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Title of the thesis

Performance prediction and techno-economic analysis of a thermal storage system

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Abstract

In the semi-arid regions, residential buildings with low thermal mass demand less heating energy during intermittent use compared to high thermal mass buildings; this is caused by a shorter preheating period. Although low thermal mass buildings are sensitive to overheating, these problems canbe alleviated, e.g., with stricter blind control strategies or a ppropriate ventilation strategies. Another solution is to increase the building's thermal storage capacity. However, the latter will reduce the low thermal mass benefit of a shorter pre-heating period. Therefore, in this project, we propose a concept with an adaptable storage capacity. The concept combines the benefits of buildings with low and high thermal mass by applying adaptable thermal storage to a lightweight building. The proposed adaptable thermal storage concept consists of phase change materials (PCMs) as thermal storage medium placed above a thermally insulating ceiling. This ceiling can be opened or closed to influence airflow to the PCMs and thus thermally couple or decouple the PCMs from the room. In this project, we investigate the potential of this concept using computational building performance simulation.

Keywords: *Thermal comfort, Buildings, Phase change materials, numerical modeling*

Résumé:

Dans les régions semi-arides, les bâtiments résidentiels à faible masse thermique nécessitent moins d'énergie de chauffage lors d'une utilisation intermittente que les bâtiments à masse thermique élevée ; ceci est dû à une période de préchauffage plus courte. Bien que les bâtiments à faible masse thermique soient sensibles à la surchauffe, ces problèmes peuvent être atténués, par exemple grâce à des stratégies de contrôle des stores plus strictes ou à des stratégies de ventilation appropriées. Une autre solution consiste à augmenter la capacité de stockage thermique du bâtiment. Cependant, cette dernière réduira l'avantage de faible masse thermique d'une période de préchauffage plus courte. Ainsi, dans ce projet, nous proposons un concept avec une capacité de stockage adaptable. Le concept combine les avantages des bâtiments à masse thermique faible et élevée en appliquant un stockage thermique adaptable à un bâtiment léger. Le concept de stockage thermique adaptable proposé consiste en des matériaux à changement de phase (PCM) comme support de stockage thermique placés au-dessus d'un plafond thermiquement isolant. Ce plafond peut être ouvert ou fermé pour influencer le flux d'air vers les PCM et ainsi coupler ou découpler thermiquement les PCM de la pièce. Dans cette thése doctorat, nous étudions le potentiel de ce concept en utilisant la simulation informatique des performances des bâtiments.

Mots clés: *Confort thermique, Bâtiments, Matériaux à changement de phase, modélisation numérique*

خلاصة:

في المناطق شبه القاحلة، تتطلب المباني السكنية ذات الكتلة الحرارية المنخفضة طاقة تسخين أقل أثناء الاستخدام المتقطع مقارنة بالمباني ذات الكتلة الحرارية العالية؛ يحدث هذا بسبب فترة التسخين الأقصر . على الرغم من أن المباني ذات الكتلة الحرارية المنخفضة احق لارتفاع درجة الحرارة، إلا أنه يمكن تخفيف هذه المشكلات، على سبيل المثال، من خلال استراتيجيات التحكم العمياء الأكثر صرامة أو استراتيجيات التهوية المناسبة . الحل الآخر هو زيادة سعة التخزين الحراري للمبنى ومع ذلك، فإن هذا الأخير سوف يقلل من فائدة الكتلة الحرارية المنخفضة لفترة التسخين المسبق الأقصر .لذلك، في هذا المشروع، نقترح مفهومًا بسعة تخزين قابلة للتكيف يجمع هذا المفهوم بين فوائد المباني ذات الكتلة الحرارية المنخفضة والعالية من خلال تطبيق التخزين الحراري القابل للتكيف على مبنى خفيف الوزن يتكون مفهوم التخزين الحراري القابل للتكيف المقترح من مواد متغيرة الطور (PCMs) كوسيلة للتخزين الحراري موضوعة فوق سقف عازل حراريًا . يمكن فتح هذا السقف أو إغلاقه للتأثير على تدفق الهواء إلى PCMs وبالتالي ربط أو فصل PCMs حراريًا عن الغرفة .في هذا مذكرة التخرج نقوم بدراسة إمكانات هذا المفهوم باستخدام محاكاة أداء البناء الحسابية.

