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Title
Thermal optimization of hollow clay brick integrated with phase change materials

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Abstract

Lightweight construction materials are increasingly adopted in high-rise and super-high-rise buildings due to their structural efficiency, ease of construction, and reduced structural mass. However, the extensive use of such materials is often associated with low thermal inertia, which adversely affects the thermal performance of building envelopes. The reduced capacity to store and release heat leads to pronounced indoor temperature fluctuations, increased peak cooling and heating demands, and a consequent deterioration of indoor thermal comfort, especially in regions with extreme climatic conditions. In hot-dry climates, where buildings are subjected to high solar radiation and large diurnal temperature variations, the limitations of lightweight walls become even more critical. Under these conditions, conventional lightweight building envelopes exhibit limited ability to attenuate heat transfer and delay thermal peaks, resulting in elevated reliance on mechanical air-conditioning and heating systems. This increased dependency not only raises energy consumption but also contributes to higher operational costs and environmental impacts. To overcome these challenges, the integration of phase change materials (PCMs) into building components has emerged as a promising passive thermal regulation strategy. When incorporated into building bricks, PCMs significantly enhance the thermal energy storage capacity of lightweight walls, thereby improving the thermal inertia of the wall system.

Within this context, the present research investigates the thermal optimization of lightweight hollow clay brick walls through the integration of PCMs under real climatic conditions representative of hot-dry regions. A novel brick configuration incorporating two different PCMs in a double-layer arrangement is proposed to enhance thermal energy storage and improve dynamic thermal performance. The study adopts a transient numerical methodology based on Computational Fluid Dynamics (CFD), incorporating phase-change heat transfer models developed and validated using ANSYS Fluent. The thermal behavior of the proposed double-PCM layer brick is systematically analyzed and compared with conventional air-filled bricks and single-PCM layer configurations. Key performance indicators, including indoor temperature evolution, heat flux, decrement factor, and time lag, are used to quantify thermal performance improvements. The results demonstrate that the double-PCM layer configuration significantly outperforms conventional and single-PCM solutions by reducing peak indoor temperatures, attenuating indoor heat flux, and enhancing time lag, thereby improving indoor thermal comfort and reducing cooling energy demand.

Furthermore, a comprehensive parametric investigation is conducted to assess the influence of PCM layer thickness and positioning on thermal performance. The findings indicate that positioning the PCM with a higher melting temperature on the exterior side and the PCM with a lower melting temperature on the interior side, with equal layer thicknesses, yields the optimal thermal response. This configuration maximizes heat storage efficiency and effectively shifts thermal loads away from peak outdoor temperature periods.

Overall, this thesis provides a detailed numerical framework and practical design guidelines for the integration of multi-layer PCM systems into lightweight building envelopes. The outcomes contribute to the development of energy-efficient and climate-responsive building materials, offering effective solutions for reducing cooling energy consumption and improving thermal comfort in buildings located in hot-dry climatic zones.

Keywords: *Lightweight walls; Energy saving; Building, Thermal performance; PCM; Computational fluid dynamic.*

Résumé

Les matériaux de construction légers sont de plus en plus utilisés dans les immeubles de grande hauteur et les gratte-ciels en raison de leur efficacité structurelle, de leur facilité de mise en œuvre et de leur masse réduite. Cependant, leur utilisation intensive est souvent associée à une faible inertie thermique, ce qui nuit aux performances thermiques de l'enveloppe du bâtiment. La capacité réduite à stocker et à restituer la chaleur entraîne d'importantes fluctuations de température intérieure, une augmentation des pics de consommation de chauffage et de climatisation, et par conséquent une dégradation du confort thermique intérieur, notamment dans les régions aux conditions climatiques extrêmes. Dans les climats chauds et secs, où les bâtiments sont soumis à un fort rayonnement solaire et à d'importantes variations de température diurnes, les limitations des murs légers sont encore plus critiques. Dans ces conditions, les enveloppes de bâtiments légers classiques présentent une capacité limitée à atténuer les transferts de chaleur et à retarder les pics thermiques, ce qui accroît le recours aux systèmes de chauffage et de climatisation mécaniques. Cette dépendance accrue augmente non seulement la consommation d'énergie, mais aussi les coûts d'exploitation et l'impact environnemental. Pour relever ces défis, l'intégration de matériaux à changement de phase (MCP) dans les composants du bâtiment apparaît comme une stratégie prometteuse de régulation thermique passive. L'incorporation de MCP dans les briques de construction améliore significativement la capacité de stockage d'énergie thermique des murs légers, augmentant ainsi l'inertie thermique du système.

Dans ce contexte, la présente recherche étudie l'optimisation thermique des murs légers en briques creuses d'argile par l'intégration de MCP dans des conditions climatiques réelles représentatives des régions chaudes et sèches. Une nouvelle configuration de brique, intégrant deux MCP différents en double couche, est proposée afin d'améliorer le stockage d'énergie thermique et les performances thermiques dynamiques. L'étude adopte une méthodologie numérique transitoire basée sur la dynamique des fluides numérique (CFD), intégrant des modèles de transfert de chaleur à changement de phase développés et validés à l'aide d'ANSYS Fluent. Le comportement thermique de la brique à double couche de MCP proposée est analysé systématiquement et comparé à celui de briques conventionnelles remplies d'air et de configurations à couche unique de MCP. Des indicateurs clés de performance, tels que l'évolution de la température intérieure, le flux de chaleur, le facteur de décrément et le temps de réponse, sont utilisés pour quantifier les améliorations des performances thermiques. Les résultats démontrent que la configuration à double couche de MCP surpasse significativement les solutions conventionnelles et à MCP unique en réduisant les pics de température intérieure, en atténuant le flux de chaleur intérieur et en améliorant le déphasage, ce qui contribue à améliorer le confort thermique intérieur et à réduire la demande en énergie de refroidissement. De plus, une étude paramétrique approfondie a été menée afin d'évaluer l'influence de l'épaisseur et du positionnement des couches de MCP sur les performances thermiques. Les résultats indiquent que le positionnement du MCP à point de fusion plus élevé côté extérieur et celui à point de fusion plus bas-côté intérieur, pour des épaisseurs de couche égales, offre la réponse thermique optimale. Cette configuration maximise l'efficacité du stockage de chaleur et décale efficacement les charges thermiques en dehors des périodes de températures extérieures maximales.

En résumé, cette thèse fournit un cadre numérique détaillé et des recommandations pratiques pour l'intégration de systèmes MCP multicouches dans les enveloppes de bâtiments légers. Les résultats contribuent au développement de matériaux de construction économes en énergie et adaptés au climat, offrant des solutions efficaces pour réduire la consommation d'énergie de refroidissement et améliorer le confort thermique dans les bâtiments situés dans les zones climatiques chaudes et sèches.

Mots-clés: *Murs légers; Économies d’énergie; Bâtiment; Performance thermique; MCP; Dynamique des fluides numérique.*

ملخص

تُستخدم مواد البناء خفيفة الوزن بشكل متزايد في المباني الشاهقة والمباني فائقة الارتفاع نظرًا لكفاءتها الهيكلية وسهولة بنائها وانخفاض كتلتها. مع ذلك، غالبًا ما يرتبط الاستخدام المكثف لهذه المواد بانخفاض القصور الحراري، مما يؤثر سلبًا على الأداء الحراري لأغلفة المباني. ويؤدي انخفاض القدرة على تخزين الحرارة وإطلاقها إلى تقلبات ملحوظة في درجات الحرارة الداخلية، وزيادة في ذروة الطلب على التبريد والتدفئة، وبالتالي تدهور الراحة الحرارية الداخلية، لا سيما في المناطق ذات الظروف المناخية القاسية. في المناخات الحارة الجافة، حيث تتعرض المباني لإشعاع شمسي عالٍ وتقلبات كبيرة في درجات الحرارة اليومية، تصبح قيود الجدران خفيفة الوزن أكثر أهمية. في ظل هذه الظروف، تُظهر أغلفة المباني التقليدية خفيفة الوزن قدرة محدودة على تخفيف انتقال الحرارة وتأخير ذروة الحرارة، مما يؤدي إلى زيادة الاعتماد على أنظمة التكييف والتدفئة الميكانيكية. لا يؤدي هذا الاعتماد المتزايد إلى زيادة استهلاك الطاقة فحسب، بل يساهم أيضًا في ارتفاع تكاليف التشغيل والتأثيرات البيئية. للتغلب على هذه التحديات، برز دمج مواد تغيير الطور في مكونات المباني كاستراتيجية واعدة للتنظيم الحراري السلبي. عند دمج مواد تغيير الطور في طوب البناء، فإنها تُحسّن بشكل ملحوظ قدرة الجدران خفيفة الوزن على تخزين الطاقة الحرارية، مما يُحسّن بالتالي القصور الحراري لنظام الجدار.

في هذا السياق، يبحث هذا البحث في التحسين الحراري لجدران الطوب الطيني المجوف خفيف الوزن من خلال دمج مواد تغيير الطور في ظروف مناخية حقيقية تُمثل المناطق الحارة الجافة. ويُقترح تصميم جديد للطوب يتضمن نوعين مختلفين من مواد تغيير الطور في ترتيب مزدوج الطبقات لتعزيز تخزين الطاقة الحرارية وتحسين الأداء الحراري الديناميكي. تعتمد الدراسة منهجية عددية عابرة قائمة على ديناميكيات الموائع الحسابية، وتتضمن نماذج نقل الحرارة لتغيير الطور التي طُوّرت ووُثّقت باستخدام برنامج ANSYS Fluent. يُحلّل السلوك الحراري للطوب المقترح ذي الطبقتين من مواد تغيير الطور بشكل منهجي ويُقارن مع الطوب التقليدي المملوء بالهواء وتكوينات الطبقة الواحدة من مواد تغيير الطور. وتُستخدم مؤشرات الأداء الرئيسية، بما في ذلك تطور درجة الحرارة الداخلية، وتدفق الحرارة، ومعامل التناقص، والتأخر الزمني، لتحديد تحسينات الأداء الحراري كميًا. تُظهر النتائج أن تصميم طبقة مادة تغيير الطور المزدوجة يتفوق بشكل ملحوظ على الحلول التقليدية والحلول أحادية الطبقة، وذلك من خلال خفض درجات الحرارة القصوى داخل المباني، وتخفيف تدفق الحرارة، وتحسين زمن الاستجابة، مما يُحسّن الراحة الحرارية الداخلية ويُقلل من استهلاك طاقة التبريد. علاوة على ذلك، أُجريت دراسة شاملة للبارامترات لتقييم تأثير سُمك طبقة مادة تغيير الطور وموقعها على الأداء الحراري. تُشير النتائج إلى أن وضع مادة تغيير الطور ذات درجة انصهار أعلى على الجانب الخارجي، ومادة تغيير الطور ذات درجة انصهار أقل على الجانب الداخلي، مع تساوي سُمك الطبقتين، يُحقق الاستجابة الحرارية المثلى. يُعظّم هذا التصميم كفاءة تخزين الحرارة، ويُحوّل الأحمال الحرارية بفعالية بعيدًا عن فترات ذروة درجات الحرارة الخارجية.

بشكل عام، تُقدّم هذه الأطروحة إطارًا عدديًا مُفصّلًا وإرشادات تصميم عملية لدمج أنظمة مواد تغيير الطور متعددة الطبقات في أغلفة المباني خفيفة الوزن. تُساهم النتائج في تطوير مواد بناء موفرة للطاقة ومُستجيبة للمناخ، مما يُوفر حلولًا فعّالة لخفض استهلاك طاقة التبريد وتحسين الراحة الحرارية في المباني الواقعة في المناطق المناخية الحارة والجافة.

الكلمات المفتاحية: جدران خفيفة الوزن؛ توفير الطاقة؛ المباني، الأداء الحراري؛ مواد تغيير الطور؛ ديناميكا الموائع الحسابية.

Publications originated from this study

Journal papers

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Dedication

To my family,

for their endless patience, love, and strength

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Nomenclature

C_p	Specific heat (J· $kg^{-1}K^{-1}$)
f	Liquid fraction
g	Gravitational acceleration (m/s^{-1})
h	Convective heat transfer coefficient (W·m^{-2}·K^{-1})
H	Enthalpy value (J·kg^{-1})
I	Solar radiation intensity (W·m^{-2})
Q	Total thermal energy storage (J)
L	Latent heat (J·kg^{-1})
m	mass of the storage medium (kg)
P	Pressure (Pa)
T	Temperature (°C)
u_i	Velocity component (m·s^{-1})
α	Solar radiation absorptivity of outer surface
β	Coefficient of volumetric thermal expansion (K^{-1})
ρ	Material density (kg·m^{-3})
μ	Dynamic viscosity (Pa· s)
λ	Thermal conductivity (W·m^{-1}·K^{-1})

Subscripts

amb	Ambient
E	Final
I	Initial
L	Liquid state
m	Melting
O	Outdoor
ref	Reference
S	Solid state

Abbreviations

CFD	Computational Fluid Dynamics
DG	Double Glazing
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
EPM	Enthalpy-Porosity Method
EHCM	Effective Heat Capacity Method
GHGs	Greenhouse gases
HDPE	High Density Polyethylene
HPCM	Higher melting temperature Phase Change Material
HVAC	Heating, Ventilation, and Air-Conditioning
IEA	International Energy Agency
LHS	Latent Heat Storage
LPCM	Lower melting temperature Phase Change Material
PCM	Phase Change Material
SHS	Sensible Heat Storage
SIMPLEC	Semi-Implicit Method for Pressure Linked Equations Consistent
SSPCMs	Shape Stabilized Phase Change Materials
TES	Thermal Energy Storage

Chapter I:

Global and national perspectives on building energy use and efficiency

Chapter I: Global and national perspectives on building energy use and efficiency

I.1. Background: Global energy consumption and environmental concerns

Energy is a core pillar of modern civilization, underpinning industrial activities, transportation, and the day-today functioning of residential and commercial buildings. Over recent decades, global energy demand has experienced a sustained and structural expansion, reflecting profound transformations in economic systems, technological intensity, and patterns of energy use. Despite continuous efforts to diversify energy sources, the global energy mix remains dominated by fossil fuels, which accounted for nearly 80% of primary energy consumption in 2024, as reported by the International Energy Agency (IEA) [1] and illustrated in Figure I.1. This persistent reliance on non-renewable resources is closely associated with environmental degradation, particularly through the emission of greenhouse gases (GHGs), with carbon dioxide (CO_2), widely recognized as the leading driver of global climate change. The long-term accumulation of these emissions in the atmosphere has intensified global warming, contributing to climate instability manifested through extreme weather events and significant disruptions to natural ecosystems. Beyond climate change, conventional energy production and consumption are also associated with air pollution, resource depletion, and adverse impacts on human health, especially in densely populated urban areas. International scientific assessments and climate agreements have consistently emphasized the urgency of reducing energy-related emissions in order to limit global temperature rise and mitigate long-term climate risks. These initiatives highlight the necessity of re-evaluating current energy-use paradigms and advancing strategies that reduce environmental impacts while meeting growing energy demands. In this context, improving energy efficiency across all sectors has emerged as a critical priority, complementing the deployment of renewable energy sources and low-carbon technologies.

Within this broader energy and environmental context, increased attention has been directed toward sectors with sustained and structurally high energy demand, among which buildings play a central role. Globally, the operation of residential and commercial buildings accounts for nearly 44.4% of final energy consumption and a comparable proportion of energy-related carbon dioxide emissions [2], positioning the building sector as a decisive factor in long-term emission trajectories. Energy use in buildings is primarily associated with maintaining acceptable indoor environmental conditions, including thermal comfort, air quality, and lighting. Heating and cooling demands constitute the dominant share of this consumption, with their relative importance strongly influenced by climatic conditions. In colder regions, space heating represents the principal end-use, whereas in warmer climates, the widespread adoption of air-conditioning systems has led to rapidly increasing electricity demand and more pronounced peak loads. These peaks exert considerable pressure on energy supply systems and often require the operation of less efficient and more emissions-intensive power generation units, thereby amplifying both environmental and economic impacts. Furthermore, the long service life of buildings implies that inefficiencies embedded in existing and future building stock will persist for decades, magnifying their cumulative impact on energy consumption and emissions. Recognizing these challenges, enhancing building energy performance has become a central focus of international research and policy efforts aimed at achieving long-term reductions in energy demand and environmental impact.

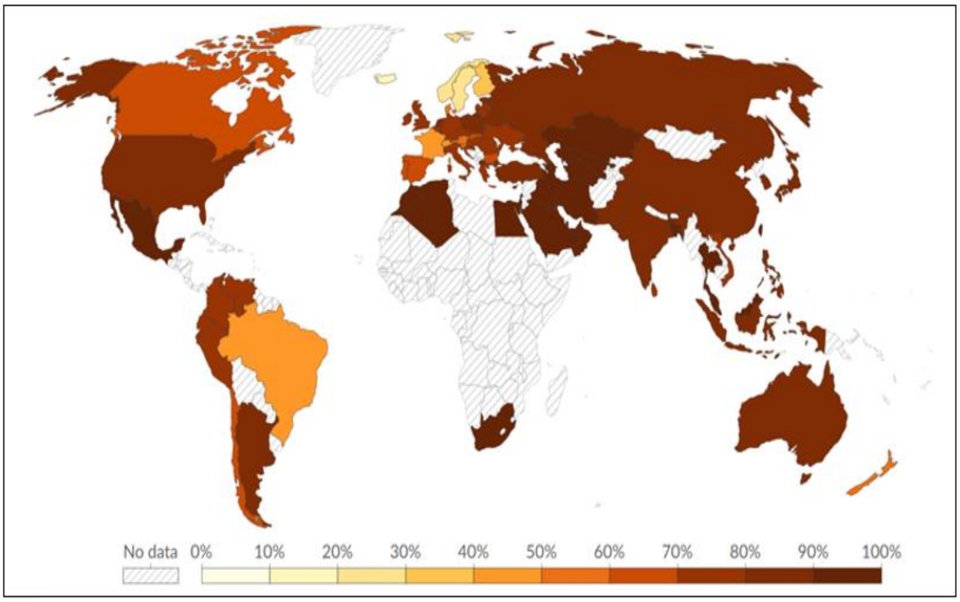


Figure I.1: Fossil fuels share of primary energy consumption (2024): Percentage of each country’s total primary energy supplied by fossil fuels [3].

Overall, the growing imbalance between energy demand and environmental sustainability has placed the built environment at the center of global mitigation efforts. As one of the most energy-intensive sectors worldwide, buildings represent a critical leverage point for reducing emissions and improving overall energy efficiency through advanced materials, technologies, and design strategies. This global perspective provides the conceptual foundation for examining national and regional contexts, such as Algeria, where climatic constraints and prevailing construction practices further amplify energy demand and pose distinct challenges for sustainable development, as discussed in the following section.

