emphasizing the importance of pre-processing and solver settings in transient heat transfer simulations.The research concludes by affirming that ANSYS Fluent is a capable and reliable platform for simulating PCM-based thermal storage systems. However, the successful application depends on several key factors, including accurate material properties, appropriate meshing strategies, time step management, and the correct implementation of boundary conditions.

2.2. Optimization of Parameters Influencing PCM Performance Integrated in Building Envelopes

This research presented a comprehensive numerical investigation into the optimization of key parameters affecting the thermal performance of PCMs when integrated into building envelopes. The study focused on a representative wall configuration typical of Miskolc, Hungary, composed of 3 [cm] cement, 15 [cm] brick, and 2 [cm] plaster layers. Using validated

CFD simulations, the chapter explored the impact of PCM layer position, thickness, and material properties on reducing indoor heat gain and enhancing thermal comfort.

The analysis began by examining the effect of PCM placement at four distinct positions within the wall assembly,as showen in Fig. 2.3. Results showed that positioning the PCM closer to the exterior surface significantly enhanced its thermal buffering capacity and led to the greatest reduction in heat transmission. This configuration was selected for further parametric analysis.

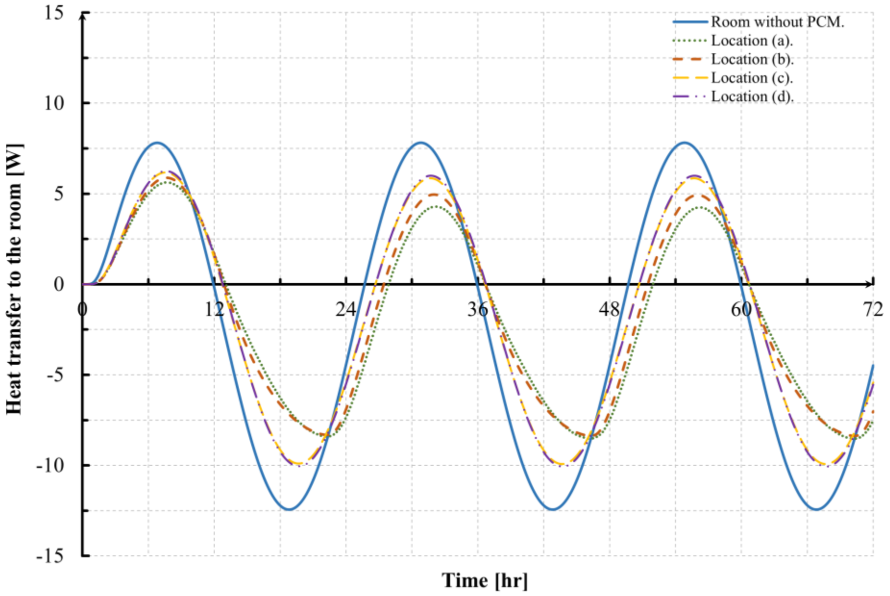

Fig. 2.3: *Heat transmission into the room when the PCM is relocated, (a) externally mounted, on the outermost surface, (b) Near the exterior, embedded between the cement and bricklayers, (c) Near the interior, placed between the brick and plaster layers, (d) Directly on the interior surface, forming the innermost layer of the envelope.*

Next, the influence of PCM thickness was assessed using RT-27. Increasing the PCM layer from 1 [cm] to 5 [cm] resulted in greater energy storage, lower interior surface temperature fluctuations, and a measurable reduction in total heat transfer to the indoor space as showen in Fig. 2.4.