الكلمات المفتاحية: الراحة الحرارية، المباني، مواد تغير الطور، النمذجة العددية.

Publications included in the thesis

The present thesis is based on a summary of the following publications:

Journal Papers:

Allam B., Nehari T. « Numerical analysis for energy performance optimization of hollow bricks for roofing. Case study: Hot climate of Algeria» **Journal :** Construction and Building Materials (**Elsevier**), Vol 367, (2023). **DOI:** https://doi.org/10.1016/j.conbuildmat.2023.130336.

Allam B., Nehari T., Benlekkam M.L., « Building brick wall thermal management optimization and temperature control based on phase change materials integration. Case study of the city of Bechar, Algeria». **Journal :** Journal of Energy Storage (Elsevier), Vol 73, (2023). **DOI:** https://doi.org/10.1016/j.est.2023.109043.

Conference papers:

Bachir Allam, Nehari Taieb, Zehouani Assala and Hadjadj Mohammed. The 1st National Conference on Green Energy (NCGE' 2023) . Title: Energy performance of phase change materials integrated into brick wall for cooling load management in residential buildings on a sunny day in Bechar, Algeria.

Bachir Allam, Nehari Taieb, Hadjadj Mohammed, and Zehouani Assala. The 1st International Congress of Environment and Sustainable Development (ICESD1'23). Title: Influence of four types of PCM integrated into a brick on the heat flux passing through the wall of a building on a sunny day in Bechar, Algeria.

Allam Bachir, Nehari Taieb, Zehouani Assala, and Hadjadj Mohammed. 1st International Conference on Hydrocarbons, Renewable Energies, Materials and Environment April 29 – 30, 2023, Adrar, Algeria ICHREME'2023 title: Optimization of heat transfer and temperature control of building brick thermal management based on phase change materials integration.

Bachir Allam, Nehari Taieb, Zehouani Assala and Hadjadj Mohammed. The 1st National Conference on Green Energy (NCGE2023) held at the University of Boumerdes, Algeria on December 02, 2023. Title: Energy performance of phase change materials integrated into brick wall for cooling load management in residential buildings on a sunny day in Bechar, Algeria.

Bachir Allam, Nehari Taieb, Hadjadj Mohammed, and Zehouani Assala. First Seminar on Engineering Materials and Energy Technologies. Title: Investigations on heat transfer properties of building bricks incorporating phase change materials.

Bachir Allam, Nehari Taieb, Hadjadj Mohammed, and Zehouani Assala. The 3rd edition of the international conference on materials science and engineering and their impact on the environment Title: Optimizing thermal management and temperature control of building brick walls through integration of phase change materials: A case study in Bechar city.

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Dedication

To my **parents**

To my brothers

Redhwane, Mohammed, Amine, Zakaria

To my sisters

Fatima Zohra, **Marwa**

To my friends

Abdellah Hammad, Khiri Tariq, Abdel Krim Mansouri, Hakim Negadi

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CHAPTER I: Background and Significance

CHPTER I: Backgraound and significance

I.1. Introduction

In Algeria, the building sector is responsible for the highest energy usage, making up over 41% of the total energy consumption. It has been experiencing an annual growth rate of 4.1% between 2016-2017. In an application for a sustainable development strategy, the recently implemented legal and regulatory frameworks have set forth the objective of decreasing energy usage for heating and cooling purposes in buildings by 40% before the year 2030. This initiative aims to promote sustainable development and reduce the overall environmental impact of buildings. Despite the presence of regulatory frameworks such as Regulatory Technical Document (RTD) C3.2, the majority of building envelopes are not adequately designed to meet climatic requirements. This indicates a significant demand for specific heating and cooling designs tailored to different climate conditions. Due to the unpredictability of energy availability, there is a need for the development of innovative technology and controls that enable the operation of systems even when electricity from renewable sources is not easily accessible [1]. So, there is a worldwide focus on creating systems and technologies that can utilize renewable energy and decrease buildings' reliance on fossil fuels. Undesirable heat transfer through walls, windows, floors, and roofs contributes to a substantial portion of a building's energy consumption. using strategies to reduce heating and cooling loads, and reducing dependence on active energy sources, is essential in enhancing their energy efficiency and sustainability. Developing systems capable of storing and releasing solar thermal energy to reduce the cooling and heating needs of buildings can positively impact indoor thermal comfort and enhance energy efficiency. Thermal insulation and thermal energy storage (TES) have shown great promise as a solution to this problem of energy availability uncertainty[2].