I.2. Energy consumption in the Algerian building sector

Algeria occupies a distinctive position within the global energy landscape as a major exporter of oil and natural gas, with fossil fuels forming the backbone of both its national economy and domestic energy system. Despite this substantial resource endowment, internal energy consumption has increased steadily over recent decades, with the building sector emerging as the largest contributor to final energy use. Current estimates indicate that residential and tertiary buildings account for more than 36% of national energy consumption, surpassing both the transportation and industrial sectors [4,5]. This structural dominance reflects long-term trends rather than short-term variability and is closely linked to the continuous expansion of the housing stock, accelerated urban development, and the increasing electrification of residential and service-related activities. Consequently, energy demand associated with buildings has evolved into a central determinant of national electricity consumption patterns, placing the sector at the core of Algeria's energy efficiency and sustainability challenges. Moreover, the predominant dependence of the national energy system on fossil fuels, accounting for approximately 97% of total energy consumption [5], translates this growing demand into substantial carbon dioxide emissions, reinforcing the environmental dimensions of the challenge.

The operational energy use of Algerian buildings is primarily associated with maintaining acceptable indoor environmental conditions, including thermal comfort, lighting, and the operation of household and service-related appliances. Among these end uses, space conditioning constitutes the dominant share, with cooling demand becoming increasingly significant over recent decades. The widespread adoption of air-conditioning systems, particularly in urban areas and southern regions, has led to pronounced seasonal variations in electricity consumption, with sharp increases during summer periods. These peaks are exacerbated by limited thermal performance of a substantial portion of the existing building stock, which is typically characterized by low insulation, insufficient thermal inertia, and envelope designs that are poorly adapted to local climatic conditions.

Climatic conditions exert a decisive influence on energy demand in Algerian buildings. The country encompasses a wide range of climatic zones, extending from Mediterranean conditions in the north to hot-arid and desert climates in the south. In such environments, maintaining acceptable indoor thermal comfort often requires substantial energy input, particularly in buildings constructed with conventional materials and limited thermal insulation. The predominance of standardized construction practices, insufficient integration of climate-responsive design principals, and the lack of effective thermal regulation of building envelopes contribute to elevated cooling and heating loads and increased buildings energy intensity.

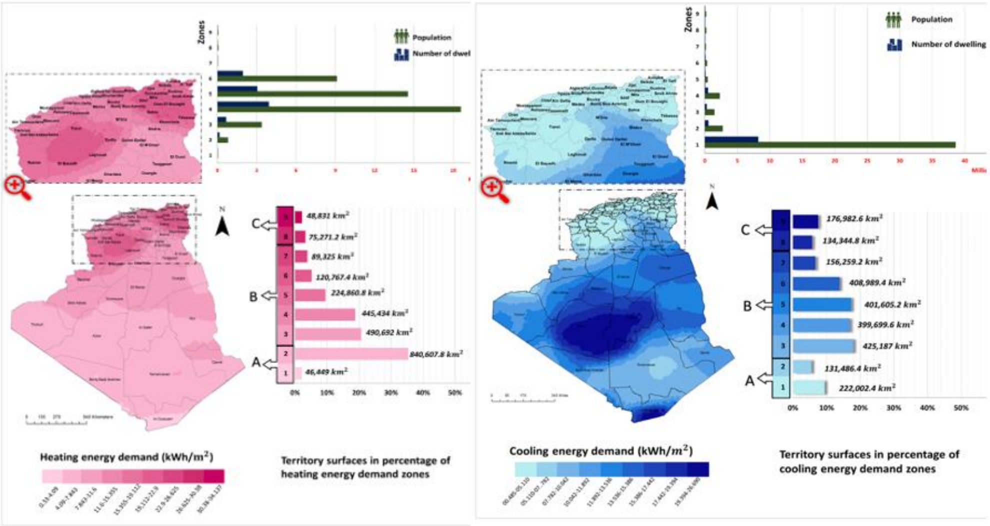


Figure I.2: Heating and cooling energy demand in Algeria: Spatial distribution of heating (left) and cooling (right) energy demand (kWh/m^2) across Algerian climatic zones [6].

In recognition of these challenges, Algerian authorities have progressively incorporated energy efficiency objectives into national energy policy frameworks. The building sector has been identified as a priority within the National Energy Efficiency Program, which establishes explicit targets for reducing residential energy consumption and improving building thermal performance. As part of this program, regulatory measures such as the introduction of thermal building regulations, the promotion of thermal insulation standards, and the implementation of minimum energy performance standards for household appliances under the supervision of the Ministry of Energy and Mines have been adopted [7]. In parallel, Algeria has launched national initiatives supporting renewable energy and energy efficiency, including the "*Taka Nadhifa*" (clean Energy) program, developed within the framework of cooperation with the European Union [2], and has announced long-term targets for diversifying the national energy mix, notably through increasing the share of renewable energy by 2030 [5]. Collectively, these policy initiatives reflect a growing institutional commitment to controlling energy demand in the building sector as a key pathway toward improving energy security, reducing environmental impacts, and supporting sustainable development.

I.3. Energy-efficient building envelopes and passive cooling techniques

Energy-efficient building envelops represent a cornerstone of sustainable architecture, fundamentally influencing a building's energy performance and indoor environmental quality. Walls, roofs and external facades are not merely separating elements but active components that control heat transfer, solar gains, and thermal storage. Thus, the energy performance of buildings is largely conditioned by the envelope's ability to moderate external thermal stresses before they translate into indoor cooling demand. An energy-efficient building envelope is characterized by its capacity to limit excessive heat ingress while maintaining indoor thermal comfort with minimal reliance on mechanical systems. This performance is achieved through a combination of envelope-related parameters, including material composition, layer configuration, thermal resistance, solar absorptivity, and heat storage capability.

Within this framework, passive cooling techniques emerge as envelope-centered strategies aimed at controlling indoor temperatures by harnessing natural heat transfer mechanisms. Rather than compensating for thermal discomfort through active cooling, passive approaches seek to prevent or delay heat penetration, store thermal energy in a controlled manner, or dissipate accumulated heat using natural processes. The effectiveness of such techniques is therefore inherently dependent on envelope design and thermophysical properties. Numerous studies have demonstrated that incorporating passive cooling techniques can significantly reduce cooling loads, particularly in buildings exposed to intense solar radiation and high ambient temperatures; for example, implementing passive energy-efficient measures, including wall insulation with extruded polystyrene, reflective window coatings, whitewashed exterior walls, and reflective coated glass window glazings, led to energy savings of 31.4% and peak load reductions of 36.8% compared to a baseline scenario [8].

In the literature, passive cooling approaches associated with building envelopes are commonly classified into three main categories. The first category includes **heat protection strategies**, which focus on reducing external heat gains through solar shading, reflective or low-absorptivity surfaces, improved insulation layers, and envelope geometries adapted to solar exposure [9]. The second category encompasses **heat modulation strategies**, which rely on the envelope's ability to absorb, store, and release thermal energy over time. Techniques such as the use of thermal mass, multi-layer wall systems, and materials with enhanced latent or sensible heat storage have been shown to attenuate temperature fluctuations and shift cooling loads to off-peak periods. These strategies are particularly relevant in climates characterized by high diurnal temperature variations [10]. The third category involves **heat dissipation strategies**, which aim to remove stored heat from the building through natural ventilation, night cooling, or radiative exchange with the environment. Envelope configurations that facilitate airflow or enhance surface heat exchange play a critical role in the effectiveness of these techniques. When climatic conditions are favorable, heat dissipation strategies can substantially improve indoor comfort without additional energy input [11]. By applying these approaches, through optimized building orientation, enhanced insulation, low-emissivity glazing, reflective coatings, and phase change materials (PCMs) integration, buildings can achieve significant reductions in energy demand while improving occupant comfort and reducing environmental impacts.

Accordingly, the literature emphasizes that passive cooling performance cannot be dissociated from the envelope design. The integration of heat protection, heat modulation, and heat dissipation strategies within an energy-efficient building envelope represents a coherent and effective approach to reducing cooling energy demand. This integrated perspective provides a solid conceptual basis for advanced envelope solutions, including the incorporation of phase change materials, which constitute a heat-modulation-based passive cooling strategy aimed at further enhancing the thermal response of building components.

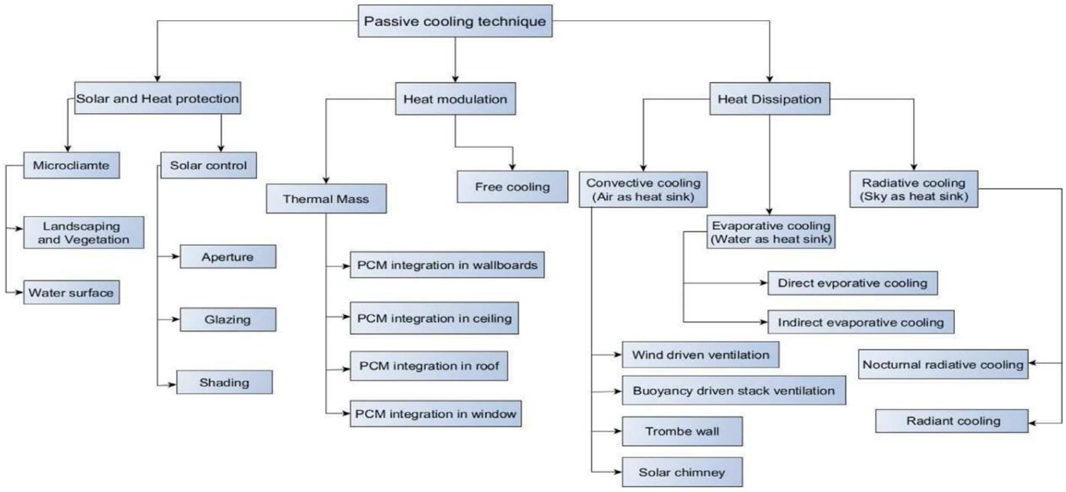


Figure I.3: Passive cooling techniques classification [10].

I.4. Problem statement and scope

Following the discussion on global and national building energy consumption, it becomes evident that improving the thermal performance of building envelopes is a key strategy for reducing cooling demand and enhancing indoor thermal comfort in hot-dry climates. The increasing reliance on lightweight masonry systems in these regions has intensified the challenge of controlling heat transfer through building envelopes while preserving constructability and cost efficiency. Hollow clay bricks, widely adopted due to their affordability and local availability, inherently exhibit low thermal inertia, which can result in pronounced indoor temperature fluctuations and increased cooling demand under extreme climatic conditions. Enhancing the thermal behavior of these masonry units, without fundamentally altering conventional construction practices, therefore remains a critical scientific and practical challenge.

Despite the growing interest in phase change materials as an effective passive strategy for reducing cooling energy demand in buildings, their practical integration into building envelopes remains constrained by several unresolved scientific and design challenges. A substantial body of research has demonstrated the potential of PCMs to enhance thermal inertia, attenuate indoor temperature fluctuations, and delay heat transfer when incorporated into various building elements, including walls, roofs, floors, and glazing systems. However, the translation of these benefits into optimized, components-level solutions, particularly at the scale of individual masonry units, has received comparatively limited attention.

Most existing studies on PCM-enhanced building envelopes have focused on the integration of a single-layer PCM within large-scale structural elements, such as full wall assemblies or roof systems, often under specific material configurations and climatic contexts. More recently, multi-layer and double-layer PCM configurations have been introduced as a promising approach to improve thermal storage efficiency by combining materials with different phase change temperature ranges. These configurations have been explored in walls, roofs, and floors, showing improved thermal regulation compared to single-layer systems. Nevertheless, this research trend has largely remained at the envelope or assembly scale, while the brick scale—despite being a fundamental and repeatable building unit—has not been systematically investigated, particularly with respect to double-layer PCM arrangements. Furthermore, the thermal performance of PCM-integrated building components is governed by a complex interaction of multiple parameters, including PCM thermophysical properties, melting temperature ranges, latent heat capacity, thermal conductivity, placement within the element, and PCM quantity. Although several studies have examined the influence of individual parameters, many investigations have addressed these factors in isolation, making it difficult to draw generalized conclusions regarding optimal PCM integration strategies. Importantly, a number of studies have already been conducted under real climatic conditions; however, a comprehensive, parametric understanding at the brick scale under realistic thermal excitations remains lacking. This gap is particularly critical for hot-dry climates, where buildings are exposed to intense solar radiation, high daytime temperatures, and significant diurnal thermal variations. In such conditions, conventional lightweight masonry units exhibit limited thermal storage capacity, leading to elevated indoor temperatures and increased cooling demand. While PCMs offer a viable solution to mitigate these effects, the absence of systematic studies addressing double-layer PCM configurations within hollow clay bricks, including the role of PCM type, layer position, and thickness under realistic boundary conditions, hinders their effective deployment in practice.

Accordingly, the scope of this PhD thesis is to address these limitations by conducting a detailed numerical investigation of hollow clay bricks integrated with PCMs, with particular emphasis on double-layer PCM configurations. The study focuses on brick-level thermal behavior, enabling precise control and analysis of heat transfer mechanisms. Using computational fluid dynamics (CFD) simulations subjected to realistic hot-dry climatic conditions, this research aims to assess the influence of PCM thermophysical properties and layer configuration on key thermal performance indicators. By narrowing the analysis to the brick scale while maintaining realistic thermal excitations, the present work seeks to provide a robust scientific basis for optimizing PCM integration strategies in masonry units intended for energy-efficient buildings in hot-dry regions.

I.5. Aims and objectives

I.5.1. Aim of the thesis

The primary aim of this thesis is to investigate and optimize the thermal performance of hollow clay bricks integrated with phase change materials as a passive cooling strategy for buildings located in hot-dry climates. This research proposes an innovative design for PCM-integrated hollow clay bricks, exploring single and double-PCM layer configurations to enhance thermal inertia at the component level. The study seeks to develop a comprehensive understanding of how PCM type, thermophysical properties and layer configurations influence heat transfer through masonry units under realistic climatic conditions. By focusing on the scale of building brick, the thesis addresses a critical gap between material-level PCM studies and full-wall or whole-building analyses, contributing to practical, climate-adapted masonry solutions capable of reducing cooling demand and improving indoor thermal comfort without altering conventional construction practices.

I.5.2. Specific objectives

To achieve this aim, the following specific objectives are pursued:

- To generate novel insights and innovative design strategies for the integration of phase change materials into hollow clay bricks, forming the basis for a fundamental understanding of PCM thermal behavior at the brick scale under hot-dry climate conditions.
- To develop and validate a numerical modeling framework, based on computational fluid dynamics, for simulating transient heat transfer in hollow clay bricks integrated with PCMs under realistic climatic boundary conditions.
- To investigate the influence of key factors, including PCM thermophysical properties and layer configuration, on the thermal performance of PCM-integrated masonry units.
- To comprehensively assess the thermal performance of PCM-integrated bricks using multiple performance indices, such as indoor surface temperature, heat flux, decrement factor, and time lag.
- To provide design guidelines for the effective implementation of PCM-enhanced hollow clay bricks in hot-dry climates, supporting energy-efficient building practices and improving indoor thermal comfort.

I.6. Thesis layout

This PhD thesis is structured into five main chapters, each addressing a specific aspect of the research and collectively providing a comprehensive investigation of phase change material integration into hollow clay bricks for improved thermal performance in hot-dry climates.

Chapter I: Global and national perspectives on building energy use and efficiency: This chapter introduces the research context, highlighting the challenges of energy consumption in buildings and the potential of PCMs as passive thermal management solutions. It presents the research significance, problem statement, and clearly defines the aims and objectives of the study. The scope and methodology overview are also outlined to set the foundation for the subsequent chapters.

Chapter II: Phase change materials in building applications: This chapter presents the principles of latent heat storage using PCMs, their classification, thermal properties, characterization techniques, encapsulation methods, and their applications in buildings for thermal comfort, energy saving, and peak load reduction.

Chapter III: Methodology and numerical modeling: This chapter details the numerical modeling framework developed in this study, based on computational fluid dynamics, to simulate transient heat transfer in PCM-integrated hollow clay bricks under realistic hot-dry climatic conditions. The chapter also discusses assumptions, simplifications, boundary conditions, and validation procedures, establishing the computational foundation for performance analysis.

Chapter IV: Results and discussion: Chapter IV presents the outcomes of the numerical simulations, investigating the influence of key factors including PCM type, double-PCM layer, and layer configuration—including the position and the thickness—on the thermal behavior of masonry units. The performance of PCM-integrated bricks is evaluated using multiple thermal indices, including indoor surface temperature, heat flux, decrement factor, and time lag. Comparative analyses with references cases without PCM are also presented.

Chapter V: Conclusions and recommendations for future work: The final chapter summarizes the key findings, emphasizing the scientific and practical contributions of this research. Innovative brick-scale designs integrating PCMs are discussed, and practical design guidelines are provided for implementation in hot-dry climates. The chapter concludes with recommendations for future research directions for further optimize PCM applications in building envelopes.

Chapter II:

Phase change materials in building applications

Chapter II: Phase change materials in building applications

II.1. Introduction

Integrating phase change materials into building envelopes represents a promising pathway toward energy-efficient and climate-responsive design. As a latent heat thermal energy storage technology, PCMs have gained significant research attention for their ability to enhance building energy performance. By absorbing and releasing heat through reversible phase transitions, they can moderate indoor temperature fluctuations, reduce peak thermal loads, and improve occupant comfort while lowering dependence on conventional HVAC systems. The effectiveness of PCM, however, is strongly influenced by intrinsic material properties and integration strategies, highlighting the need for a systematic evaluation to ensure their reliable and optimized application.

Accordingly, this chapter presents a comprehensive and structured review of PCMs in building applications. It discusses the fundamental principles of latent heat storage, and the key thermophysical properties governing their performance. It further discusses material classification, thermal characterization techniques, and suitable encapsulation and integration methods for building materials. Applications of PCMs in buildings, including thermal comfort enhancement, energy savings, ad peak load shifting, are reviewed, followed by an analysis of previous studies on PCM integration in building envelopes. This synthesis establishes the theoretical foundation of the research developed in the subsequent chapters of this thesis.