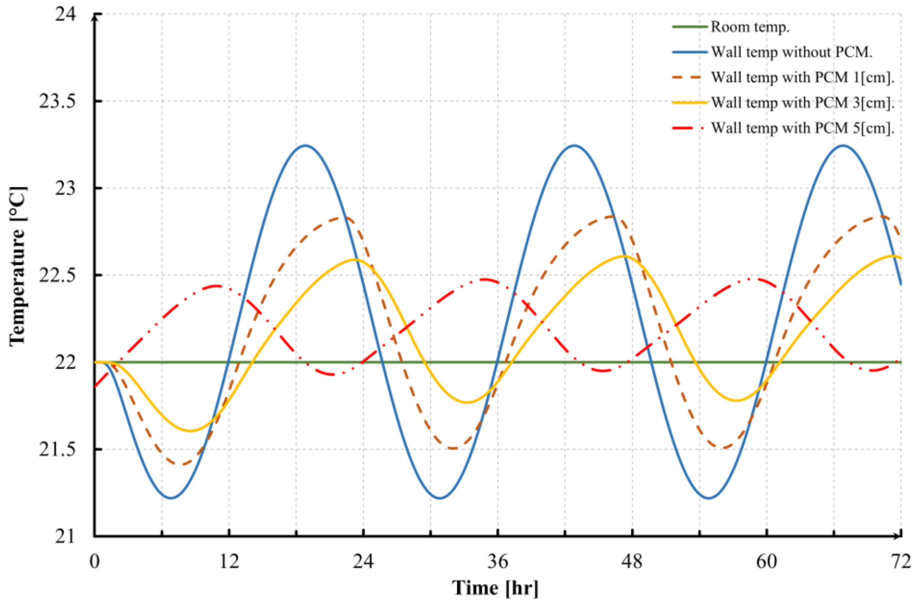

Fig. 2.4: *Indoor surface temperature distribution with different thicknesses of PCM (RT-27)*

The research also evaluated the performance of different PCM types, demonstrating that thermal properties particularly melting temperature and thermal conductivity play a decisive role in effectiveness. Among the tested materials, SP-25E2 achieved the lowest overall heat transmission, confirming the importance of matching PCM properties to the climate and application. From the simulation results, several key conclusions were drawn:

- Incorporating PCMs into wall assemblies reduces heat transfer and improves thermal stability.
- Temperature fluctuations at the indoor surface are significantly dampened by PCM integration.
- Low thermal conductivity is a desirable characteristic, as it correlates with lower heat flux into the room.
- Optimal performance is achieved when the PCM is placed near the outer surface of the wall, where it intercepts and absorbs incoming heat early.
- Increasing PCM thickness allows for higher thermal energy storage within the envelope, further enhancing performance.

Overall, this research highlights the critical role of design variables in PCM-based envelope systems and provides practical insights for energy-efficient building strategies in moderate continental climates like that of Miskolc.

2.3. Optimization of PCM Capsule Shape for Enhanced Building Envelopes

This research focused on optimizing the geometric configuration of PCM capsules embedded within building envelopes to enhance thermal performance. Using RT-27 paraffin wax selected for its favorable thermal characteristics and suitability for Miskolc's climate, the study evaluated how different capsule shapes influence energy storage and heat transfer in building walls.

Three primary capsule shapes were examined: cuboid, cylindrical, and prismatic, each offering distinct thermal and structural advantages. Cuboid-shaped capsules demonstrated superior heat transmission reduction, as showen in Fig. 2.5, achieving the highest performance in limiting indoor temperature fluctuations. Their flat surfaces promote uniform phase transitions and make them structurally compatible with modular wall components, while also being cost-effective and easy to manufacture.