I.2. Thermal energy storage

A long time ago, when constructing traditional buildings, the manufacturing process took into account the climatic conditions. During that time, it was customary to use materials with high thermal mass as a conventional approach to maintain indoor coolness during summers and warmth during winters[3]. Nevertheless, as the population has grown and architectural engineering has advanced, high-rise construction designs that suit human needs better have emerged. As a consequence, traditional building materials with high thermal mass and heat capacity have been replaced by lighter materials that lack these properties. As a result of this change, buildings now require mechanical equipment to fulfill their heating and cooling demands, which comes with significant energy expenses. To address this issue, the adoption of thermal energy storage systems integrated into buildings has been encouraged. This technology demonstrates its effectiveness and potential by reducing energy demand, shifting cooling and heating loads (peak shaving), and improving overall thermal efficiency, all while minimizing harmful greenhouse gas emissions. This advancement showcase its capability to contribute to sustainable energy practices and environmental conservation. Moreover, the utilization of this technology is expected to play a crucial role in addressing the challenges of climate change and promoting energy efficiency in building sector.[4]. TES plays an essential role in enabling buildings to achieve Energy Flexibility[5]. Thermal energy storage can be classified into three categories: sensible heat storage, latent heat storage, and thermal chemical heat storage (see Figure I.1. below). Latent heat storage techniques are the most common method among the three TES methods for buildings due to their ability to be simply integrated into the system. The main reasons for its popularity are the high energy storage capacity and the ability to store energy at a constant temperaturare[6].

Phase change materials have demonstrated significant potential as a means of the thermal energy storage and regulating building temperatures, thereby reducing fluctuations. Consequently, numerous researchers have directed their efforts toward the integration of PCMs into building structures. Recent studies have focused on identifying the most suitable PCM for building constructions, as well as the optimal methods and dimensions for integration.

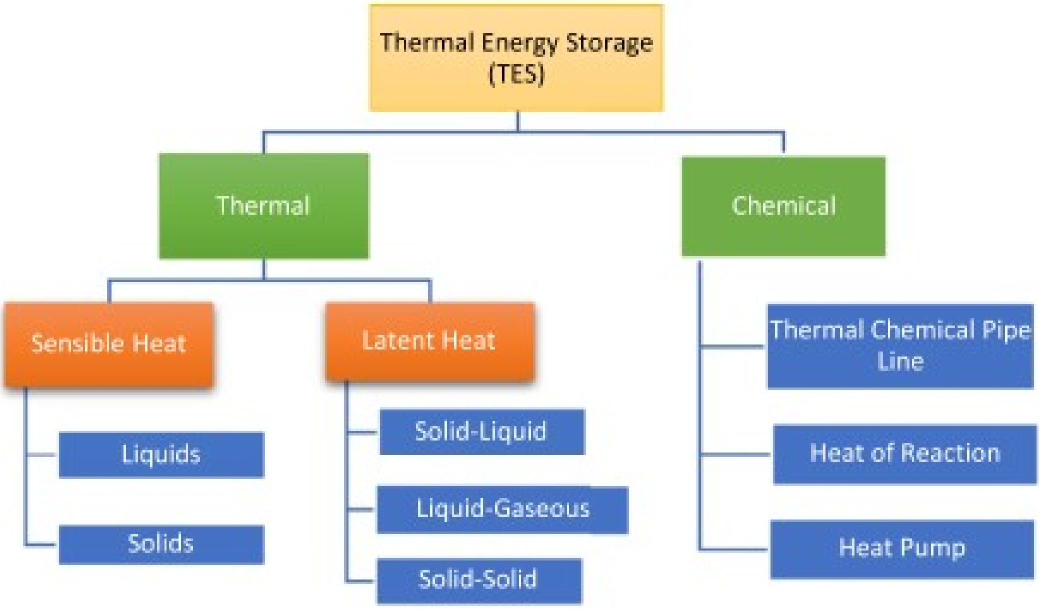


Figure I.1 Different methods for thermal energy storage [7]

I.3. **Phase Chang Materials (PCMs) in general**

In the last decade, PCM has played a significant role in the thermal regulation of a variety of industries. These sectors include aerospace, clothing, defense, agriculture, electricity generation, refrigeration technology, and electronics, as depicted in the Figure. I.2. Additionally, PCMs are used in buildings to decrease energy consumption and improve indoor comfort levels. At present, PCMs are widely utilized in the practical realization of buildings with net-zero energy consumption. This adoption carries considerable economic and social advantages, positively impacting society by conserving energy and preserving the environment [8].