II.2. Latent heat storage with phase change materials

The building envelope has evolved from a passive shield against external conditions into a dynamic component of climate regulation, with its thermal mass governing heat storage and transfer. However, fluctuating outdoor conditions often cause overheating or heat losses, increasing reliance on energy-intensive HVAC systems. To mitigate this dependency, a sustainable alternative lies in thermal energy storage (TES), which enables buildings to moderate temperature variations by temporarily storing thermal energy within a suitable medium for later utilization [12,13]. Numerous studies have explored the application of TES in the building sector, consistently highlighting their potential to reduce energy consumption [14], enhance energy efficiency [15], support peak load management [16], and extend periods of indoor thermal comfort [17]. The operation of TES is generally described through three main stages: during charging, surplus thermal energy is absorbed by the storage medium; in the storage phase, the absorbed energy is maintained until a demand arises; and during discharging, the stored heat or cold is progressively released into the indoor environment, thereby assisting or even substituting conventional heating and cooling systems [18,19]. Thermal energy in buildings can be stored either by changing the temperature of a material, known as sensible heat storage (SHS), or by exploiting phase transition processes, referred to as latent heat storage (LHS). Conventional construction materials such as clay bricks and concrete store heat through SHS, where energy is accumulated as the material undergoes a temperature rise. Although this method is simple and cost-effective, its relatively low energy density necessitates large volumes of material to achieve significant storage capacity [13]. In contrast, LHS is based on phase transitions—most commonly the solid–liquid transition—where thermal energy is absorbed or released almost isothermally. This enables a much higher storage density within a narrow temperature range, making LHS particularly effective in moderating indoor temperature fluctuations and reducing building energy demand [20,21,22]. The two principal modes of thermal energy storage—sensible and latent—are illustrated in Fig. II.1. Unlike SHS, where effective energy storage demands substantial temperature swings, LHS exploits the isothermal characteristics of phase transitions to store significant amounts of thermal energy within a limited temperature interval, thereby providing enhanced energy density and improved thermal regulation potential. The total energy stored during a complete phase transition process can be expressed as [23]:

$$Q = m\,[C_{sp}\,(T_m - T_i) + \Delta H + C_{lp}\,(T_e - T_m)] \tag{II.1}$$

Where, Q is the total thermal energy storage, m is the mass of the storage medium (kg), C_{sp} and C_{lp} are the specific heats in the solid and liquid states (J/kg. K), respectively, T_i and T_e are the initial and final temperatures (K), T_m is the melting temperature (K), and ΔH is the latent heat of fusion associated with the phase change (J/Kg).

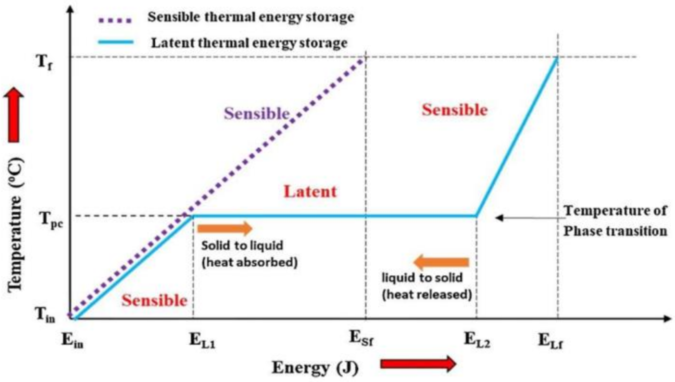


Figure II.1: Sensible and latent thermal energy storage during phase transition [24].

For practical implementation in buildings, latent heat storage is most effectively achieved through phase change materials, which can absorb and release substantial amounts of energy during phase transitions at nearly constant temperatures. Depending on the type of transition involved, PCMs can undergo solid–solid, solid–liquid, liquid–gas, or solid–gas transformations. However, transitions involving a gaseous phase are generally impractical for building applications due to the large volumetric changes they entail, while solid–solid transitions are limited by low energy storage densities and slow kinetics [23,25,26]. For this reason, solid–liquid PCMs are predominantly employed in the building sector, as they combine high latent heat of fusion with relatively small volume change, good reversibility, and practical adaptability [25,27]. A comparative summary of these transition mechanisms, together with their main advantages and limitations, is provided in Table II.1. During operation, these PCMs absorb heat isothermally when ambient temperatures exceed their melting point, storing energy through an endothermic process. As the temperature drops below the solidification temperature, the materials solidify and release the stored energy exothermally. This reversible cycle enables PCMs to act as efficient thermal regulators, stabilizing indoor temperatures, delaying peak loads, and reducing the reliance on mechanical heating and cooling systems [28,29]. Their effectiveness, however, depends on selecting PCMs with phase change temperatures matched to indoor comfort ranges, along with favorable thermophysical properties [30].

Table II. 1. Classification of PCMs according to phase transition type and their suitability for building applications [19].

Transition Type	Description	Advantages	Limitations	Suitability in buildings
Solid-Solid	Heat stored/released during crystal structure rearrangement in solid state.	Negligible volume change; high cycling stability.	Very low enthalpy change; slow transition rates.	Limited
Solid-Liquid	Heat stored/released during melting/solidification at nearly constant temperature.	High latent heat storage; moderate volume change; suitable melting ranges.	Risk of leakage; need for encapsulation or support matrix.	Widely used (most suitable)
Solid-Gaz	Heat stored/released through sublimation processes.	Very high energy storage density.	Extremely large volume change; complex containment; impractical for buildings.	Not suitable
Liquid-Gaz	Heat stored/released during vaporization/condensation.	Very high latent heat; rapid heat transfer.	Excessive volume change; high pressure required; safety concerns.	Not suitable

II.3. Performance-defining properties of phase change materials for building applications

The performance of phase change materials in buildings is primarily governed by their thermophysical and kinetic properties, which together define storage capacity and operational efficiency. The phase change temperature is considered the most critical criterion, as it dictates whether the material can effectively interact with the building's thermal environment. Zhou et al. [31] have emphasized that, for passive applications, the melting range must align with indoor thermal comfort levels, typically between 18 °C and 30 °C, to provide significant reductions in heating and cooling demand. Equally important is the latent heat of fusion, as higher values enable greater energy storage density and enhanced ability to moderate indoor temperature fluctuations. For instance, PCMs with latent heat values in the range of 150–250 kJ/kg have been reported as effective for energy management in building applications [32,33].

Despite their high storage potential, PCMs generally exhibit low thermal conductivity (0.2–0.8 W/m. K) which constrains heat transfer rates and delays phase transitions, resulting in incomplete utilization of storage potential under dynamic building conditions [34,35]. To mitigate this drawback, conductivity enhancements approaches—such as adding highly thermal conductive nanoparticles—have been extensively explored, yielding notable improvements in thermal responsiveness [36,37,38]. Beyond these thermal aspects, the kinetic behavior of PCMs is also decisive. A high nucleation rate minimizes supercooling, while rapid crystal growth ensures that stored energy can be efficiently recovered [39].

Alongside these energy-related aspects, the long-term feasibility of PCMs is defined by their technical and chemical characteristics. Durability under repeated melting–solidification cycles is critical, as degradation of latent heat or shifts in melting temperature can compromise effectiveness over time [40]. Excessive volume changes during phase transition must also be controlled to prevent leakage or mechanical stress that compromise system integrity. Moreover, compatibility with common construction materials (concrete, gypsum, polymers) is essential, as undesirable reactions or leakage may reduce both PCM efficiency and structural durability. Chemical stability is equally critical, since decomposition, oxidation, or segregation over repeated cycles can reduce the reliability of the system [41,42]. Finally, safety concerns such as flammability and toxicity impose further constraints, particularly in residential applications where occupant exposure is a concern [43,44].

II.4. Classification of phase change materials

Phase change materials' classification is fundamental to understanding their potential applications in thermal energy storage, particularly in building materials. Based on their chemical composition, PCMs are divided into three main categories: organic, inorganic, and eutectic mixtures. Each class exhibits specific thermophysical properties, benefits, and limitations that define its suitability for particular applications.

II.4.1. Organic PCMs

Organic compounds—primarily paraffins and non-paraffins—have dominated commercial PCM development due to their reliable and reversible phase transitions. Paraffins, consisting of straight-chain alkanes derived from petroleum distillation, have been extensively integrated in building envelopes to reduce heating and cooling loads [45,46]. Their key advantages include congruent melting, negligible subcooling, and high chemical stability. Their main limitations, however, are low thermal conductivity, flammability, and significant volume change, often requiring encapsulation or conductivity-enhancement measures [47,48]. Non-paraffin organics—such as fatty acids and esters—exhibit sharp melting points and reduced subcooling, with the added advantage of potential bio-based production. Despite these benefits, their higher cost, reported to be up to three times greater than paraffins, along with concerns over mild corrosiveness, odor, and flammability, restricts their large-scale use in buildings [48,49].

II.4.2. Inorganic PCMs

Inorganic PCMs, mainly salt hydrates and, to a lesser extent, metallic alloys, offer clear advantages over organic types due to their higher volumetric energy density, superior thermal conductivity, low cost, and non-flammable nature. Salt hydrates are especially promising due to their high latent heat and sharp phase transition, which make them attractive for building applications [50,51]. Yet, challenges such as supercooling, phase segregation, and corrosiveness often hinder stable performance. Voelker et al. [52], for example, found that calcium chloride hexahydrate could reduce indoor peak temperatures but suffered from supercooling and incomplete solidification. Their corrosive nature may also degrade common metals, raising the question of selecting durable encapsulation or container materials. Metallic PCMs, by contrast, provide excellent heat transfer and compact storage, but their high density, cost, and challenging implementation restrict their use to highly specialized thermal management systems. Despite renewed interest in low-melting metallic eutectics, their integration into building materials remains largely unexplored [53].

II.4.3. Eutectic mixtures

Eutectic PCMs are formed by combining two or more components that melt and solidify congruently at a fixed composition, producing a sharp and predictable transition temperature. Their main advantage lies in the ability to tailor melting points to match specific thermal comfort ranges, which is particularly valuable in building applications. Depending on the formulation, eutectics can be organic–organic, inorganic–inorganic, or organic–inorganic, thereby combining complementary properties such as the stability of organics with the high conductivity or storage density of inorganics. Although their latent heat of fusion is generally lower than that of pure compounds, they provide reliable thermal performance and design flexibility. However, the lack of extensive long-term cycling studies and limited commercial availability continue to restrict their adoption [47,54].

II.4.4. Bio-based PCMs

Beyond the conventional organic, inorganic, and eutectic types, bio-based PCMs have recently emerged as a sustainable alternative. Derived from renewable resources such as plant oils and animal fats, they are non-toxic and exhibit a broad operating temperature range, making them suitable for both low and high-temperature applications. Despite their renewable origin and reduced environmental impact, key limitations—including low conductivity, leakage risk, and performance variability—remain, though these can be mitigated through chemical modification, composite development, or the incorporation of conductive additives [55,56].

II.5. Thermal characterization techniques

The aforementioned thermophysical properties must be accurately determined to evaluate the suitability of PCMs for building applications. These properties are generally characterized at the material stage, prior to PCM incorporation into building envelopes, in order to provide reliable input data for both modeling and experimental validation. Among the different techniques available, Differential Scanning Calorimetry and the T-history method are the most widely used, and are therefore discussed in this section. Additional methods are also employed in PCM research and are summarized in Table II.2. The choice of a suitable thermal characterization technique depends on factors such as measurement accuracy, experimental requirements, sample size, ease of implementation, and maintenance.

- **Differential Scanning Calorimetry (DSC)**

In DSC analysis, the differential heat flow between a sample and an inert reference is measured under a controlled temperature program, enabling the determination of melting and freezing points, latent heat of fusion, specific heat capacity, and transition phenomena such as supercooling and hysteresis [57,58]. DSC systems are generally classified as heat-flux DSC, which measures the heat exchange between the sample and its environment, and power-compensation DSC, which supplies or removes energy to maintain the sample at the reference temperature [59]. This technique is valued for its precision and its ability to generate detailed enthalpy-temperature curves. However, DSC typically examines small samples (1-10 mg), which may not fully reflect the heterogeneous behavior of practical PCM quantities [60]. Moreover, results are highly sensitive to factors such as heating/cooling rate, sample mass, pan type, calibration, ad atmospheric conditions, all of which must be carefully controlled to ensure reproducibility [61].

Figure II.2 illustrates the working principle of a heat-flux DSC and the corresponding signal generation during heating and cooling cycles, showing the endothermic and exothermic peaks used to determine the enthalpy of phase change.

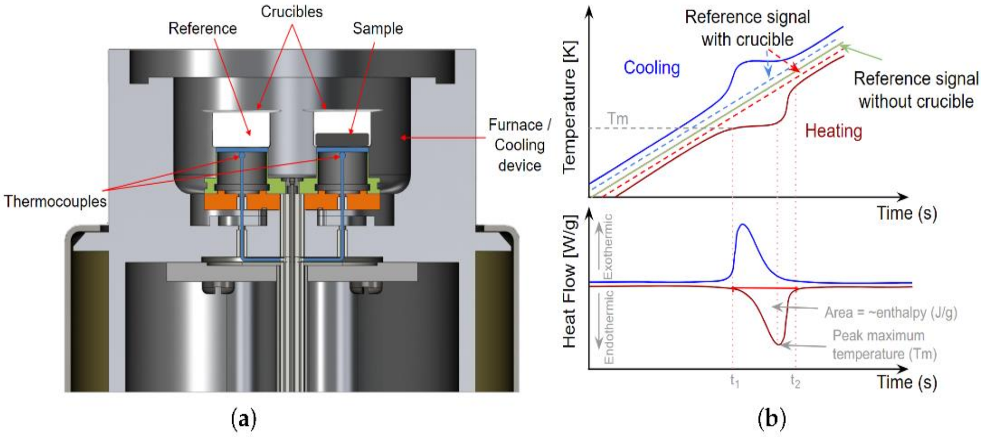


Figure II.2: (a) Operating principle of DSC, **(b)** Heat-flux DSC signal generation [62].

- ## T-History method

The T-history method, first proposed by Yinping et al. [60], is widely regarded as an alternative to DSC, overcoming its limitations related to small sample sizes. In this technique, a PCM sample and a reference material with known thermal properties, typically water, are subjected to a controlled heating or cooling process, and their temperature evolution is recorded over time. From these temperature-time curves, the main thermophysical properties—latent heat, phase change temperature, specific heat capacity, thermal conductivity, and the extent of subcooling—can be derived [61,63]. Compared with DSC, the T-history approach is simple, cost-effective, and allows the use of larger samples, making the results more representative of real-scale applications. It also enables the distinction between hysteresis and subcooling effects. However, the method is time-consuming, requires careful calibration, and its accuracy strongly depends on the design of the calorimeter and the measurement protocol [64].

Table II.2. Thermal characterization techniques commonly used for PCMs [58,65,66].

Technique	Principle of working	Purpose in PCM studies
Fourier Transform Infrared Spectroscopy (FTIR)	Based on the absorption of infrared radiation by molecular bonds at characteristic wavenumbers, producing a spectrum that reflects the chemical structure of the material	Identification of functional groups and assessment of the chemical stability of PCMs after thermal cycling.
Thermogravimetric Analysis (TGA)	Measures the variation in sample mass as temperature increases at a constant heating rate under a controlled atmosphere.	Determination of thermal stability and degradation behavior of PCMs.
Differential Thermal Analysis (DTA)	Measures the temperature difference between a sample and an inert reference subjected to the same thermal program.	Detection of phase change events and thermal transitions in PCMs.

II.6. Integration methods of PCMs into building materials

II.6.1. Integration techniques

The effective use of PCMs in buildings depends not only on the selection of a suitable PCM but also on the method by which it is integrated into construction elements. A wide range of techniques has been reported in the literature, each developed with the objective of exploiting the latent heat storage potential of PCMs while mitigating typical shortcomings such as leakage, or mechanical incompatibility with the host matrix. Broadly, the methods of PCM incorporation can be classified into direct incorporation, immersion, encapsulation, and shape-stabilization.

Direct incorporation consists of mixing liquid or powdered PCMs directly into construction materials during production. This method enhances the thermal mass of the host material without adding significant volume or weight, making it both simple and cost-effective [67]. For successful application, the PCM should not compromise the chemical composition, mechanical strength, or durability of the host material. However, its practical use is limited by issues such as leakage, reduced structural performance, and long-term durability concerns [31]. Flammability has also been reported, although this drawback can be alleviated through encapsulation [68]. Similar limitations are observed in the **immersion technique**, where building materials such as bricks or gypsum boards are immersed in liquid PCM, enabling absorption through capillary action. While this method is simple and adaptable—allowing existing components to be modified and reused with minimal processing—it is also prone to leakage and poor long-term stability [31,69].

To address the challenges associated with direct incorporation and immersion, encapsulation has been proposed as an effective strategy to stabilize PCM behavior and improve reliability under repeated thermal cycling [70,71]. In this approach, the PCM is enclosed within a protective shell or container that prevents direct interaction with the host material and minimizes losses during phase transition. Capsules of various materials, forms and sizes have been developed, including cylinders, spheres, tin-plated aluminum cans, steel cans, or other shapes [67], each offering different performance attributes in terms of thermal conductivity, durability, and compatibility. Encapsulation is typically classified into macro-encapsulation and micro-encapsulation. **Macro-encapsulation** involves enclosing relatively large volumes of PCM in a shell material with dimensions larger than 5 mm. Although effective in preventing leakage, this method often suffers from slow charging and discharging due to poor heat transfer, and the large capsule size can create integration and stability issues [72]. **Micro-encapsulation**, in contrast, confines PCMs within micron-scale shells, offering high surface-to-volume ratios that enhance heat transfer, reduce leakage, and allow direct incorporation into gypsum, concrete, or wallboards. Nonetheless, it often entails higher production costs and may reduce the mechanical strength of the host matrix [42,73]. Despite such limitations, encapsulation remains a key technique for PCM integration in buildings, balancing thermal reliability, safety, and material compatibility.

Shape-stabilized PCMs (SSPCMs) are produced by dispersing PCMs within supporting matrices such as HDPE, styrene-butadiene, or other porous materials, which prevents leakage and preserves structural integrity during phase transitions. With PCM loadings up to 80%, they provide higher storage capacity than direct incorporation and remain stable over repeated thermal cycles [42]. When incorporated into walls, ceilings, or floors, SSPCMs have been shown to reduce indoor temperature fluctuations, shift peak loads, and lower energy demand while maintaining occupant comfort, though their relatively low thermal conductivity remains a challenge, often addressed with additives like graphite or carbon fibers [74].

II.6.2. Integration considerations

Successfully integrating PCMs into building envelopes requires careful evaluation of several practical considerations beyond the intrinsic PCM properties and encapsulation techniques, which have been discussed previously. As mentioned before, PCM thermophysical properties—such as latent heat, melting temperature, and thermal conductivity—together with the encapsulation method, fundamentally influence energy storage performance and system feasibility. However, additional integration-specific considerations must be addressed.

The location and configuration of PCMs within a building envelope are critical determinants of their thermal performance. Proper placement ensures the moderation of indoor temperature fluctuations and the potential shifting of peak heating or cooling loads to off-peak periods, thereby enhancing occupant comfort and overall energy efficiency. The optimal location depends on several factors, including the position within the room or building assembly [75], the local climate, which is directly linked to the choice of PCM type [76], and the orientation of the exposed surfaces [77]. For example, Liu et al. [78] reported that placing the PCM layer closer to the interior side of the wall significantly improves thermal performance by enhancing heat exchange with indoor air, highlighting the importance of strategic placement in maximizing the benefits of PCM integration in building designs. The geometrical configuration, including layer thickness and surface area, also affects the rate of energy storage and release, with larger exposed areas typically enabling faster thermal response [79].

Structural and mechanical considerations in another key factor; the integration of PCMs can alter the mechanical behavior of building materials, as demonstrated by several studies [80,81]. Such potential drawbacks emphasize that the method of PCM incorporation must be carefully chosen, since it governs not only the thermal effectiveness but also the long-term mechanical performance of building materials.