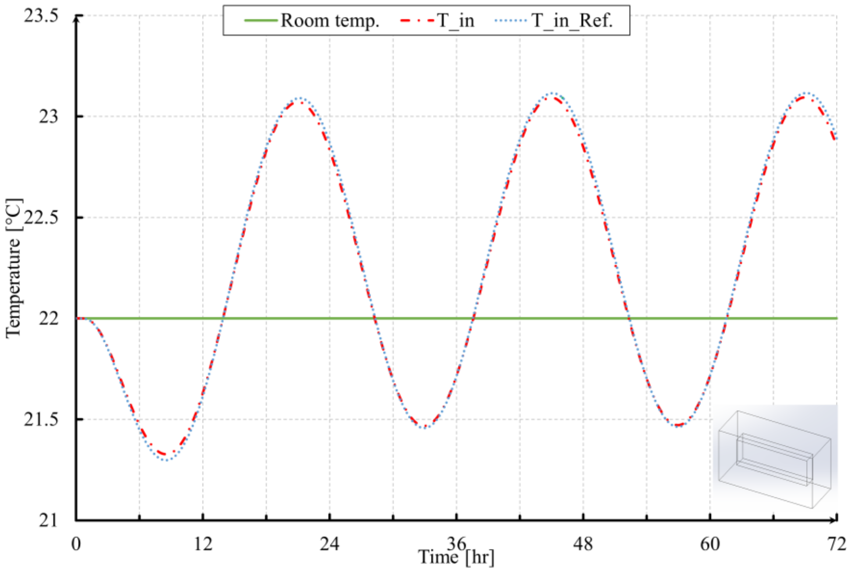

Fig. 2.5: *Indoor surface temperature distribution with cuboid capsule*

Cylindrical capsules offered good mechanical stability and directional heat flow, making them well-suited for integration into hollow or tubular masonry systems. These shapes also exhibited strong thermal damping with moderate energy savings, particularly with optimal configurations, as showen in Fig. 2.6.

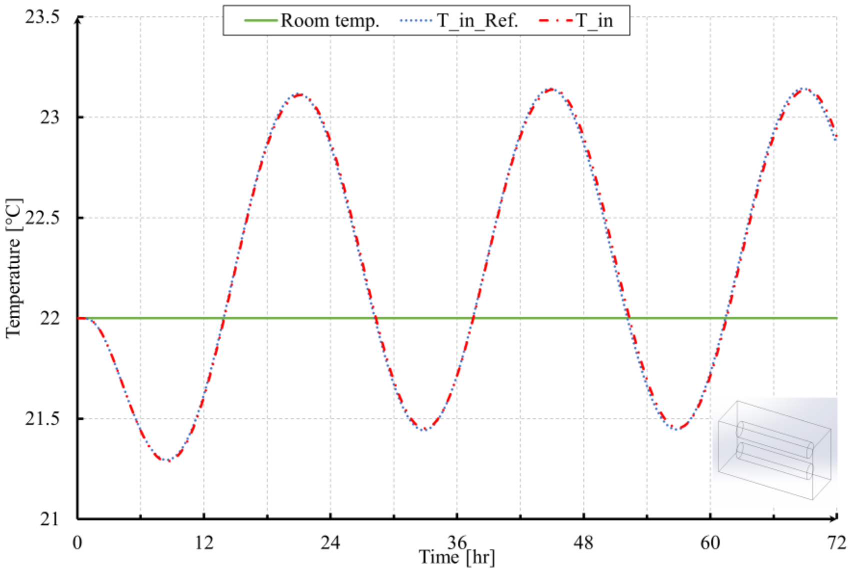

Fig. 2.6: *Indoor surface temperature distribution with two horizontal cylindrical capsules*

Prismatic capsules, despite being more complex and costly to manufacture, as showen in Fig. 2.7, excelled in applications requiring space efficiency and controlled heat release. Their enhanced packing density and consistent thermal behavior made them ideal for high-performance energy regulation needs.