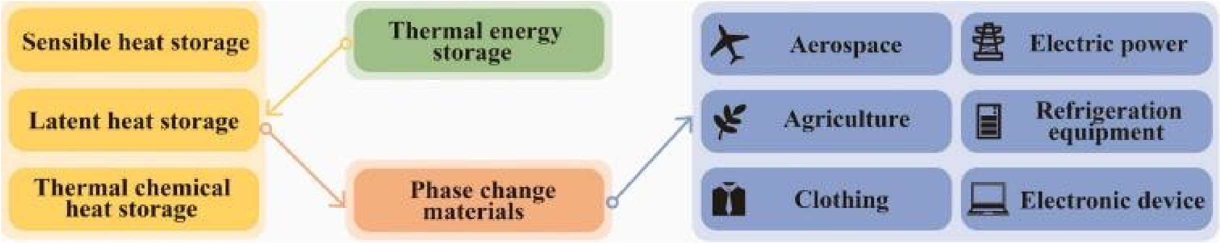


Figure. I.2. The application fields of PCM[8].

PCMs are referred to as "latent" heat storage materials as they undergo an iso-thermal phase change between solid and liquid states. This change occurs when a substance melts (heat storage) or solidifies (recovery of crystallization). In the process of changing from a solid to a liquid state, PCMs store thermal energy through an endothermic process. This process involves the dissolution of chemical bonds within the PCM. Subsequently, the PCM releases the stored thermal energy exothermically when it is cooled, causing it to revert back to its solid state[3][9][10]. The analogous phase change of PCM is illustrated in Figure I.3. The storage capability of these materials can be represented by equations (I.1) and (I.2) [11]. PCMs have the remarkable capacity to maintain constant temperatures by absorbing and releasing large amounts of latent heat during phase transitions. This property allows them to regulate temperature effectively in various applications. Additionally, PCMs exhibit a high energy storage density, making them highly efficient for thermal management and energy conservation. Their ability to store and release heat over repeated cycles without significant degradation further enhances their suitability for use in a wide range of industries, including building construction, electronics cooling, and renewable energy systems. Integrating PCMs into building envelopes serves to cushion against daily temperature fluctuations. PCMs offer benefits in terms of shifting peak loads for heating and cooling, enhancing indoor thermal comfort, and mitigating environmental impact through reduced energy demand in buildings[12].