Economic and environmental impacts must also be considered when integrating PCMs. From an economic perspective, cost analysis is essential, as feasibility depends not only on material price and installation but also on long-term energy savings and payback periods, which have been shown to vary strongly with climate conditions [82]. Environmentally, PCMs reduce building energy demand and CO_2 emissions, yet their production can offset part of these benefits. Therefore, while PCMs hold clear potential for balancing cost-effectiveness and sustainability, context-specific evaluation remains essential for their successful implementation [51,83].

Finally, safety and operational reliability are equally critical. Fire hazards, chemical interactions with building materials, and supercooling effects must be carefully addressed during the design stage. Organic PCMs, though chemically stable under normal operation, may pose flammability risks at high loadings, and mitigation strategies such as flame retardants or surface treatments have been proposed to reduce this risk [84,85]. In contrast, inorganic salt hydrates, while generally less flammable, may induce corrosion of metal reinforcements and present environmental concerns during disposal due to varying toxicity levels [50]. In addition, repeated thermal cycling and long-term exposure to temperature and moisture can degrade PCM performance, lead to phase segregation, or compromise encapsulation integrity, affecting both efficiency and material compatibility [86,87]. Addressing these durability issues through careful PCM selection, encapsulation design, and protective measures are therefore essential to ensure reliable performance throughout the service life of building applications.

II.7. Applications of PCMs in buildings

II.7.1. Applications of PCMs for thermal regulation and thermal comfort

The integration of PCMs into building envelopes represents a highly effective strategy for thermal regulation and maintaining stable indoor conditions. Through latent heat storage, PCMs absorbs excess thermal energy during high-temperature periods and release it when temperatures drop, thereby stabilizing indoor temperatures within a narrow and comfortable range. This passive regulation not only extends the period during which indoor conditions remain within the comfort zone but also reduces reliance on mechanical heating and cooling systems, contributing to significant energy savings. Experimental and numerical studies [88,89,90] demonstrated that PCM-integrated envelopes can reduce indoor temperature fluctuations by 2-5 °C and delay peak heat transfer by several hours, effectively smoothing indoor temperature profiles. Overall, PCMs enable the building envelope to passively regulate internal conditions, promoting a more comfortable, energy-efficient, and resilient indoor environment.

II.7.2. Applications of PCMs for peak load shifting

Periods of high electricity demand, commonly referred to as peak loads, present significant challenges for energy management, particularly in buildings with substantial heating or cooling requirements. These peaks often coincide with extreme outdoor conditions or intensive building operation, resulting in elevated demand on HVAC systems and electrical grids, which can increase operational costs and place additional pressure on power generation and distribution systems. Phase change materials, due to their latent heat storage capability, offer an effective passive strategy to address these challenges. By storing thermal energy during off-peak periods and releasing it during peak hours, PCMs help redistribute heating and cooling loads, reducing peak energy requirements while maintaining consistent indoor thermal conditions. This process is schematically illustrated in Figure II.3. This ability not only mitigates peak demand, but also enhances occupant comfort by ensuring more stable indoor temperatures during periods of extreme weather.

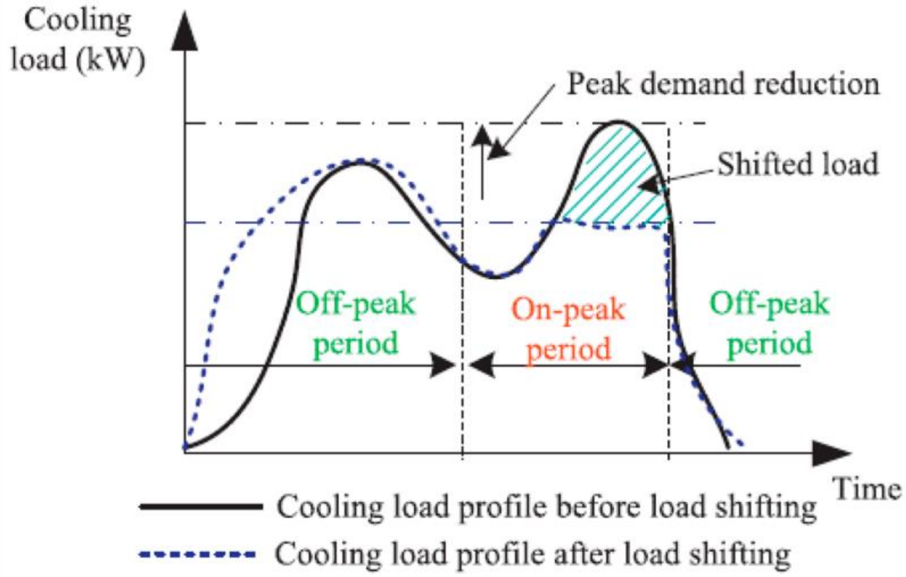


Figure II.3: Schematic representation of peak load shifting achieved through PCM thermal storage, showing the reduction and delay of peak energy demand [91].

The effectiveness of PCM-based peak load shifting largely depends on how thermal storage is integrated and managed within the building system. Two main configurations are generally identified: passive integration, where PCMs are incorporated into building envelopes (e.g., walls, ceilings, or floors) to enhance thermal inertia, and active integration, where PCMs are embedded within HVAC systems or dedicated storage units [92]. In the passive systems, PCMs leverage natural diurnal temperature variations for charging and discharging, offering a simple, durable, and energy-efficient approach to moderate indoor temperature fluctuations and reduce peak heating or cooling loads without the need for mechanical control or external energy input.

II.7.3. Applications of PCMs for energy saving

Reducing indoor temperature fluctuations is a crucial strategy for lowering building energy demand and associated operational costs, particularly in climates with significant day-night temperature variations. Beyond their role in peak load management, PCMs have been extensively applied to building envelopes to enhance energy performance and achieve substantial reductions in heating and cooling requirements. By moderating temperature variations, delaying and offsetting peak thermal loads, and reducing the rate of heat transfer through the envelope, PCM integration decreases the operational burden on mechanical systems and lowers energy consumption per unit area. Their high latent heat capacity allows for significant energy storage within narrow temperature ranges, increasing the thermal inertia of the building, smoothing daily temperature profiles, and contributing to more stable indoor conditions. Strategically implemented, PCMs facilitate passive energy savings, reduce reliance on active heating and cooling systems, and mitigate peak energy demands, resulting in measurable reductions in operational expenses. This approach not only addresses the growing trend of energy consumption in buildings, but also demonstrates the practical and sustainable potential of PCMs to optimize energy efficiency, maintain occupant comfort, and support long-term environmental and economic objectives.

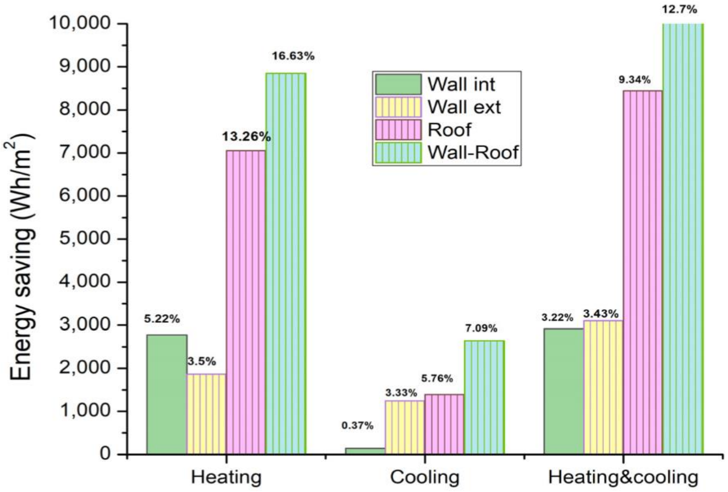


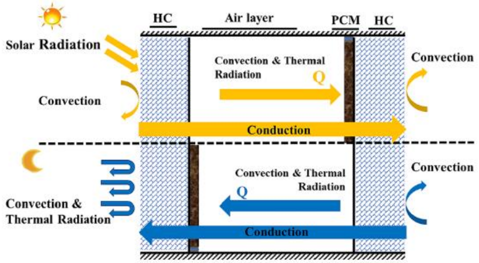
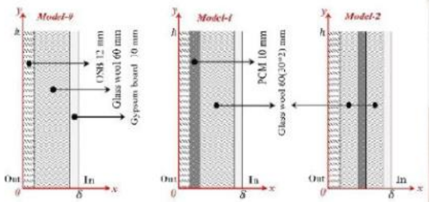
Figure II.4: Example of energy savings for heating, cooling, and combined heating and cooling achieved through different PCM-integrated envelope configurations in Sousse [93].

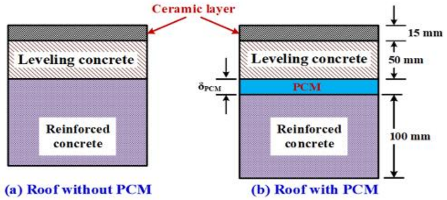
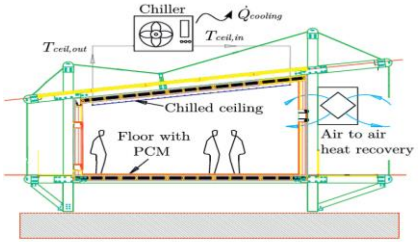
II.8. Previous studies on PCM integration in building envelopes

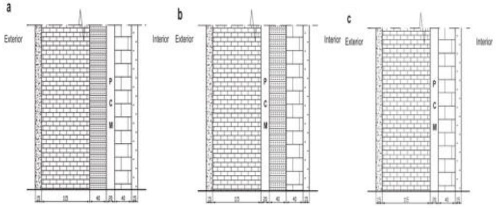
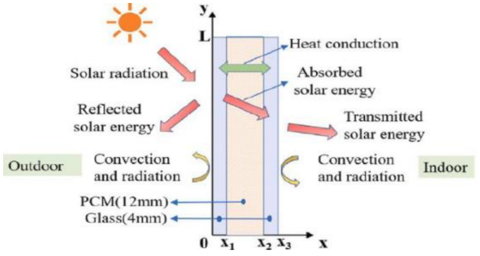
Over the past two decades, extensive research has investigated the integration of PCMs into different building envelope components as a passive strategy for improving thermal comfort and reducing energy demand. In walls, PCM wallboards [94,95] and gypsum boards [96,97] were among the earliest and most widely studied configurations. Zhao et al. [98] investigated expanded graphite/paraffin PCM wallboards and reported that the optimized configuration reduced the average maximum indoor temperature by 1.24 °C and the cooling load by 935 W/m^2, while Sharifi et al. [46] demonstrated that PCM-impregnated gypsum boards improved thermal comfort and reduced HVAC energy demand, with performance depending on climate conditions. Similarly, PCMs have also been integrated into ceilings [99,100] and floors [101], for example through ceiling panels and PCM-layered floor slabs. Arivazhagan et al. [102] experimentally evaluated PCM-integrated ceilings under real atmospheric conditions, reporting temperature reductions up to 5.79 °C and highlighting the effectiveness of PCM ceilings for thermal management. In flooring systems, Royon et al. [103] studied floor panels filled with a paraffin-polymer composite PCM and showed that the integration enhanced thermal inertia, reduced surface temperature fluctuations, and improved heat storage capacity. Roof applications have likewise received considerable attention [104,105], with findings demonstrating that concrete roofs with an interior PCM layer reduced thermal loads by up to 57% compared to conventional roofs, as reported by Xaman et al. [106]. Beyond opaque elements, transparent and semi-transparent PCM systems have been investigated for windows and glazing facades [107,108,109]. Silva et al. [110] showed that

PCM-integrated window shutters decreased peak indoor temperatures by 8.7%, increased night temperatures by 16.7%, and extended the time lag by up to 1h, while Goia et al. [111] found that PCM-Double Glazing (DG) windows reduced summertime energy gains by 50% compared to conventional DG windows. A summary of representative studies on PCM applications across different building elements is further presented in Table II.3.

Table II.3. A summary of representative studies on PCM applications across different building elements.

Building element	Reference	Aim of the study	Main performance outcomes	Physical model
Walls	Li et al. [112]	Evaluating the effectiveness of a dynamic PCM wall system in enhancing thermal performance and energy savings.	-The dynamic PCM system reduced summer heat gain by up to 535.73% and winter heat loss by 58.8%. -The optimal PCM thickness was 2 cm for summer and 4 cm for winter conditions. -Energy savings were influenced by PCM placement and overall wall thickness. -Dynamic PCM performed better than both static PCM systems and walls without PCM.	
Floors	Xu et al. [113]	Developing a shape-stabilized composite PCM with adjustable transition temperature for radiant floor heating applications.	-An extended duration of thermal comfort. -Enhanced thermal stability while preventing PCM leakage. -The small supercooling degree of 0.29 °C contributed to a stable and reliable performance.	
Walls	Liu et al. [109]	Numerical and experimental evaluation of the optimal-phase-change temperature, positioning, and orientation of PCM within lightweight walls.	-East and south-facing walls: placing PCM at the center reduced heat flux by 62.8% and 29.5%. -West and north-facing walls: locating PCM on the interior/exterior surface lowered heat flux by 66.4%. -Optimal PCM thickness: 10 mm for east and west walls, and 5 mm for south and north walls. -Latent heat: A value of 125 kJ/kg provided a balanced combination of thermal comfort and energy savings.	

Roofs	Elawady et al. [114]	Investigating the long-term thermal performance of a PCM-integrated roof and assessing how PCM type and thickness influence indoor temperatures and energy gain.	-Reduction in indoor heat flux and maintained wall temperature closer to indoor comfort requirements. -A decrease in indoor wall temperature from 32.5 °C (without PCM) to 29.4 °C (with PCM). -Using 40 mm of RT31 PCM reduced total summer energy gain by approximately 40% over four months.	
Windows	Jalil et al. [115]	Numerical and experimental investigation of thermal performance of a paraffin-based PCM double-glazed window and its impact on cooling load reduction and indoor thermal comfort.	-The PCM-filled double-glazed window lowered peak room temperature by 8 °C (ground floor), 6 °C (first floor), and 5 °C (ceiling) compared to a conventional single-glazed window. -For ground and first floors, the interior surface temperature was slightly lower than that of single glass; however, ceiling installation showed performance limitations due to early PCM melting. -The optimal window thickness was recommended to be between 20-25 mm.	
Floors	Belmonte et al. [116]	Performance optimization of a chilled ceiling system coupled with PCM-based flooring for cooling applications.	-The incorporation of PCM lowered cooling loads by as much as 85%. -It minimized on/off cycling, enhancing overall system efficiency. -Higher melting temperatures led to greater energy savings but caused a slight reduction in thermal comfort.	

Walls	Barrientos et al. [117]	Numerical assessment of the effects of PCM placement, phase-change temperature, and wall orientation on building energy efficiency.	-Interior PCM reduced winter heat loss, whereas exterior PCM lowered summer heat gain. -The optimal phase-change temperature was 1-3 °C above the average indoor temperature. -PCM integration contributed to HVAC load stabilization by attenuating the amplitude of heat flux fluctuations.	
Windows	Wang et al. [118]	Numerical investigation of paraffin-based PCM in double-glazed windows for reducing summer energy consumption.	-Combining PCM with solar control glass helps mitigate the risk of overheating during summer. -Energy savings of 14.25% were achieved when using glass with a high refractive index. -Optical characteristics of the glass, such as absorption and refraction, significantly influence PCM performance.	

While PCMs have been widely explored in diverse building components, the present review narrows its scope to studies involving brick-based elements, which are directly relevant to the present study on hollow clay bricks integrated with phase change materials. Accordingly, in the following review, previous studies are organized according to the parameters that influence thermal performance including PCM thermophysical properties, PCM layout—covering both its position within the building element and the encapsulation shape—and the PCM layer configuration. This approach provides a concise and structured discussion of key findings while emphasizing the parameters most critical to the design and performance of PCM-integrated brick systems.

II.8.1. The impact of PCM thermophysical properties

The thermal performance of PCM-integrated building components largely depends on their thermophysical properties. Key parameters such as melting temperature, latent heat of fusion, and thermal conductivity govern heat storage capacity and transfer efficiency. Several studies have therefore examined how these thermophysical properties influence the thermal behavior of PCM-based building elements. For instance, Hamdaoui et al. [25] developed a numerical model to study heat transfer in hollow clay bricks with PCM encapsulated in their solid matrix. By analyzing the influence of PCM melting temperature, latent heat, and external conditions on thermal performance, they showed that a PCM with a melting temperature of 32 °C provided optimal stabilization of the inner surface temperature, while higher latent heat improved thermal energy storage by reducing temperature peaks and increasing the time lag. In a similar study, Mahdaoui et al. [119] investigated PCM integration into hollow clay bricks under Moroccan climate conditions. Using a validated numerical model, they evaluated the effects of PCM thermophysical properties alongside outdoor and indoor conditions on thermal behavior. The findings demonstrated that latent heat and melting temperature are the key parameters influencing performance: higher latent heat reduced peak temperatures and attenuated the thermal wave, whereas an optimal melting temperature, close to the mean of the external thermal wave, stabilized inner surface temperature near comfort range while maximizing latent storage. Nadezhda et al. [120] conducted a numerical study on brick blocks with PCM inserts to examine the influence of PCM position and melting temperature under unsteady outdoor conditions. Accounting for natural convection effects, the analysis showed that both parameters strongly influence thermal performance. PCMs with melting points close to or above daily maximum temperatures provided benefits only during very hot days, while lower melting point

PCMs activate more reliably. Li et al. [121] investigated the integration of thirteen different PCMs into conventional walls in Isfahan, Iran, using a numerical model. The study focused on walls composed of plaster, clay brick, and cement, evaluating the effects of PCM position, thickness, and thermophysical properties on heat transfer, as illustrated in Figure II.5. Results revealed that thermal conductivity was the most influential parameter, with lower conductivity significantly reducing interior heat transfer. Latent heat and melting temperature were also critical: higher latent heat enhanced energy storage and reduced heat transfer, while a melting temperature closer to room conditions optimized phase-change effectiveness.