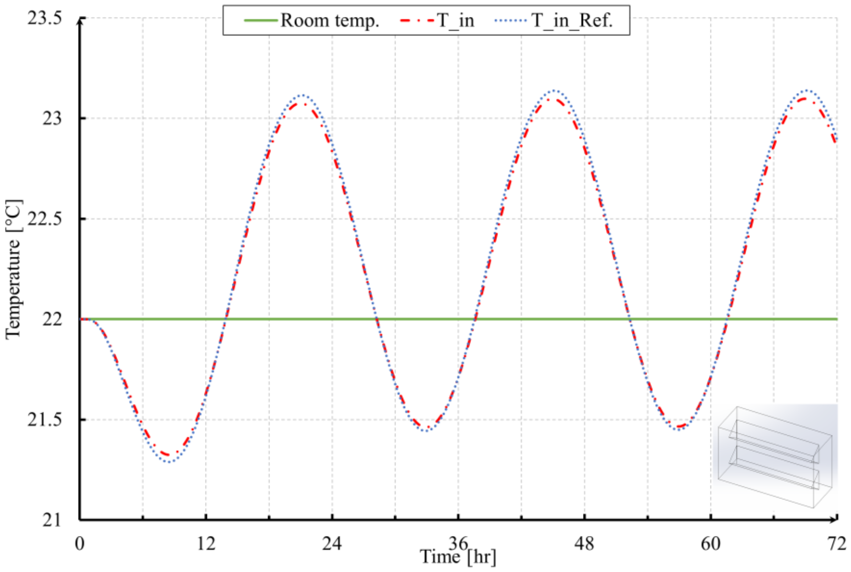

Fig. 2.7: *Indoor surface temperature distribution with two horizontal prismatic capsules*

Across all tests, numerical simulations confirmed that incorporating PCM in various optimized capsule shapes effectively reduced heat transmission into the indoor environment, thereby lowering energy loads. Among the designs studied, cuboid capsule (a) achieved the greatest heat transfer reduction, as shown in Fig. 2.8 highlighting the importance of geometric optimization in PCM applications.

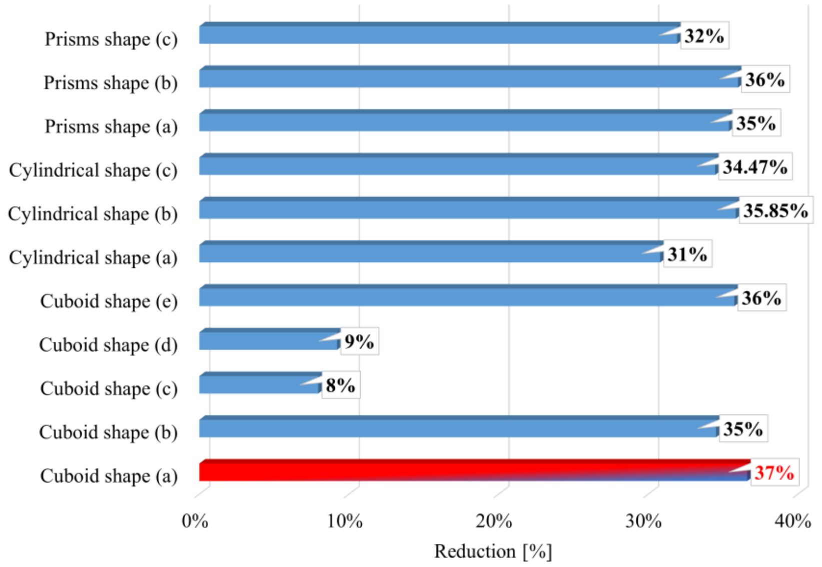

Fig. 2.8: *Total amount of heat transfer reduction to the room for different capsules*

Ultimately, the research concludes that capsule shape selection should be based on the specific thermal, spatial, and economic requirements of the application. Cuboid designs are optimal for cost-effective thermal regulation, cylindrical shapes serve well in directed systems, and prismatic forms are ideal where space utilization and thermal uniformity are critical.

2.4. Combining Aesthetics and Efficiency PCM Applications in Flemish Bond Walls

This research presented a detailed numerical investigation into the thermal and energy performance of Flemish bond masonry walls, with and without the integration of PCM. Traditionally appreciated for their architectural aesthetics and historical use in masonry, Flemish bond walls were analyzed in this study not only for their structural benefits, but also for their thermal behavior in the context of energy-efficient building design.

Simulations using representative climatic data from Miskolc, Hungary, demonstrated that the Flemish bond wall configuration on its own contributed to a 6 % reduction in heat transfer to the indoor environment compared to a standard reference wall, as showen in Fig. 2.9. This improvement is attributed to the increased mass and layered pattern of the Flemish bond, which inherently moderates temperature fluctuations by acting as a passive thermal buffer.