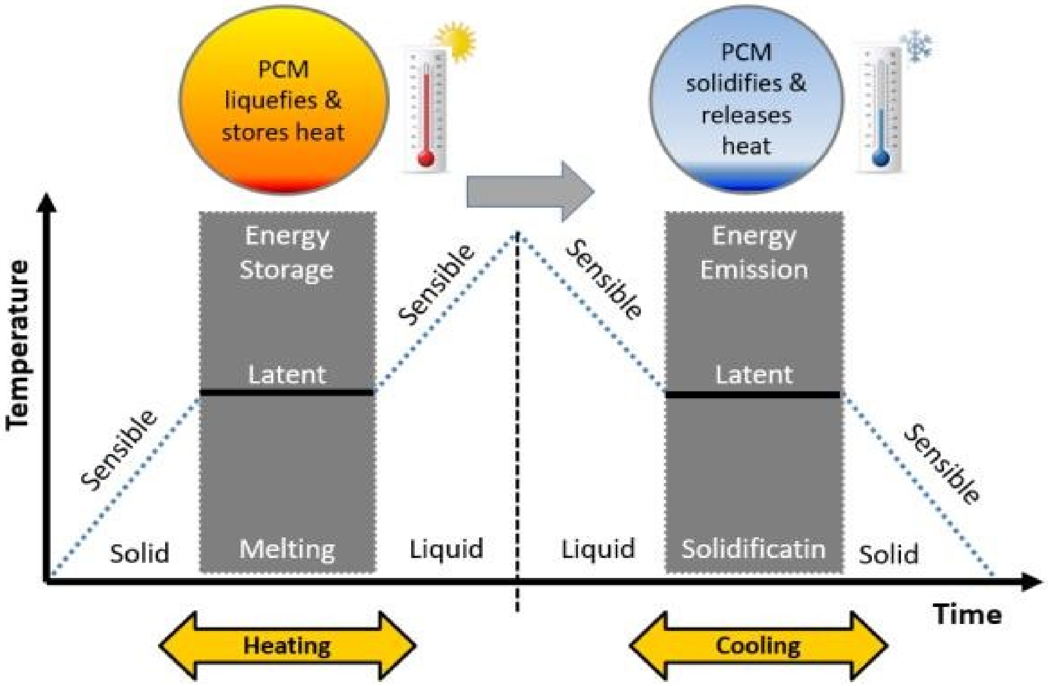


Figure I.3. PCM phase change transition.

$$Q=\int_{T_i}^{T_m} mC_P dT + m\Delta h_m + \int_{T_m}^{T_f} mC_P dT \quad \text{(I.1)}$$

$$Q=m[C_{sp}(T_m - T_i) + \Delta h_m + C_{lp}(T_f - T_m)] \quad \text{(I.2)}$$

Where m is the amount of heat storage medium (kg), Δh_m is the heat of fusion per unit mass (J/kg), T_m is the melting temperature of the PCM (°C), C_{sp} (J/kg·°C) is the average specific heat between T_i and T_m, and C_{lp} is the average specific heat between T_m and T_f (J/kg).

I.3.1 PCM properties

PCMs exhibit various properties associated with a transition between solid and liquid states[13]. When selecting PCMs for use as materials in latent heat thermal energy storage systems (LHTES) within buildings, there are several important factors that need to be carefully considered and thoroughly examined. Process for choosing the appropriate PCM depends on several established guidelines. The first step is to determine the desired melting temperature. It is recommended that the melting temperature range for building applications falls within 15–30 °C[14] or 20–32 °C [3], as these ranges align with thermal comfort standards. According to Sharma et al[13], PCMs exhibit a variety of thermo-physical, chemical, and kinetic properties. Low heat conductivity, presence in both liquid and solid phases, and accelerated energy charging and discharging times are a few examples of the thermophysical characteristics of PCMs. Sharma et al[13]. Also provide some examples of chemical properties, including stability under various conditions and no signs of degradation even after numerous freezing and melting cycles. Nonetheless, PCMs need to possess particular anticipated attributes in the field of thermo-physical, kinetic, chemical, technical, and economic properties, as detailed below[15][16][17][18]:

I.3.2 Thermo-physical properties

In addition to maintaining an optimal temperature range, PCMs should possess several key characteristics to enhance their efficiency and reliability. These include a substantial latent heat of fusion, which allows for the storage and release of significant amounts of energy during phase transitions. PCMs should also have a high specific heat capacity to absorb and store heat without undergoing a large temperature change. High thermal conductivity is essential to ensure efficient heat transfer within the material. Furthermore, PCMs should exhibit high density to maximize the amount of energy stored per unit volume. Limited volume variation during phase change is important to avoid structural damage or containment issues. Low vapor pressure at working temperatures is crucial to prevent material loss and maintain safety. Lastly, consistent melting behavior ensures predictable performance and reliability over multiple thermal cycles. These combined properties make PCMs highly effective for thermal energy storage and temperature regulation in building application.

Most PCMs have low thermal conductivity, typically around 0.2 $Wm^{-1} K^{-1}$ for paraffin and 0.5 $Wm^{-1} K^{-1}$ for salt hydrates, which limits their usage. The Figure I.4 illustrates the general distribution trend of thermal conductivity of PCMs. The low thermal conductivity of PCMs reduces heat transfer rates, resulting in longer charging and discharging times in TES systems. Solar heating during the day and natural cooling at night are utilized for the charging and discharging of thermal energy in buildings, following a 24-hour cycle. PCMs exhibiting low thermal conductivity might not effectively utilize their latent heat capacity, potentially necessitating slower rates of charging or discharging throughout the day. In recent years, there has been a growing emphasis on enhancing the thermal conductivity of PCMs for their application in building structures. This emphasis is driven by the need for more efficient and sustainable energy use in buildings [19][20][21][22][23]. Various methods have been explored to improve the thermal conductivity of PCMs, and these methods can be broadly categorized into two groups: the integration of additives, such as nanoparticles, with high thermal conductivity, and the augmentation of surface area through PCM encapsulation. The enhancement of thermal conductivity in PCMs is of critical importance for improving the overall energy efficiency of buildings. By developing a deeper understanding of the mechanisms and materials involved in enhancing thermal conductivity, we can contribute to the development of more effective building materials that promote energy conservation and sustainability.