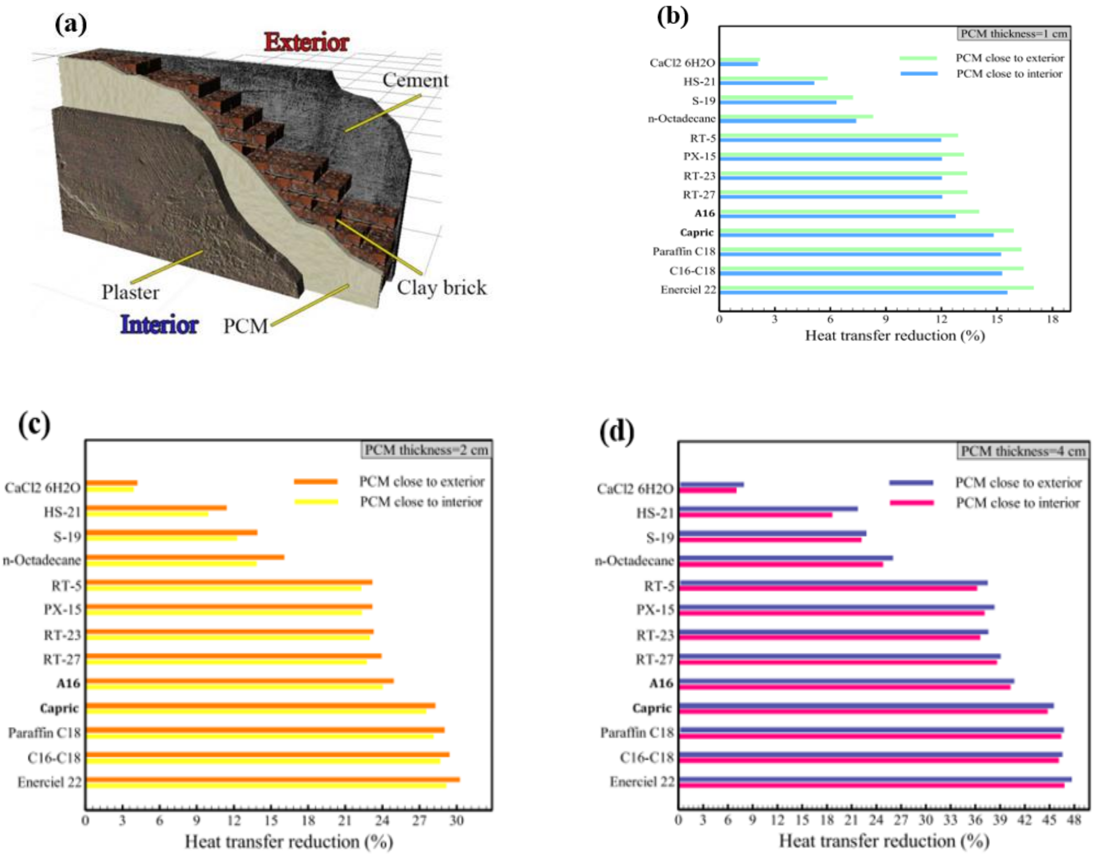


Figure II.5: (a) Simulated wall, **(b-d)** Heat transfer reduction with respect to the installation position and type of PCM for different thicknesses.

II.8.2. The impact of PCM layout

The thermal performance of building components incorporating PCMs depends not only on the material properties but also on how the PCM is arranged within the building element. The positioning of PCM within brick-based components has proven to be a critical factor influencing peak load reduction, thermal delay, and overall energy performance, driving focused research on optimal integration strategies [122,123,124]. Hamidi et al. [125] numerically investigated the thermal performance of hollow brick walls with incorporated PCMs, highlighting the effect of PCM positioning. Four distinct positions were evaluated in the warm-climate city of Er-Rachidia, Morocco, as illustrated in Figure II.6. The findings indicated that selective filling, particularly at positions 3 and 4, effectively reduced peak heat flux and enabled up to 97% energy savings while maintaining indoor comfort at 26 °C, demonstrating that strategic PCM positioning can optimize wall performance without full-brick filling. In a similar study, Zhang et al. [126] employed a two-dimensional enthalpy model to investigate the influence of structural configurations on the thermal performance of composite PCM hollow brick walls. Five factors were analyzed, including PCM location, and the results showed that PCM position was the dominant parameter, with placement closer to the interior side significantly enhancing performance. Staggered PCM hole arrangements were further recommended, highlighting that precise positioning of PCM is essential to optimizing the energy-saving effectiveness of hollow brick walls.

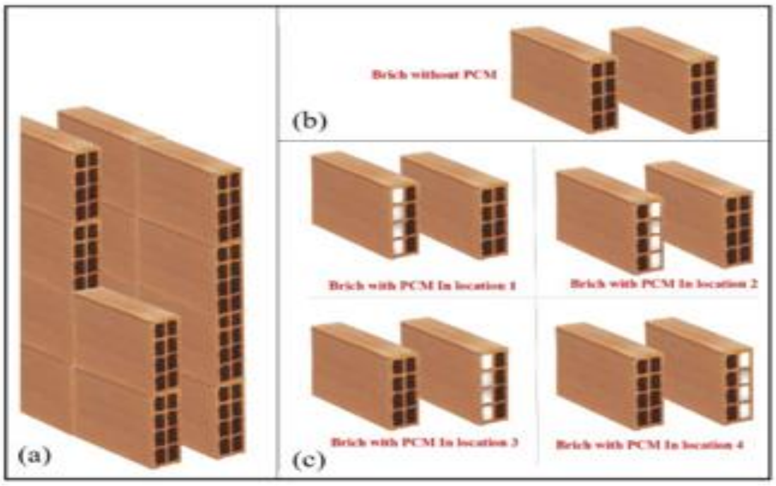


Figure II.6: Schematic representation of **(a)** a conventional wall, **(b)** a hollow brick without PCM, and **(c)** a hollow brick with PCM integrated in all four locations.

Gao et al. [127] conducted a combined numerical and experimental study on hollow bricks filled with PCM, considering five different filling locations with a 20% filling ratio (Figure II.7). Their results demonstrated that PCM incorporation significantly improved thermal performance, reducing peak heat flux from 45.26 W/m^2 to 19.19-21.4 W/m^2, decreasing the attenuation rate from 13.07% to 0.92-1.93%, and increasing the time lag from 3.83h to 8.83-9.83h. The study also showed that PCM placement notably influences thermal behavior, with inner cavity fillings preserving nearly 90% of the PCM's phase-change potential under varying outdoor conditions, maximizing latent heat utilization.

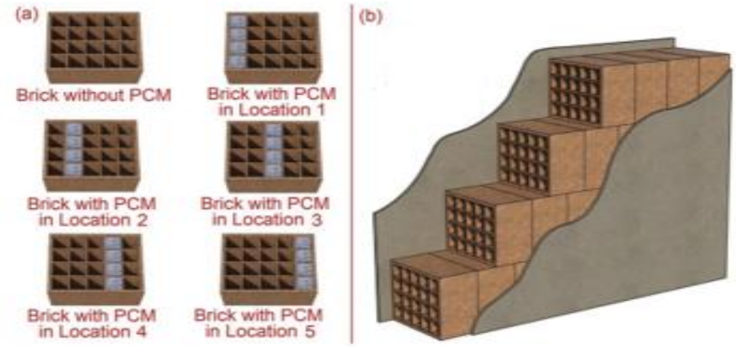


Figure II.7: Graphic representation of **(a)** hollow clay bricks with and without PCM at different positions and **(b)** the corresponding brick wall configuration.

Beyond the positioning of PCM layers, the shape of encapsulated PCM also plays a vital role in heat transfer performance. Several studies have examined how capsule geometry, such as cylindrical or rectangular, affects melting and solidification behavior, influencing the overall thermal efficiency of PCM-integrated systems [128,129]. Allam et al. [130] investigated the influence of cavity geometry and PCM type on the thermal performance of brick walls under Algeria's hot climate. Using ANSYS Fluent, they evaluated three cavity shapes—square, polygonal, and circular—filled with four PCMs, as shown in Figure II.8. Their findings showed that PCM integration significantly improved thermal comfort and reduced energy demand. Among the tested configurations, square cavities filled with Capric acid achieved the best performance, decreasing peak indoor heat flux by 67.8%, and lowering total energy consumption by 61.8%, compared to conventional bricks. In another study, Gupta et al. [131] examined the impact of macro-capsule shape on thermal performance of clay bricks incorporating hybrid PCMs under a tropical climate. Three capsule geometries—tubular, square, and rectangular—were tested with two PCM types, with and without graphite. Results showed that tubular capsules without graphite achieved the greatest reduction in peak temperature and heat flux, as well as the largest time lag, emphasizing the crucial role of capsule geometry in enhancing indoor thermal regulation.

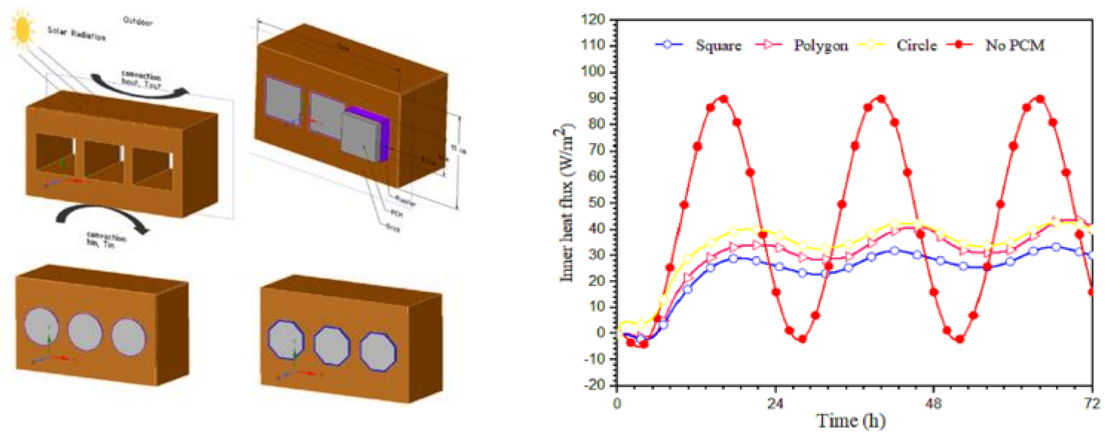


Figure II.8: Representation of hollow clay bricks incorporating PCM with different cavity shapes and their effect on the inner surface heat flux.

II.8.3. The impact of PCM layers

In recent years, an emerging line of research has focused on incorporating PCMs in the form of continuous layers within building envelopes such as walls and roofs, with growing interest in the development of double-layer PCM configurations. A key advantage of these systems is their ability to address seasonal variations in thermal demand, thereby overcoming a limitation of many conventional passive strategies that are typically optimized for either heating or cooling, but rarely both. Although this novel approach has not yet been applied directly within brick cavities, its integration into brick-based wall assemblies has been the subject of recent investigations. Rehman et al. [132] investigated a novel dual-layer PCM configuration for brick walls under the subtropical climate of Islamabad, Pakistan. Using numerical simulations with ANSYS Fluent, the study evaluated PCM layers with distinct melting points—29 °C and 13 °C—designed to address seasonal variations in thermal comfort. The results demonstrated that dual-layer PCM configuration substantially enhanced thermal mass, stabilizing indoor temperatures while maintaining consistent charging and discharging cycles over extended operation. The authors highlighted that strategic implementation of dual-layer PCMs provides superior year-round energy savings and improved occupant comfort compared to conventional single-PCM integration.

Zhu et al. [133] proposed a simplified dynamic model to evaluate a three-layer wall system with double layers of SSPCMs. The outer and inner SSPCM layers were designed with different melting temperatures—higher for summer and near the indoor setpoint for winter—

with a conventional brick layer in between. Using RC networks and genetic-algorithm-based parameter identification, the model accurately predicted the thermal performance of walls under varying conditions. The study emphasized the importance of proper model configuration and parameter identification for reliable simulations, providing a methodological foundation for further research on the design and integration of double-layer SSPCMs in building envelopes. Refahi et al. [134] evaluated the impact of double-layer PCM wallboards integration with thermal insulation layer on the energy performance of four-story residential building in Tehran. Two PCM layers with distinct melting points were analyzed to assess their advantages over single-layer arrangements, considering the effect of layer positions. Simulation results demonstrated that employing double layers reduced energy consumption compared to single-layer arrangements. The study also highlighted that both the relative positioning and sequencing of the PCM layers significantly influence thermal performance, with floor-specific optimal configurations achieving up to 6.6% heating and 2.8% cooling energy savings.

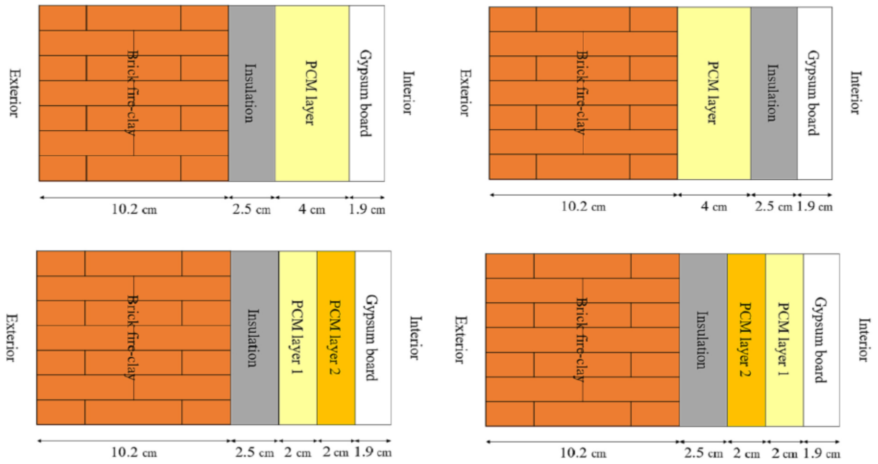


Figure II.9: Representation of the different cases studied.

II.9. Numerical simulation of PCM based buildings

The study of heat transfer in building components containing phase change materials involves complex, transient, and nonlinear processes driven by the simultaneous effects of conduction, natural convection, and latent heat exchange during phase transitions. Accurately capturing these coupled phenomena requires accounting for the strong temperature dependence of PCM thermophysical properties, including thermal conductivity, specific heat, and density, as well as the influence of encapsulation geometry and boundary conditions. While experimental investigations provide essential insights, they are often constrained by high cost, scale limitations, and challenges in controlling boundary conditions, which restrict their applicability for extensive parametric analysis. Consequently, numerical modeling and simulation have become indispensable tools for analyzing and optimizing the thermal performance of PCM-integrated systems. Two principal approaches are widely employed to simulate phase change behavior: the enthalpy-porosity method and the apparent heat capacity method. Both methods are implemented across advanced numerical platforms such as ANSYS Fluent, COMSOL Multiphysics, TRNSYS, and EnergyPlus, which enable detailed analyses of heat transfer, phase transition evolution, and the overall thermal response of PCM-enhanced envelopes under realistic climatic and operational conditions. These simulation tools facilitate systematic parametric studies examining the influence of PCM type, layer thickness, placement, and environmental factors, supporting the optimization of design and material selection strategies. Model validation against experimental or benchmark data remains a crucial step to ensure predictive reliability and physical consistency. By integrating these modeling approaches and computational environments, it becomes possible to establish a comprehensive understanding of PCM thermal dynamics—from microscopic phase transition behavior to macroscopic building performance—thereby advancing the design of energy-efficient, thermally stable, and environmentally sustainable building systems.

II.10. Conclusion

Phase change materials have been extensively explored as passive thermal energy storage solutions for building applications due to their capacity to store and release significant amounts of latent heat within a narrow temperature interval. When integrated into building envelopes, PCMs can moderate indoor temperature variations, enhance thermal inertia, and contribute to reducing cooling and heating demands. The thermal effectiveness of these materials is governed by a combination of factors, including phase change temperature, latent heat capacity, thermal conductivity, and long-term thermal stability, all of which must be carefully matched to the climatic conditions and operational requirements of the building.

Successful application of PCMs in buildings also relies heavily on appropriate encapsulation and incorporation strategies that ensure material compatibility, prevent leakage, and maintain structural integrity. Various integration approaches reported in the literature demonstrate that the arrangement of PCMs within building components—such as interior, middle, or exterior placement—has a pronounced influence on heat transfer behavior and indoor thermal regulation. In addition, multilayer configurations and optimized PCM layouts have shown potential for improving thermal performance by better synchronizing the phase change process with daily thermal loads.

Recent research trends indicate an increasing use of numerical and computational fluid dynamics methods to investigate the transient thermal behavior of PCM-enhanced building elements. These approaches enable detailed analysis of phase change process, heat flux evolution, and temperature distribution under realistic boundary conditions, offering valuable insights that are difficult to obtain experimentally. Overall, the findings synthesized from the reviewed studies underline the importance of a holistic design approach that combines suitable PCM properties, effective integration techniques, and advanced numerical modeling, thereby establishing a solid scientific foundation for the optimization and numerical investigations presented in the subsequent chapters of this thesis.

Chapter III:

Methodology and numerical modeling

III.1. Introduction

Numerical simulation has become a central approach for investigating heat transfer and phase change phenomena in building materials incorporating phase change materials, particularly where experimental analysis is constrained by cost, time, or measurements complexity. Advanced numerical techniques allow detailed examination of transient thermal behavior and provide insight into the coupled mechanisms of heat conduction, latent heat storage, and fluid flow occurring during melting and solidification processes. Such methods offer a flexible framework for evaluating multiple design configurations and operating conditions, making them especially suitable for the parametric analysis and optimization of PCM-integrated building components.

Accurate modeling of PCM-enhanced building materials requires appropriate representation of solid-liquid phase transitions and their interaction with heat transfer processes. Several numerical approaches have been proposed in the literature to describe phase change behavior, including effective heat capacity formulations, source-based methods, and enthalpy-based models. Among these, the enthalpy-porosity approach has been widely adopted due to its robustness and ability to capture the evolution of the phase interface while accounting for conduction and natural convection within the molten PCM. The numerical framework employed in this thesis is based on this approach, enabling the simulation of coupled thermal and flow phenomena within PCM-integrated building elements.

To ensure physical consistency, the modeling strategy relies on the fundamental conservation laws of mass, momentum, and energy to describe the governing heat transfer and phase change processes. These equations are formulated under clearly defined assumptions and solved numerically using an appropriate computational methodology. The chapter details the mathematical model, including the description of the physical domain, governing equations, and initial and boundary conditions, followed by the investigated configurations and thermal performance indicators. Finally, the computational procedure and model validation are presented to demonstrate the accuracy and reliability of the numerical results used in the subsequent analysis.

III.2. Numerical simulation of heat transfer and phase change in building materials

The prediction of heat transfer in building materials relies on advanced numerical approaches capable of capturing transient and multidimensional phenomena that are often beyond the reach of analytical formulations. The thermal response of such materials is governed by the coupled effects of conduction, convection and in some cases phase change, all of which contribute to the dynamic behavior of building envelopes under varying boundary conditions. Numerical modeling, therefore, provides a reliable means of analyzing these coupled mechanisms and quantifying the influence of material composition, geometry and environmental excitation on overall thermal performance.

Among the available numerical techniques, Computational Fluid Dynamics is particularly effective for investigating coupled heat and fluid flow in construction materials. It enables the prediction of velocity, pressure, and temperature fields within the computational domain, offering detailed insight into local thermal phenomena that are otherwise difficult to measure experimentally. By numerically solving the fundamental conservation equations of mass, momentum and energy, CFD provides a comprehensive framework for investigating heat and fluid flow within geometrically complex configurations.

In the context of brick modeling, CFD facilitates the study of conjugate heat transfer between the solid clay matrix and the internal cavities, which may contain air or phase change materials. This approach allows simultaneous consideration of conductive and convective heat transfer, together with latent heat storage and release during the phase transition of PCMs. Such comprehensive modeling is essential for assessing the transient thermal performance of PCM-integrated bricks and optimizing their design for energy-efficient building applications. The mathematical formulation of CFD is governed by the Navier-Stokes equations, which express the conservation of mass, momentum and energy within the computational domain. These equations can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \qquad \text{(III.1)}$$

This equation is referred to as the continuity equation. The first term describes the temporal change or accumulation of mass per unit volume within a fixed control element, while the second term represents the net outward mass flux per unit volume of the element due to advective transport.