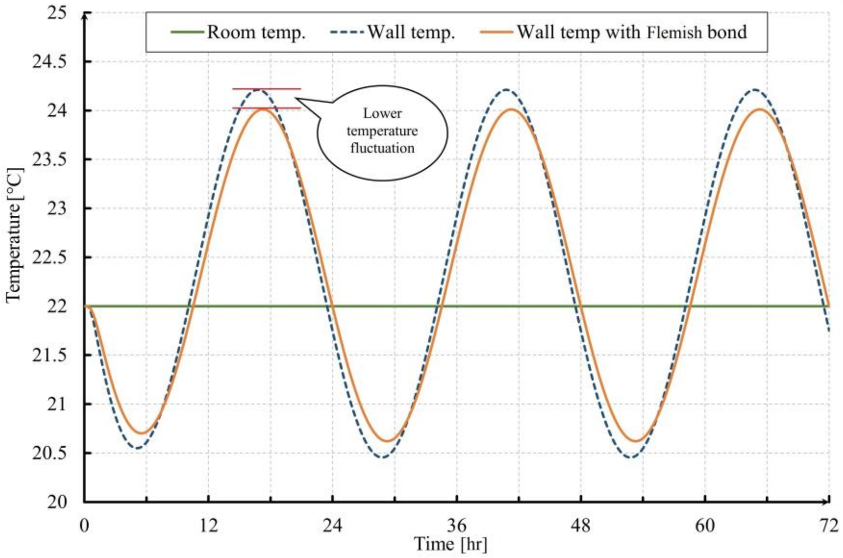

Fig. 2.9: Indoor surface temperature distribution with Flemish bond

The innovative focus of the chapter was the integration of RT-27 paraffin wax PCM into the Flemish bond configuration. When incorporated, the PCM capitalized on its latent heat storage capability, absorbing excess thermal energy during high external temperatures and releasing it during cooler periods. This dual function of storage and release significantly improved thermal stability, reducing temperature fluctuations across the wall's indoor surface. As shown in Fig. 2.10 and Fig. 2.11, the wall with both Flemish bond and PCM experienced markedly lower peak temperatures and smoother heat flux patterns over a 72 [hr] period.

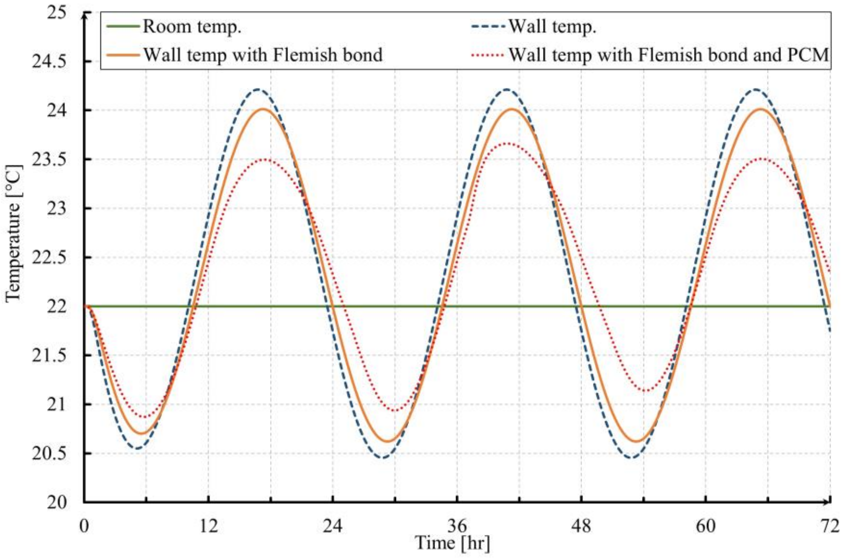

Fig. 2.10: Indoor surface temperature distribution with Flemish bond and phase change material