Numerous studies[24][25] indicate that PCM thermal conductivity has negligible influence on interior temperature fluctuations. Additional research is necessary to establish the suitable thermal conductivity of PCM in buildings across diverse climatic conditions, as conflicting information currently exists.

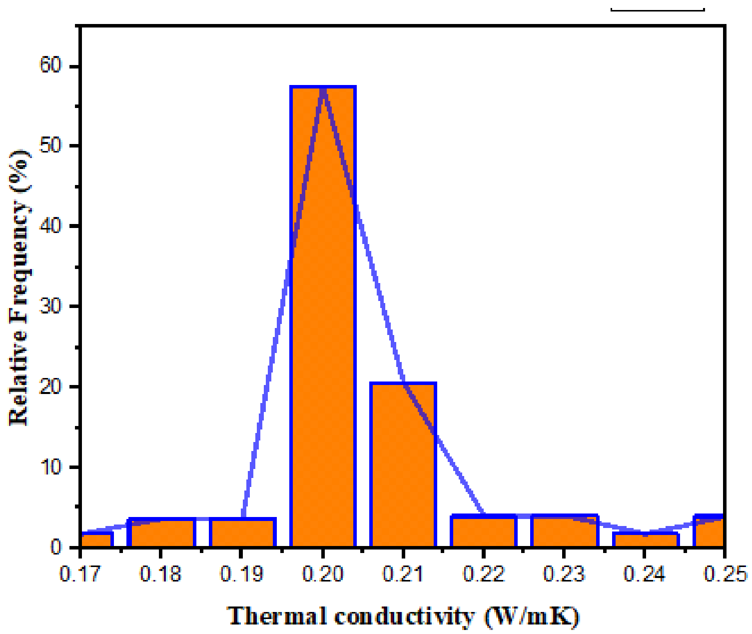


Figure I.4. summarizes the thermal conductivity of PCMs in building applications.

To passively manage the temperature of a building, PCMs function as a barrier against heat transfer from outside the building. During the day, as temperatures exceed their melting point, phase-change materials (PCMs) absorb and store substantial amounts of latent heat by transitioning from a solid to a liquid state. Later, when external temperatures drop below the PCM's solidification temperature, usually at night, this stored heat is gradually released as the material reverts to its solid form. The selection of an appropriate melting temperature is a critical factor for PCMs, as it directly influences their effectiveness in enhancing building energy efficiency. By maintaining a stable indoor climate and reducing the need for additional heating or cooling, PCMs can significantly contribute to energy savings and improved thermal comfort within buildings. When it comes to building applications the PCM melting point should be in close to the human thermal comfort range, particularly when the PCM is integrated into the inner inside of the building envelope [26][27].

I.3.2.1 *Kinetic properties*

Incorporate two critical elements: a high nucleation rate to prevent supercooling of the liquid phase and a rapid crystal growth rate to fulfill heat recovery requirements from the storage system.

I.3.2.2 *Chemical properties*

Involve a fully reversible cycle, chemical stability without any degradation after numerous freezing and melting cycles, compatibility with construction and encapsulation materials, non-corrosiveness, non-toxicity, non-explosiveness, and non-flammability.

I.3.2.3 *Environmental properties*

Minimal environmental impact, causing no pollution throughout its service life, and having potentially recyclable.

I.3.2.4 *Economic properties*

The economic effectiveness of utilizing a TES system is determined by the number of melting/freezing cycles it undergoes. Several research studies[28][29][30] have been conducted to investigate the long-term stability of various PCMs It is crucial to recognize that extending the operational lifespan of a TES system in building applications necessitates a thorough understanding of the thermal durability of PCMs. This durability must be validated through rigorous thermal cycling tests. These tests involve repeatedly heating and cooling the PCM to ensure it can withstand numerous phase transitions without significant degradation.