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u.u) = -\nabla P + \nabla.(\mu \nabla \mathrm{u}) + \rho g \tag{III.2}$$

This equation represents the conservation of momentum. The first term denotes the temporal accumulation of momentum per unit volume, while the second term describes the net convective transport of momentum due to fluid motion. On the right-hand side, the pressure gradient term accounts for surface forces, the viscous term represents momentum diffusion due to internal friction, and the body force term corresponds to volumetric forces acting within the fluid.

$$\frac{\partial(\rho c_p T)}{\partial t} + \nabla.(\rho c_p u T) = \nabla.(\lambda \nabla \mathrm{T}) + S_E \tag{III.3}$$

This equation expresses the conservation of energy. The first term represents the temporal accumulation of thermal energy per unit volume, and the second term describes its convective transport by the flow. The term on the right-hand side accounts for heat diffusion by conduction, while any additional source term represents volumetric heat generation.

III.3. Phase change modeling

Accurately describing the phase change process within PCM regions requires a numerical formulation capable of capturing both latent heat effects and the progressive motion of the phase front. Two main approaches are commonly employed for this purpose: the Effective Heat Capacity Method (EHCM) and the Enthalpy-porosity Method (EPM) [135,136,137]. The EHCM simulates phase change by treating it as a sensible heat process with an increased or ‘’effective’’ specific heat capacity within the phase transition temperature range. This approach simplifies the governing equations and eliminates the need for explicit interface tracking making it computationally efficient for problems dominated by heat conduction. Here, the effective heat capacity (C_{eff}) is defined as follows:

$$\begin{cases} C_{eff} = C_{solid}, \quad T < T_{solidus,} \\ C_{eff} = \left[(1-f)C_{solid} + fC_{liquid}\right] + \dfrac{L_f}{T_{liquidus} - T_{solidus}}, \qquad T_{solidus} \le T \le T_{liquidus} \\ C_{eff} = C_{liquid}, \quad T > T_{liquidus,} \end{cases} \tag{III.4}$$

Where L_f is the latent heat of fusion, f is the liquid fraction, T_{liquidus} and T_{solidus} are the temperatures defining the phase-change range, C_{liquidus} and $C_{solidus}$ are the specific heat values for the solid and liquid phases, and T is the temperature of the PCM.

The corresponding energy equation incorporating the effective heat capacity is expressed as follows:

$$\frac{\partial}{\partial t}(\rho C_{eff}T) + \nabla\left(\rho C_{eff}u_jT\right) = \nabla(\lambda\nabla T) \pm S_E \tag{III.5}$$

Here, S_E denotes any external heat source. The latent heat effect is embedded in the temperature-dependent effective heat capacity C_{eff}, so no latent heat source term appears explicitly.

The EPM on the other hand, expresses the energy balance in terms of enthalpy, where the total enthalpy is defined as a function of temperature, ΔH = f(T), encompassing both sensible and latent components. The method introduces a liquid fraction parameter f that represents the proportion of liquid phase within the mushy region, enabling a smooth transition between solid and liquid states. This formulation implicitly captures the evolution of the phase interface without the need for explicit tracking.

In the enthalpy-based formulation, the conservation of energy is expressed in terms of the total volumetric enthalpy, which inherently accounts for both sensible and latent heat effects. The total enthalpy is expressed as a function of temperature as follows:

$$H = h_{ref} + \int_{T_{ref}}^{T} C_P dT + fL_f \tag{III.6}$$

Where the first term represents the reference enthalpy, the second term corresponds to the sensible heat, and the final term captures the latent heat contribution through the liquid fraction *f*.

To evaluate the total enthalpy, the liquid fraction f is defined as a function of temperature within the mushy region:

$$\begin{cases} f = 0, \;\; T < T_{solidus,} \\ f = \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, \qquad T_{solidus} < T < T_{liquidus,} \\ f = 1, \;\; T > T_{liquidus,} \end{cases} \tag{III.7}$$

Hence, by substituting the enthalpy-temperature relationship into the energy conservation equation, the governing equation for heat transfer with phase change can be written as:

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho u_j H) = \nabla(\lambda \nabla T) \pm S_E \tag{III.8}$$

III.4. Numerical methodology

In this study, the enthalpy-porosity method implemented in ANSYS Fluent was employed to simulate the melting and solidification behavior of phase change materials embedded within the cavities of hollow clay bricks. This numerical approach was selected due to its proven ability to represent both heat conduction through the solid clay matrix and natural convection within the molten PCM, ensuring a realistic depiction of the coupled heat transfer processes during phase transition. The method, as incorporated in fluent, integrates the latent heat effect directly into the enthalpy-based energy equation through a temperature-dependent liquid fraction, allowing a smooth and continuous transition between solid and liquid phases without explicit front tracking.

Accordingly, a two-dimensional transient CFD model was developed to investigate the thermal behavior of a hollow clay brick filled with PCM under realistic operating conditions. The computational domain was designed to account for conjugate heat transfer between the clay matrix and the PCM-filled cavities, where phase change occurs under dynamic boundary conditions. The governing continuity, momentum, and energy equations were discretized using the finite volume method, ensuring accurate resolution of both conductive and convective heat transfer. Boundary conditions were defined to represent realistic outdoor and indoor thermal loads typical of hot climates, allowing for the assessment of the brick’s transient thermal response under real environmental excitation.

Overall, the developed numerical framework provides a comprehensive and reliable approach for evaluating the thermal performance and energy-saving potential of PCM-integrated brick systems. It offers a rigorous foundation for analyzing the underlying physical mechanisms governing heat transfer in such composite materials and supports the optimization of passive cooling strategies for building envelopes exposed to extreme climatic conditions.

III.5. Mathematical model

III.5.1. Description of the physical model

The present numerical investigation focuses on transient heat transfer within a hollow clay brick incorporating PCMs as a passive thermal regulation strategy. A two-dimensional transient heat transfer model was developed using ANSYS fluent to simulate the thermal response of the composite structure under diurnal temperature variations typical of hot climates. The model employed a building brick design with 10 cylindrical cavities, as illustrated Figure III.1, each filled with PCM encapsulated in a 1 mm-thick acrylic plastic container to prevent leakage during phase transition and ensure effective thermal contact with the surrounding material.

Heat transfer in the brick is governed by conduction in the solid regions and convective flow within the molten PCM. The phase change process was modeled using the enthalpy-porosity approach, which incorporates latent heat effects through the evolution of the PCM liquid Fraction [138]. The thermophysical properties of all materials employed in the model are summarized in Table III.1.

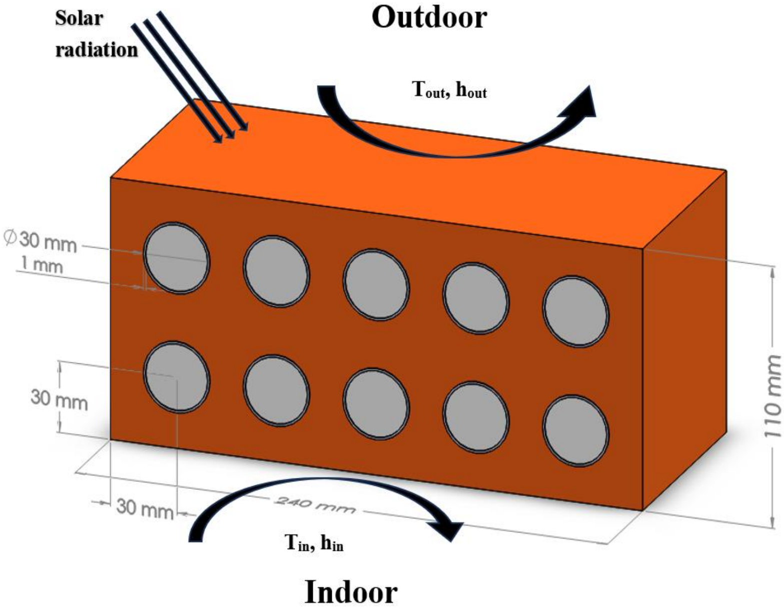


Figure III.1: Schematic representation and dimensions of the physical model.

Table III.1. The thermophysical properties of the materials used in this study [89, 138, 139].

Material	RT-42	n-Eicosane	RT-27	Air	Brick	Acrylic plastic
Density, (kg/m^3)	885 (s) 820 (l)	885 (s) 778 (l)	870 (s) 760 (l)	1.225	1600	1190
Specific heat capacity, (J/kg. k)	1800 (s) 2400 (l)	2010 (l) 2040 (s)	1800 (s) 2400 (l)	1001.43	840	1470
Thermal conductivity, (W/m. k)	0.2	0.15	0.24 (s) 0.15 (l)	0.026	0.7	0.18

Viscosity, (Pa.s)	0.02534	0.00355	0.00342	$1.846.10^{-5}$	-	-
Thermal expansion coefficient, (1/k)	0.001	0.001	0.005	0.00353	-	-
Latent heat, (kJ/kg)	141.6	241	179	-	-	-
Solidus temperature, (°C)	39	36	24	-	-	-
Liquidus temperature, (°C)	43	38	27	-	-	-

Three PCMs—RT-27, RT-42, and n-Eicosane—were selected based on their melting temperatures and thermal storage capacities, ensuring effective thermal response under the climatic conditions of Bechar, Algeria. RT-27 (~27 °C) is suited to moderating indoor temperature peaks, while RT-42 (~42 °C) and n-Eicosane (~38 °C) correspond to the higher surface temperatures typically experienced by exterior brick walls. Using PCMs with different melting points broadens the operational temperature range and enhances the latent heat storage capability of the system.

Initially, single-layer PCM configurations were assessed by integrating each PCM individually into the brick and comparing their performance to a reference case without PCM (Figure III.2). These preliminary simulations helped identify the PCM with the most favorable thermal regulation. Building on these results, a double-layer configuration was developed by combining two PCMs with different melting temperatures. In this arrangement, the higher-melting PCM was positioned on the exterior, while the lower-melting PCM was placed on the interior side. This sequential activation strategy enables each PCM to respond within its optimal temperature range, enhancing latent heat utilization and contributing to improved indoor temperature stability over daily cycles.

By integrating materials with complementary melting points and modeling coupled conduction and convection processes, the proposed framework provides a robust and comprehensive tool for evaluating the thermal performance of PCM-enhanced hollow bricks under realistic environmental conditions.

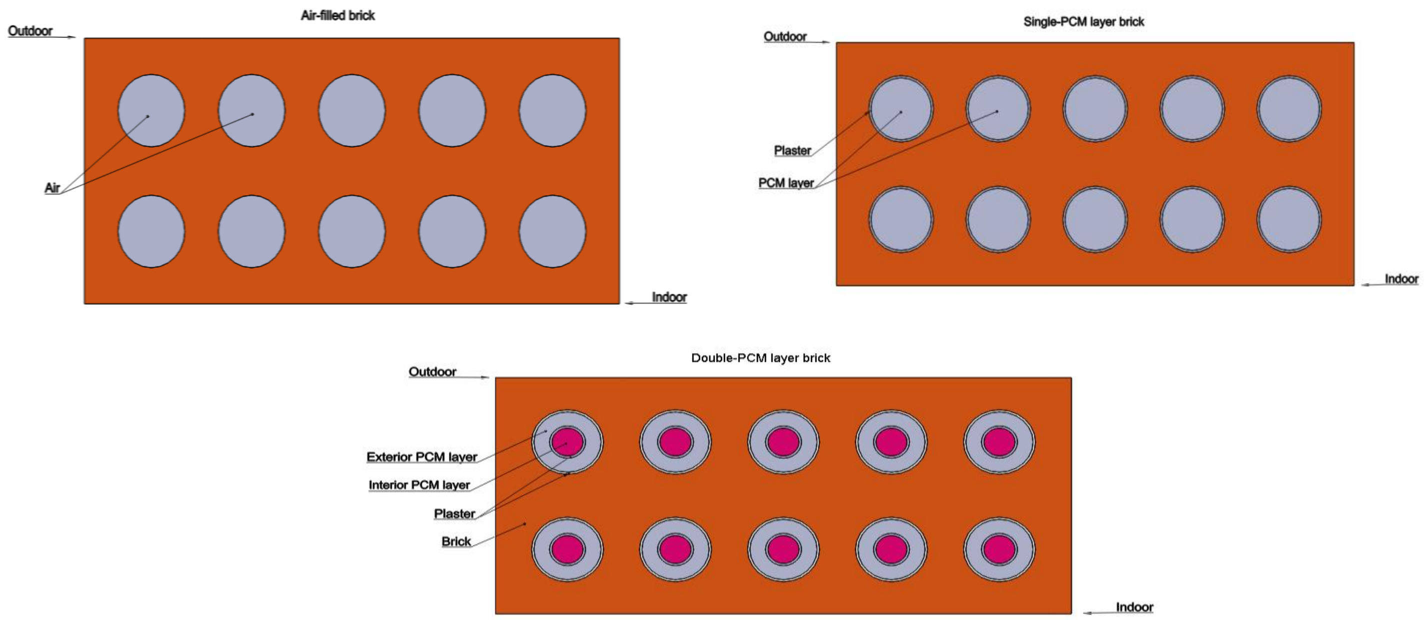


Figure III.2: Illustration of the different hollow clay brick configurations.

III.5.2. Model assumptions and governing equations

To simulate heat transfer and phase change within the hollow bricks containing PCMs, the following assumptions were adopted:

- The problem is treated as two-dimensional and transient, capturing time-dependent thermal responses.
- The PCM in its liquid state is considered a laminar, incompressible, and Newtonian fluid.
- No-slip walls.
- Thermophysical properties of materials are assumed constant, while the PCM’s heat capacity and thermal conductivity are temperature-dependent and vary as piecewise linear.
- Lateral walls are assumed adiabatic, simplifying the analysis by concentrating on heat transfer through the primary wall section.
- Cavity surfaces are treated as diffuse-gray with uniform emissivity, ensuring consistent radiative heat exchange.

Based on the above assumptions, the thermal-fluid behavior of the PCM-integrated brick is governed by the conservation equations of mass, momentum, and energy. These equations describe the evolution of velocity, pressure, temperature, and enthalpy within both the liquid PCM and the surrounding solid regions. In the present work, the governing equations are discretized using the finite-volume method and solved iteratively in ANSYS Fluent under transient conditions. The conservation equations of mass, momentum, and energy can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{III.9}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\,\mu\left(\frac{\partial(u_i)}{\partial x_j} + \frac{\partial\left(u_j\right)}{\partial x_i}\right) + \rho\beta g\Delta T + S_u \tag{III.10}$$

$$\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial x_j}\left(\rho u_j H\right) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) \tag{III.11}$$

Where ρ, u_i, μ, p, β, λ are the density (kg/m^3), the velocity component (m/s), the dynamic viscosity (Pa. s), the pressure (Pa), the coefficient of volumetric thermal expansion (1/°C) and the thermal conductivity (W/m. K), respectively. The term S_u is the source term, it acts as a momentum sink that adjusts the momentum balance according to the local phase state of the material. Its magnitude changes continuously—taking large values that suppress fluid motion in the solid region and gradually decreasing to zero as the PCM becomes fully liquid. S_u is defined as:

$$S_u = A\frac{(1-f)^2}{f^3 + \varepsilon}u_i \tag{III.12}$$

Where f is the liquid volume fraction and A denotes the mushy-zone constant, which varies according to its morphology. Increasing A enhances the damping of velocity within the mushy region, resulting in a sharper solid-liquid transition that tends toward the behavior of a pure material.

Buoyancy is introduced through the Boussinesq approximation, whereby the density is expressed as:

$$\rho = \rho_{ref}[1 - \beta\left(T - T_{ref}\right)] \tag{III.13}$$

For the PCM zone, the phase-change effects are introduced through the enthalpy-porosity formulation previously detailed in section III.3 while for the solid zone, the governing equation can be expressed as follows:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\frac{\lambda_S}{\rho_S C_{P,S}}\frac{\partial T}{\partial x_i}\right) \quad \text{(III.14)}$$

III.5.3. Initial and boundary conditions

To accurately represent the thermal response of the hollow brick under realistic conditions, transient boundary conditions were applied at the exterior surface to account for fluctuating outdoor weather and solar radiation. The brick's outer surface was subjected to both incident solar radiation and convective heat transfer, represented through the sol-air temperature. The corresponding boundary conditions at the exterior surface is given by:

$$-\lambda\frac{\partial T}{\partial x}\,\Big|_{y=H} = h_o\left(T_{sa} - T_{y=H}\right) \quad \text{(III.15)}$$

Where $h_0 = 20$ W/m^2. K is the convective heat transfer coefficient at the outer surface, and T_{sa} denotes the sol-air temperature (*Tsol-air*), which incorporates the combined effects of ambient temperature and outdoor solar radiation. The weather data of the considered city between July 1st and 3rd are presented in Figure III.3, and were derived from a TRNSYS weather data file (TRNSYS, 2021).

The sol-air temperature is calculated according to [140]:

$$T_{sa}(t) = T_{amb} + \frac{\alpha}{h_0}I(t) - \frac{\xi\Delta\mathrm{R}}{h_o} \quad \text{(III.16)}$$

Here, T_{amb} is the ambient temperature, $I(t)$ is the instantaneous solar radiation, α is the solar absorptivity, and $\xi\Delta R/ho$ is the correction factor, taken as 4 °C for horizontal surfaces facing up as recommended by ASHRAE.

For the interior surface, heat exchange was governed by free convection, expressed as:

$$-\lambda\frac{\partial T}{\partial x}\,\Big|_{y=0} = h_i(T_{indoor} - T_{y=0}) \quad \text{(III.17)}$$

With $h_i = 8.3$ W/m^2. K and a maintained indoor temperature of $T_{indoor} = 25$ °C [138].

All remaining boundaries of the brick were considered adiabatic, and the computational domain was initially set to a uniform temperature of 25 °C.