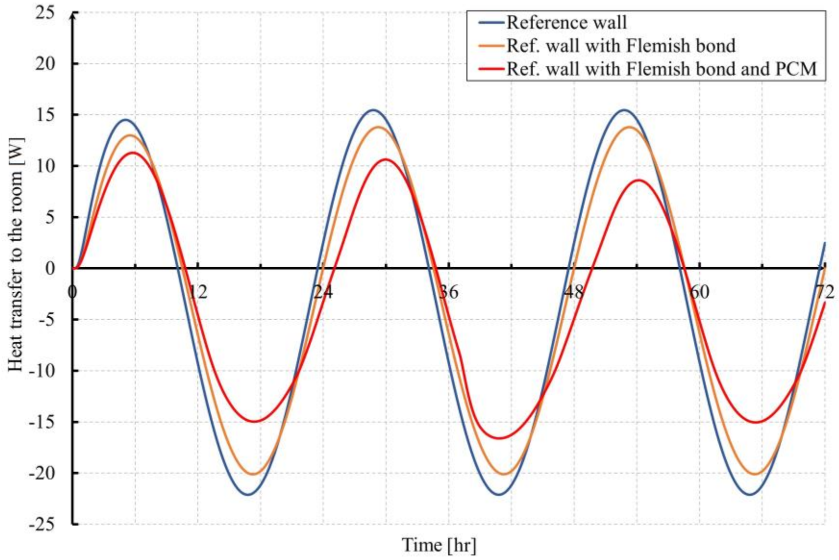

Fig. 2.11: *Heat transfers to the room when the phase change material is incorporated in the Flemish bond*

Most notably, as illustrated in Fig. 2.12, the total reduction in heat transfer reached 21 %, underscoring the synergistic impact of combining the thermal mass benefits of the Flemish bond with the dynamic energy buffering properties of PCM.

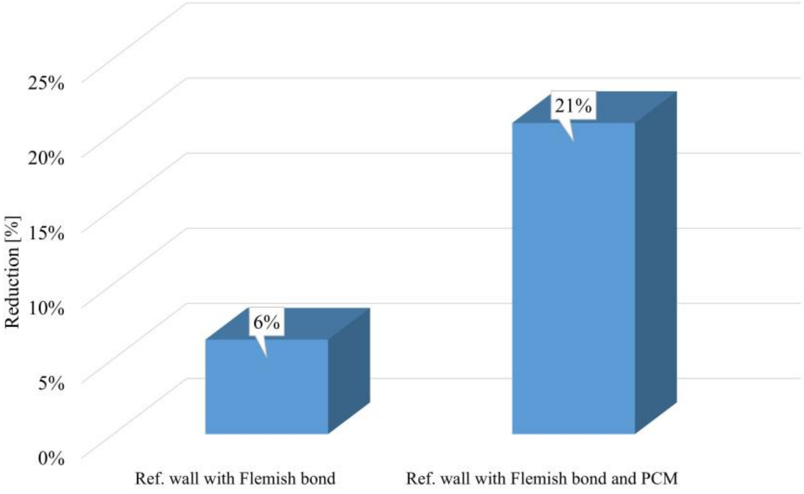

Fig. 2.12: *Total amount of heat transfer reduction to the room for different building envelope designs*

These findings not only validate the role of PCMs in enhancing building envelope performance, but also propose a novel use case: leveraging the geometric and aesthetic structure of traditional masonry patterns to augment energy efficiency. The integration of PCM into Flemish bond structures introduces a compelling path forward in sustainable architecture, preserving historical design while meeting modern energy performance demands.

3. NEW SCIENTIFIC RESULTS – THESES

T1. I developed and validated a reliable CFD-based approach to simulate the melting of RT-27 PCM under convective heating conditions. I implemented the model in ANSYS Fluent using the enthalpy–porosity method and established a reproducible workflow that addresses key numerical aspects, including mesh generation, boundary conditions, and solver settings. Using this framework, I analyzed the transition from conduction-dominated to convection-dominated heat transfer during melting and quantified the influence of buoyancy-driven flow and thermal stratification on the charging process. This work provides a practical simulation methodology for optimizing PCM integration in building energy systems. *Publications* (1-3).

T2. I systematically analyzed the effect of PCM layer positioning within building envelopes under realistic environmental conditions. Using CFD simulations, I showed that placing the PCM layer closer to the exterior surface can enhance wall thermal performance and reduce heat transfer to the indoor space by up to 23%. This result provides practical, climate-specific guidance for optimal PCM placement in wall assemblies and supports improved passive thermal regulation in building design. *Publications* (1,4).