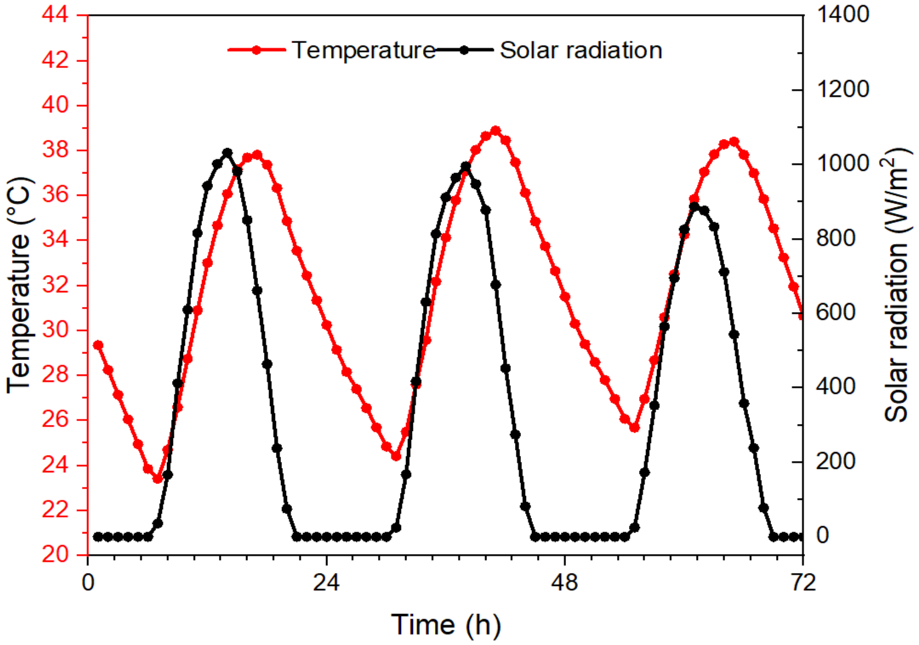


Figure III.3: Diurnal variation of weather conditions in Bechar city.

III.6. Configurations investigated

To further improve the performance of the proposed double-layer PCM configuration, additional simulations were carried out focusing on two key design parameters: the relative position of the two PCMs within the cavity and the distribution of their respective thicknesses. These parametric variations aim to identify the most effective arrangement for enhancing the thermal stabilization capacity of the brick.

III.6.1. Effect of PCM position

The first parametric analysis investigated how the placement of the two PCMs influences the heat transfer process. Starting from the base configuration—where the higher melting temperature PCM (HPCM) is positioned on the exterior side and the lower melting temperature PCM (LPCM) on the interior—an alternative arrangement was created by reversing their locations. Comparing these two arrangements provides insight onto how the sequence of PCM activation during the daily heating cycle affects the overall thermal response of the brick.

III.6.2. Effect of PCM layer thickness

A second investigation addressed how the thickness of PCM layer impacts the thermal performance of the double-layer design. Three thickness distributions were considered: equal thicknesses for both exterior and interior PCM layers, 20 mm for the exterior PCM layer and 10 mm for the interior PCM layer in one scenario, and vice versa in another.

III.7. Thermal performance indices

To assess the effectiveness of PCM integration in improving the dynamic response of the hollow brick, several thermal performance indicators were analyzed. These indices quantify the extent to which the PCM-enhanced configurations improve temperature regulation and mitigate heat transfer toward the indoor environment. The evaluation includes indoor temperature, heat flux, decrement factor, and time lag, each capturing a distinct aspect of the wall’s thermal behavior under transient outdoor conditions.

III.7.1. Indoor temperature and heat flux

Indoor temperature and inner-surface heat flux were analyzed to characterize the fundamental thermal response of the PCM-integrated bricks. Indoor temperature reflects the ability of the PCM-enhanced brick to moderate internal conditions, while the heat flux quantifies the rate at which external heat is transmitted through the wall. Lower heat flux peaks and reduced indoor temperature ranges reflect the enhanced thermal moderation achieved through latent heat effects.

III.7.2. Decrement factor

The decrement factor quantifies how effectively the wall attenuates temperature fluctuations transmitted from the exterior. It measures the relative reduction in the amplitude of the indoor temperature swing compared to that of the reference brick. It is defined as:

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{n,\max} - T_{n,\min}} \tag{III.18}$$

Where f is the decrement factor, $T_{i,max}$ and $T_{i,min}$ are the maximum and minimum indoor temperatures of wall brick with PCM (°C), $T_{n,max}$ and $T_{n,min}$ are the maximum and minimum indoor temperatures of traditional wall brick (°C).

A decrement factor below unity ($f < 1$) indicates effective damping of thermal swings, signifying improved indoor thermal stability.

III.7.3. Time lag

The time lag quantifies the delay between the peak outdoor thermal excitation and the corresponding peak indoor temperature. It is a key indicator of the wall's thermal inertia and its capacity to shift heat gains to later hours, when their impact on comfort or energy demand may be reduced. It can be calculated as follows:

$$\varphi = \tau_{\mathrm{n,max}} - \tau_{\mathrm{i,max}} \qquad \text{(III.19)}$$

Where φ is the peak temperature lag time, $\tau_{n,max}$ is the time of peak indoor temperature for the PCM-integrated brick wall, $\tau_{\mathrm{i,max}}$ is the peak time for the traditional wall brick.

III.8. Computational procedure and model validation

The numerical simulation of the thermal behavior within the PCM-integrated brick was carried out using the ANSYS fluent computational fluid dynamics software. The conservation equations of mass, momentum, and energy, coupled with the phase-change process of the PCM, were solved using the finite volume method. A pressure-based solver was employed with the Semi-Implicit Method for Pressure Linked Equations-Consistent (SIMPLEC) algorithm for pressure-velocity coupling, while the diffusion terms in the momentum and energy equations were discretized using the second-order central-difference scheme to ensure higher accuracy. Radiative heat exchange within the brick domain was modeled using the Surface-to-Surface (S2S) radiation model, while the transient boundary conditions, including solar radiation and ambient temperature variations, were implemented through User-Defined Functions (UDFs) developed within the fluent environment. A time-step size of 1s and a maximum of 20 iterations per time step were used to maintain numerical stability, with convergence achieved when the scaled residuals of all governing equations dropped below 10^{-6}.

To ensure grid-independent results, a mesh dependency test was conducted by comparing the temperature profiles obtained from several grid resolutions. The mesh that provided stable results with negligible variation in the output parameters while maintaining an optimal balance between accuracy and computational efficiency, was selected for all subsequent simulations. The numerical model was further validated to assess the accuracy and reliability of the adopted computational approach. Specifically, validation was performed against the numerical results reported by Hamdaoui et al. [25] by simulating the temperature distribution under similar boundary conditions. As shown in Figure III.6, the two datasets exhibited highly consistent trends, with the maximum relative deviation not exceeding 2.1%. Such agreement confirms that the implemented numerical framework accurately captures the coupled heat-transfer mechanisms governing the system, thereby establishing the robustness and predictive capability of the developed model.

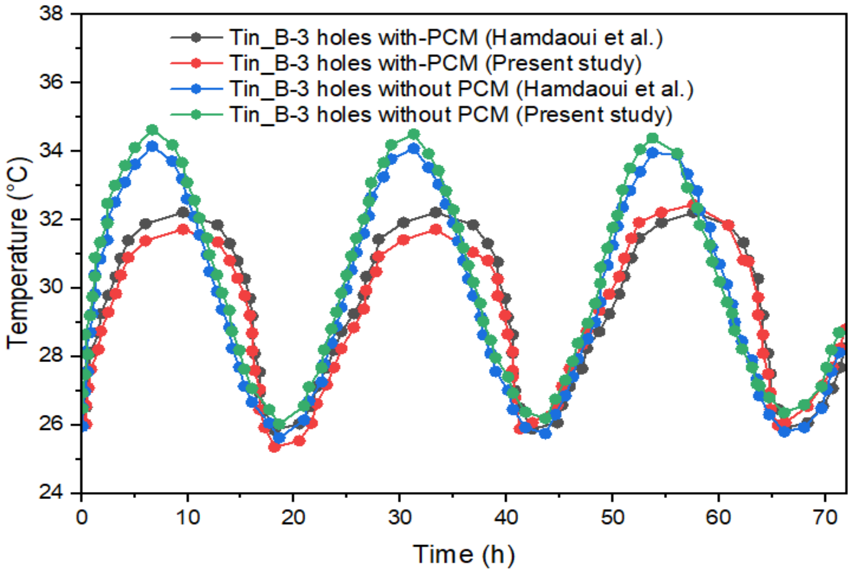


Figure III.4: Validation of the numerical model with Hamdaoui et al. [25].

III.9. Conclusion

The numerical framework presented in this chapter provides a robust and reliable approach for analyzing heat transfer and phase change phenomena in PCM-integrated building materials. By employing a coupled heat transfer and phase change model based on the enthalpy-porosity formulation, the transient thermal behavior of the system ca be accurately captured, including the effects of latent heat storage and natural convection within the molten PCM. The governing conservation equations, model assumptions, and boundary conditions were carefully defined to ensure physical consistency and numerical stability.

The adopted numerical methodology enables systematic investigation of different PCM configurations and integration strategies under realistic thermal loading conditions. The selected thermal performance indices offer meaningful metrics for evaluating the effectiveness of PCM incorporation in building envelopes. Furthermore, the validation procedure confirms the capability of the computational model to reproduce results reported in the literature, thereby establishing confidence in the simulation outcomes. The modeling approach presented in this chapter forms a solid foundation for the parametric analyses and performance assessments discussed in the following chapter.

Chapter IV:

Results and discussion

IV.1. Introduction

This chapter presents and discusses the numerical results obtained from the developed computational model to evaluate the thermal performance of PCM-integrated building elements. The analysis focuses on the transient thermal response under realistic boundary conditions, emphasizing the influence of PCM integration on temperature evolution, heat flux, and overall thermal regulation. The effects of key parameters, including PCM type, double-layer configuration, layer thickness, and position are examined through a comparative assessment of the investigated configurations. The numerical findings are interpreted in light of the underlying heat transfer and phase change mechanisms and are discussed to highlight their physical significance and practical implications for building envelope design.

IV.2. Effect of PCM type on thermal performance

To examine the effect of using different PCM types inside hollow clay bricks, three PCMs—n-Eicosane, RT-42, and RT-27—were selected and integrated separately. Their performance was then compared with that of air-filled bricks in order to evaluate their influence on thermal efficiency under the climatic conditions of Bechar, Algeria. Figure IV.1 presents the inner surface temperature profiles of the bricks with and without PCM, taking into account the variation in ambient temperature and solar radiation. The results clearly show that, regardless of the PCM used, incorporating PCM in the brick cavities improves its thermal behavior. The presence of PCM reduces fluctuations in the inner surface temperature and enhances thermal stability. Among the tested PCMs, the n-Eicosane brick achieved the greatest reduction, keeping the inner surface temperature closer to the desirable comfort range during summer. Peak temperatures were reduced by approximately 3.3 °C, 2.3 °C, and 1.5 °C for n-Eicosane, RT-42, and RT-27, respectively, compared to the traditional air-filled brick, along with a noticeable delay in peak occurrence. Such reductions in peak temperature suggest potential energy savings throughout the daytime period.

The dynamic variations of indoors heat flux when using the three PCMs are depicted in IV.2. Compared with the reference air-filled case, adding PCM effectively lowered and shifted the peak heat flux. The maximum indoor heat flux decreased from 93W/m² in air-filled bricks to approximately 83 W/m², 79 W/m², and 71 W/m² for RT-27, RT-42, and n-Eicosane, respectively. This improvement is mainly due to the low thermal conductivity of PCM and its capacity to absorb heat during melting, which increases the overall thermal resistance of the brick. Thus, integrating PCM into the brick increases its thermal storage capacity, contributing to improved thermal behavior and a smoother distribution of heat loads throughout the day, ultimately lowering cooling demands.

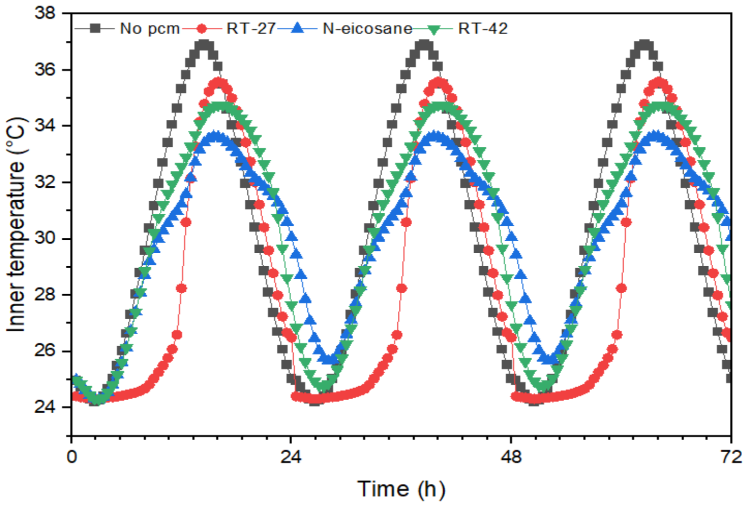


Figure IV. 1: Inner surface temperature evolution for different PCM types.

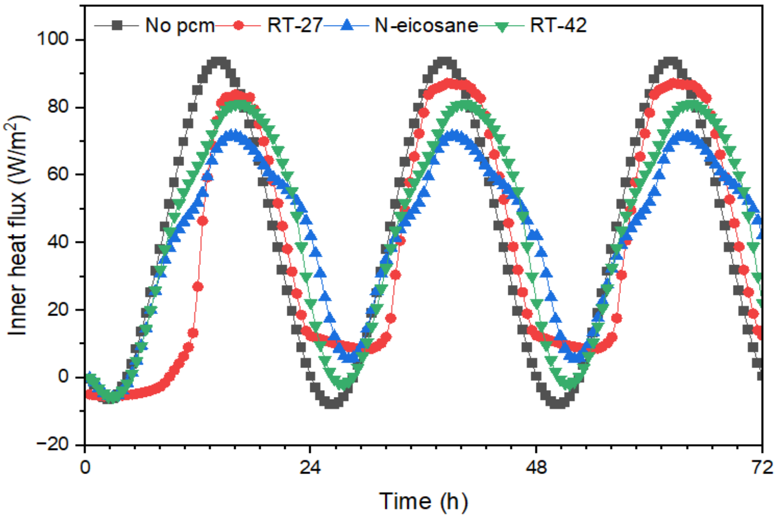


Figure IV.2: Inner heat flux evolution for different PCM types.

IV.3. Effect of double-layer PCM on thermal performance

To assess the performance of the newly developed double-PCM layer brick, n-Eicosane—previously identified as the most effective in the single-PCM layer configuration—was combined with RT-27 in one configuration and with RT-42 in another. In both cases, the PCM with the higher melting temperature was placed on the exterior side. Each PCM layer was encapsulated in 1-mm-thick capsules with a diameter of 15 mm, as shown in Figure III.2. These double-layer configurations were compared with the single-PCM layer and reference air-filled brick to evaluate their influence on the thermal behavior and energy efficiency of the hollow clay brick.

Fig. IV.3 illustrates the transient inner surface temperatures for the different configurations considered in this study. Indeed, the use of two distinct PCM layers significantly reduced temperature fluctuations at the inner surface. While the single-PCM layer (n-Eicosane) brick achieved a reduction of about 3.3 °C, the double-PCM layer resulted in more pronounced reductions: 4.5 °C for the -Eicosane/RT-27 configuration and 3.5 °C for the RT-42/n-Eicosane configuration. Additionally, a noticeable delay in the occurrence of peak temperature was also observed. The superior performance of the n-Eicosane/RT-27 configuration can be attributed to the complementary melting temperatures of the two PCMs, which allow latent heat to be absorbed over a broader temperature range. These findings demonstrate that combining PCMs with distinct thermal properties broadens the effective phase-change range and enhances the brick’s energy-storage capacity, thereby improving indoor temperature regulation and reducing the influence of external heat loads. This ultimately leads to improved overall thermal performance.

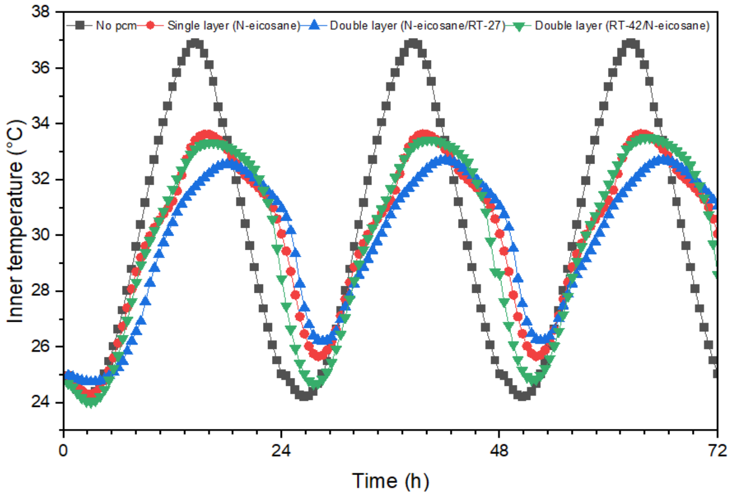


Figure IV.3: Inner surface temperature evolution for different PCM layer configurations.

The transient indoor heat flux for the double-PCM, single-PCM, and air-filled configurations is shown in Fig. IV.4. It is observed that incorporating two PCM layers with distinct melting temperatures substantially reduced the variation of the heat flow through the inner surface by limiting the rate of energy transfer from exterior to the interior. The maximum heat flux decreased by 33.02% and 25.04% for the n-Eicosane/RT-27 and RT-42/n-Eicosane configurations, respectively, compared to the air-filled brick, whereas the single-PCM configuration achieved a 23.48% reduction. This performance is mainly attributed to the increased thermal storage capacity and enhanced thermal inertia provided by the double-PCM layer arrangement. Therefore, integrating a double-PCM layer can effectively decrease cooling-related energy consumption.

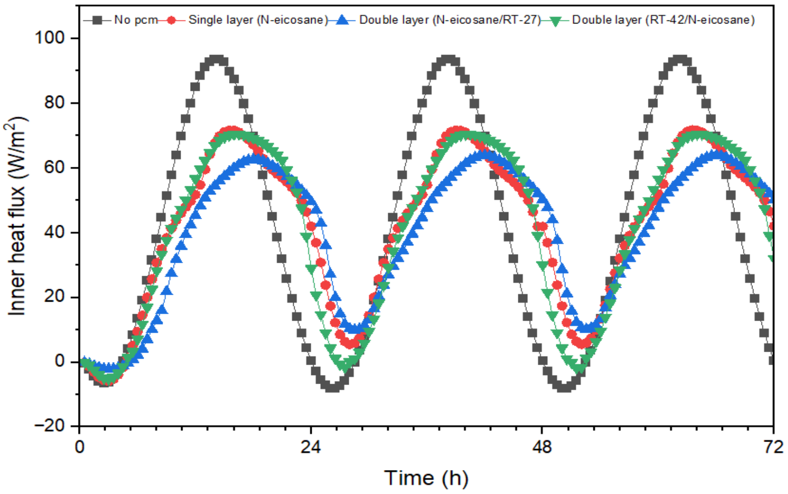


Figure IV.4: Inner heat flux evolution for different PCM layer configurations.

IV.4. Effect of PCM layer thickness on thermal performance

To refine the design of the double-PCM layer system and further enhance its thermal performance, the n-Eicosane/RT-27 configuration—previously identified as the most effective—was selected for detailed parametric study. This analysis focuses on how different PCM layer thicknesses influence the inner surface temperature and heat flux. Three configurations were examined: (i) equal thicknesses for both the exterior (n-Eicosane) and interior (RT-27) layers, (ii) 20 mm for the exterior layer and 10 mm for the interior layer, and (iii) 10 mm for the exterior layer and 20 mm for the interior layer.

The transient inner surface temperature variations of the double-PCM layer brick for different PCM layer thicknesses are depicted in Figure IV.5. The results show that equal-thickness arrangement achieved the greatest reduction in temperature fluctuations, lowering the inner surface temperature by 4.5 °C and significantly delaying the occurrence of the peak temperature. The configuration with thicker exterior layer also showed good performance, achieving a 4.2 °C reduction, likely due to the increased thermal inertia and enhanced heat absorption and dissipation capabilities. In contrast, the configuration with thicker interior PCM layer exhibited reduced effectiveness, indicating that this arrangement is less suitable for mitigating heat transfer toward the indoor environment.

The influence of PCM layer thickness on inner surface heat flux is shown in Figure IV.6. Consistent with the temperature results, the equal-thickness configuration produced the highest reduction in peak heat flux, decreasing it by approximately 33.02%. This was followed by the thicker exterior layer configuration, which achieved a reduction of 31.39% whereas the thicker interior layer configuration resulted in a lower decrease of 25.89%. These results highlight the advantage of balanced PCM distribution, which enhances thermal resistance and improves the overall heat-storage capability of the double-layer system.

Overall, the findings demonstrate the strong dependence of thermal performance on PCM layer thickness in double-layer configurations. They emphasize that an optimized and balanced distribution of PCM layers is key to achieving effective thermal regulation, providing valuable guidance of the design of energy-efficient building components.

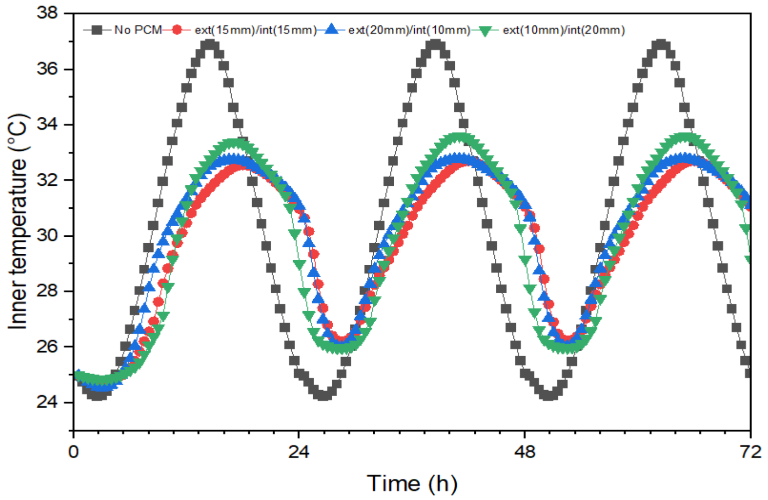


Figure IV.5: Influence of PCM layer thickness on the inner surface temperature.

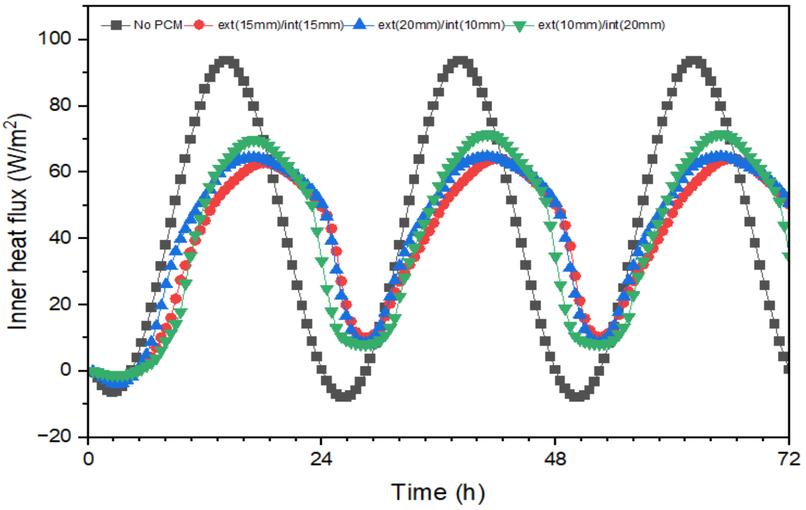


Figure IV.6: Influence of PCM layer thickness on the inner surface heat flux.

IV.5. Effect of PCM layer position on thermal performance

To assess how the arrangement of PCM layers affects the performance of double-PCM layer bricks, two configurations were examined by varying the placement of the high-melting-temperature PCM and the low-melting-temperature PCM. In the first configuration, the HPCM layer was placed on the exterior side and the LPCM on the interior side, whereas in the second configuration, the arrangement was reversed. The results of both configurations were compared with those of air-filled bricks, as illustrated in Figures IV.7 and IV.8.

The findings indicated that positioning the PCM with the higher melting temperature on the exterior side yielded superior thermal performance. This arrangement reduced the maximum inner surface temperature by approximately 4.5 °C, outperforming the configuration where the LPCM was placed externally, which achieved a 3.1 °C reduction compared to the air-filled brick. The improved performance of the exterior HPCM arises from its ability to absorb a larger portion of the incident heat before it reaches the interior, thereby limiting heat penetration and promoting a more gradual thermal exchange. Moreover, the higher thermal inertia of the HPCM enables gradual heat absorption and release, contributing to more effective attenuation of indoor temperature rise.

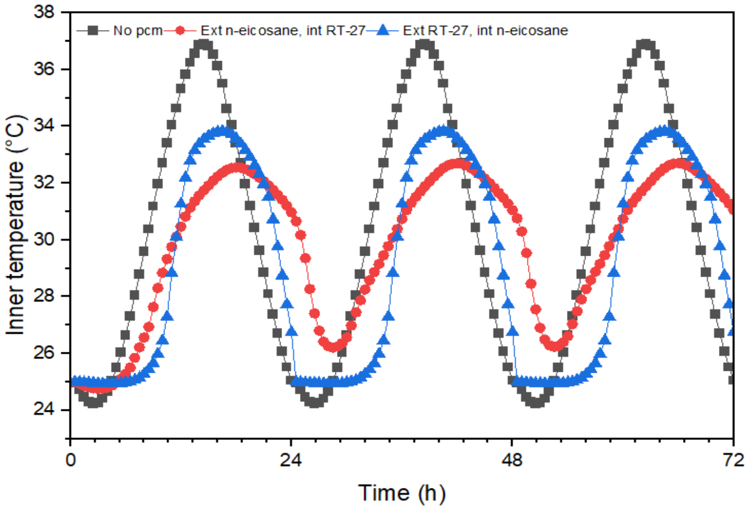


Figure IV.7: Variation of the inner surface temperature for different PCM layer positions.

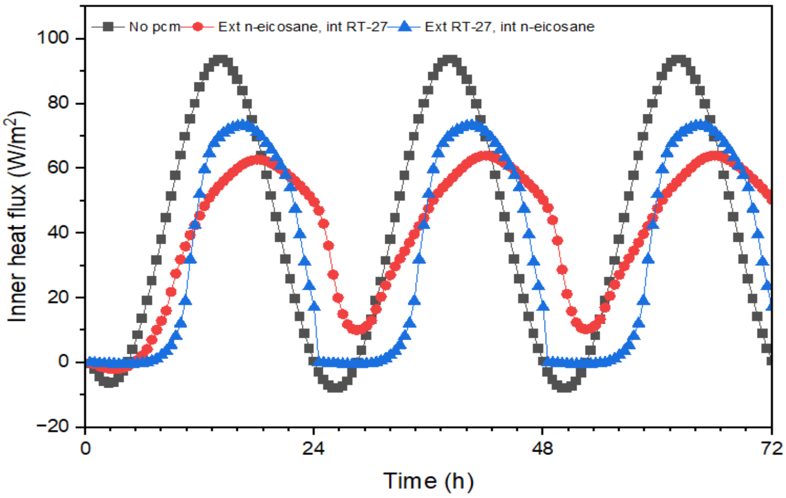


Figure IV.8: Variation of the inner heat flux variations for different PCM layer positions.

The dynamic indoor heat flux for the investigated configurations is shown in Figure IV.8. The results clearly demonstrate that PCM placement significantly influences the reduction in heat flux. The configuration with the HPCM as the exterior layer shows superior performance, reducing the peak indoor heat flux by 33.02%. In comparison, the configuration with the LPCM placed externally achieved a reduction of 21.99%. This performance difference is derived from the alignment of PCM melting temperatures with outdoor thermal conditions, whereby the exterior HPCM acts as a thermal shield against external heat loads while the interior LPCM contributes to internal temperature regulation.

Overall, these findings highlight the critical role of PCM layer positioning in maximizing the effectiveness of double-PCM layer systems. Strategically placing the PCM layer according to their melting temperatures can significantly improve heat attenuation and enhance the overall thermal efficiency of PCM-integrated building envelopes.

IV.6. Liquid fraction evolution of phase change materials

To gain deeper insight into how PCM phase change process influences the overall thermal performance of the considered brick configurations, the liquid fraction evolution of each PCM was evaluated. Figure IV.9 presents the liquid fraction profiles under the defined sol-air temperature boundary conditions for both single- and double-PCM layer arrangements.

In the single-PCM layer configuration, RT-27 showed a stable and complete phase change cycle, with its liquid fraction nearly reaching unity on a daily basis. This behavior indicates that its melting temperature (~27 °C) is well aligned with the local climatic excitation, enabling full exploitation of its latent heat storage capability. In contrast, n-Eicosane and RT-42 reached peak liquid fractions of about 60%, demonstrating that they were indeed activated under the prevailing climatic conditions, though to a reduced extent owing to their higher melting temperatures.

In the double-layer configuration (Figure IV.9 b), where n-Eicosane was positioned on the exterior side and RT-27 on the interior side, a clear sequential phase change behavior was identified. RT-27 consistently exhibited a liquid fraction close to 100%, indicating complete phase transition and effective latent heat utilization over the daily temperature range. Meanwhile, n-Eicosane achieved a peak liquid fraction of around 80%, demonstrating significant contribution to thermal energy storage. This behavior results from the thermal gradient across the brick: The exterior layer (n-Eicosane) absorbed the incoming heat flux and partially melted, thereby moderating heat transfer toward the interior. As the thermal wave penetrated further, the interior layer (RT-27), with its lower melting point, underwent full phase change and effectively regulated the inner surface temperature. This sequential activation ensures an expanded operating range for latent heat storage and more efficient use of both PCMs throughout the daily temperature cycle.

Overall, the double-PCM layer configuration demonstrates superior adaptability to daily temperature fluctuations and provides more effective passive cooling compared to the single-PCM layer configuration. The complementary thermal response of n-Eicosane and RT-27 validates their selection and confirms their potential for passive thermal regulation in hot climatic regions such as Bechar.

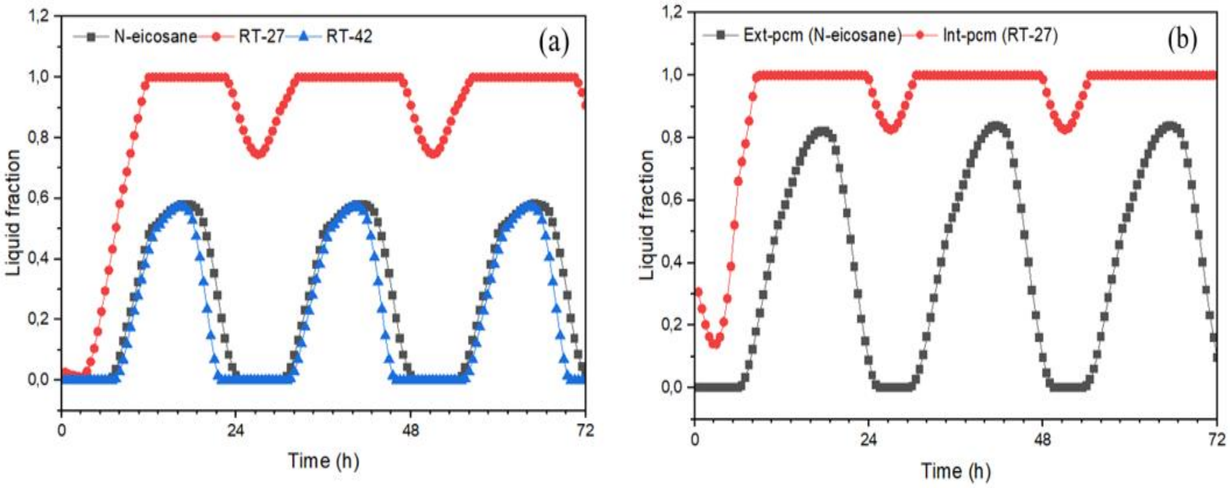


Figure IV.9: Variation of the liquid fraction for: **(a)** the three PCMs in a single-layer configuration, **(b)** the optimal double-layer configuration.

IV.7. Decrement factor and time lag

Time lag and decrement factor are two key indicators for characterizing the thermal inertia and transient thermal behavior of building envelopes subjected to fluctuating outdoor conditions. These parameters are essential for assessing the heat storage capacity of PCM-integrated materials and their effectiveness in attenuating indoor thermal variations. In this study, both parameters were evaluated for bricks incorporating single- and double-PCM layers, with an air-filled brick used as the baseline for comparison.

As illustrated in Figure IV.10, the double-PCM layer configuration (n-Eicosane/RT-27) yielded a decrement factor of 0.62614, indicating a clear improvement over the single-PCM layer configuration, which exhibited a higher value of 0.73609. A lower decrement factor indicates reduced amplitude of indoor temperature fluctuations, reflecting the enhanced thermal regulation capacity provided by the double-PCM layer system.

In terms of time lag, Figure IV.10 indicates that the double-PCM layer delayed the occurrence of the indoor temperature peak by approximately 3.5h, whereas the single-PCM layer achieved a delay of only 1.5h. This substantial increase in time lag reflects the configuration's ability to delay heat penetration into the indoor space, which is particularly advantageous during periods of peak outdoor conditions. Such a delay is pivotal in moderating indoor temperature variations and minimizing cooling energy consumption, reinforcing the suitability of the proposed system for sustainable and climate-responsive building design.

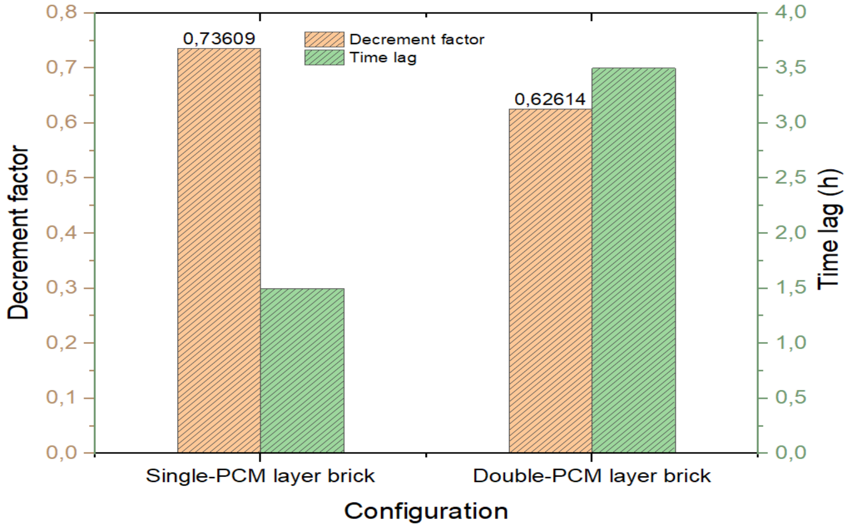


Figure IV.10: Variation of decrement factor and time lag for the studied configurations.

Chapter V:

Conclusions and recommendations for future works

Chapter V: Conclusions and recommendations for future works

V.1. Conclusions

This doctoral research tackled the challenge of improving the thermal inertia of lightweight masonry systems in hot-dry climates without altering conventional construction practices. Focusing on hollow clay bricks, commonly used in North Africa and Saharan regions, the study shifted the focus from full wall assemblies to the brick level, enabling a detailed parametric analysis of heat transfer under realistic climatic conditions. Three PCMs—RT-27, RT-42, and n-Eicosane—were examined in single and double-layer brick configurations using a comprehensive CFD-based modeling framework. The analysis evaluated their effect on indoor temperature regulation, heat flux reduction, and latent heat utilization. Results showed that integrating PCM fundamentally changes the transient thermal behavior of hollow clay bricks. Single-layer PCM brick significantly reduced peak inner surface temperatures and moderated indoor heat flux, with n-Eicosane showing the best performance by lowering peak temperatures by approximately 3.3 °C and considerably reducing maximum heat flux. These findings confirm that PCM integration is an effective passive strategy for enhancing thermal inertia in hot-dry climates.

The study further demonstrated that double-layer PCM configurations outperform single-layer systems in thermal regulation. Combining PCMs with complementary melting temperatures widened the effective phase-change range and improved latent heat utilization throughout the diurnal cycle. The optimal n-Eicosane/RT-27 configuration reduced peak inner surface temperature by up to 4.5 °C and decreased peak indoor heat flux by about 33% compared to the reference brick. Time lag also increased to around 3.5h, while the decrement factor decreased, indicating more effective attenuation of indoor temperature fluctuations. Beyond material selection, the research highlighted key design considerations, including the effects of layer thickness and placement within the brick cavities. Results showed that equal thickness distribution of the two PCM layers maximized heat absorption and release, while positioning the PCM with higher melting temperature on the exterior side produced the most effective reduction in heat transmission toward the indoor environment. These findings provide a clear understanding of the relationship between PCM properties, layer configuration, and climatic conditions.

Overall, the numerical results confirm that optimized double-layer PCM-integrated hollow clay bricks can significantly enhance passive thermal regulation, reduce indoor temperature fluctuations, and shift peak thermal loads. The study provides clear design guidance on PCM selection, layer configuration, and placement, demonstrating the value of CFD-based simulation as a tool for thermal optimization of building materials in hot-dry climates.

V.2. Future Works

Based on the findings of this research, the following directions are recommended for future investigations:

1. **Expanded PCM Combinations**
   Future studies may investigate additional hybrid PCM configurations involving varied melting temperatures and volumetric proportions to further optimize latent heat storage and release across daily and seasonal temperature cycles in hot-dry climates.
2. **Wall-level and Building-Level Simulations**
   The numerical analysis may be extended from brick scale to full wall assemblies and entire building envelopes in order to evaluate the cumulative impact of double-layer PCM-integrated bricks on overall energy demand, thermal inertia, and indoor thermal comfort.
3. **Climatic Adaption Studies**
   Further simulations under different climatic conditions could be conducted to identify optimal PCM selection and layering strategies for various regions, including extreme hot-dry, hot-arid, and transitional climates.
4. **Parametric Sensitivity Analysis and Economic Feasibility**
   A comprehensive parametric sensitivity analysis may be conducted to quantify the relative influence of key PCM thermophysical properties on thermal performance indicators, alongside a life cycle cost analysis (LCCA) to evaluate the economic viability of PCM-integrated hollow clay bricks.

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