T3. I investigated how PCM layer thickness influences the thermal performance of PCM-enhanced walls within the tested range 1–5 cm. I found that increasing thickness increases latent storage capacity and thermal inertia and reduces temperature fluctuations; within the investigated range, the maximum heat-transfer reduction (up to 42%) was achieved at 5 cm. This result provides practical guidance for thickness selection in the examined range and highlights that further increases may exhibit diminishing returns and must be balanced against construction constraints. *Publications* (1,4).

T4. I compared the performance of multiple PCM materials for building-envelope applications by evaluating how their thermophysical properties influence wall heat transfer. Under the tested conditions, I identified SP-25E2 as the best-performing PCM among the selected candidates, achieving up to a 26% reduction in heat transfer. Based on these results, I formulated practical material-selection guidance that links PCM characteristics (especially melting range and volumetric storage potential) to the climatic loading and wall requirements for effective PCM integration in energy-efficient construction. *Publications* (1,4).

T5. I systematically analyzed how PCM capsule geometry affects the thermal performance of building envelopes. Using CFD simulations, I compared cuboid, cylindrical, and prismatic capsule configurations under realistic climatic boundary conditions and quantified their impact on indoor-side heat transfer and temperature regulation. Under the fixed study constraints (same wall and boundary conditions, and a constant PCM quantity), I found that the capsule configuration, through its geometry and the resulting PCM distributioncontact area within the wall, significantly influences PCM charging/discharging behavior and overall heat transfer reduction. In the tested cases, cuboid capsules produced the largest reduction (up to 37%), followed by cylindrical capsules (≈36%) and prismatic capsules (up to 35.85%), depending on space utilization and constructability constraints. Based on these results, I proposed practical configuration recommendations and established a validated simulation workflow for evaluating encapsulated PCM systems in building envelopes. *Publications* (1,5).

T6. I investigated, for the first time in this dissertation, the combined effect of integrating PCM into a Flemish-bond masonry wall to improve thermal performance under realistic climatic boundary conditions. I found that the tested Flemish-bond wall configuration reduces indoor-side heat transfer by approximately 6% compared with the reference wall. I further showed that embedding RT-27 PCM within the Flemish-bond cavities provides an additional performance gain, leading to a total heat transfer reduction of about 21% relative to the conventional wall assembly. This work also establishes a CFD-based workflow for simulating the transient thermal behavior of complex masonry PCM configurations and provides design insight into combining masonry detailing with latent thermal storage for passive temperature control. *Publications* (6).

4. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

(1) A. Saliby and B. Kovács, "Minimization of annual energy consumption by incorporating phase change materials into building components: a comprehensive review," *Heat Transfer Research*, vol. 54, no. 13 pp. 65-91, 2023.

DOI: 10.1615/HeatTransRes.2023047570. **(Q_2, IF: 1.7)**

(2) A. Saliby and B. Kovács, " Melting process simulation of phase change material layer used in the building envelope," *Heat Transfer Research*, vol. 55, no. 4 pp. 15-26, 2024.

DOI: 10.1615/HeatTransRes.2023048367. **(Q_2, IF: 1.7)**

(3) A. Saliby and B. Kovács, " CFD modelling for phase change materials integrated to building envelope," *Pollack Periodica*, vol. 19, no. 1 pp. 67-72, 2024.

DOI: 10.1556/606.2023.00930. **(Q_3)**

(4) A. Saliby and B. Kovács, " Enhancing thermal performance of phase change materials in building envelopes," *Pollack Periodica*, vol. 20, no. 1 pp. 87-94, 2025.

DOI: 10.1556/606.2024.01153. **(Q_3)**

(5) A. Saliby and B. Kovács, " Optimizing PCM capsule shape for enhanced building envelope thermal management," *Heat Transfer Research*, vol. 56, no. 13 pp. 19-31, 2025.

DOI: 10.1615/HeatTransRes.2025056163. **(Q_2, IF: 1.7)**

(6) A. Saliby and B. Kovács, " Combining aesthetics and efficiency: PCM applications in Flemish bond walls," *Pollack Periodica,* 2025.

DOI: 10.1556/606.2025.01346. **(Q_3)**

5. LITERATURE CITED IN THE THESES BOOKLET

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