I.4. **PCM Types**

Various substances can serve as PCMs. They are typically categorized into organic, inorganic, and eutectic PCMs. futher categorizations are established according to their distinct components, as illustrated in Figure I.5. And Figure I.6. offers a comparison of the melting temperatures and enthalpy for the most common materials used as PCMs [31]. Determining the operational range of each PCM is crucial to ensure it aligns with the requirements, taking into account its thermal capacity at the same time[32]. Moreover, PCMs can be classified into three categories based on the temperature ranges at which the phase change occurs. The first group consists of low-melting temperature PCMs, with phase change temperatures under 15 °C, typically utilized in applications such as air conditioning and the food industry. The second category includes mid-temperature PCMs, which are the most commonly utilized, featuring phase transition temperatures ranging from 15 to 90 °C. These find applications in solar, medical, textile, electronic, and energy-efficient solutions for building design. The third category consists of high-temperature PCMs having a phase transition above 90 °C, which are largely used for industrial and aerospace applications. PCMs may also be categorized by the method of phase change, which includes gas-liquid, solid-gas, solid-liquid, and solid-solid systems.

Although PCMs with high latent heat are beneficial, those that undergo a solid-gas or liquid-gas phase change in TES systems are restricted in their applications due to significant volume changes during the phase transition. Solid-solid and solid-liquid transitions result in significantly smaller volume variations, typically around 10% or less. This characteristic allows them to be economically and practically attractive as materials for TES systems, regardless of their lower heat of phase change. Solid-solid PCMs utilize the heat generated during the change from one crystalline form to another and could serve as an acceptable substitute for solid-liquid PCMs. Typically, solid-solid PCMs possess a lower phase transition heat compared to solid-liquid PCMs. This means they store and release less energy during their phase change process. However, solid-solid PCMs offer a distinct advantage: they can prevent the leakage issues that frequently occur with solid-liquid PCMs when temperatures exceed the phase transition point. This leakage is a significant technical challenge, as it can lead to material loss, reduced efficiency, and potential damage to the surrounding structure. By avoiding these leakage problems, solid-solid PCMs provide a more stable and reliable option for thermal energy storage, making them particularly suitable for applications where maintaining the integrity of the PCM is critical. Additionally, the use of solid-solid PCMs can simplify system design and reduce maintenance requirements, further enhancing their practicality and appeal in various building and industrial applications [11].

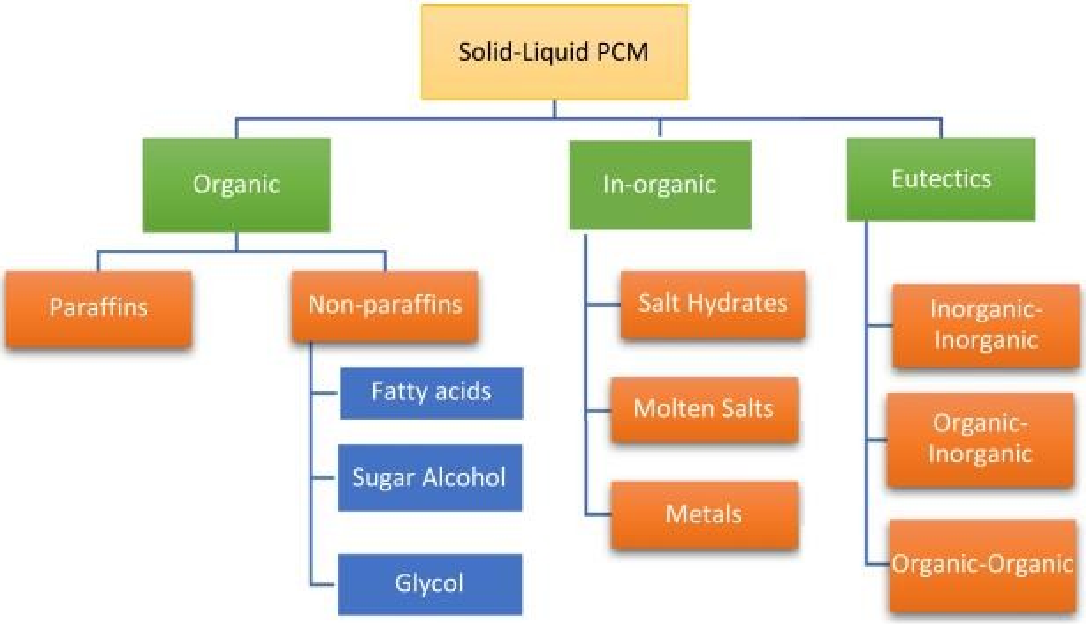


Figure I.5. Classifications of PCMs [32]

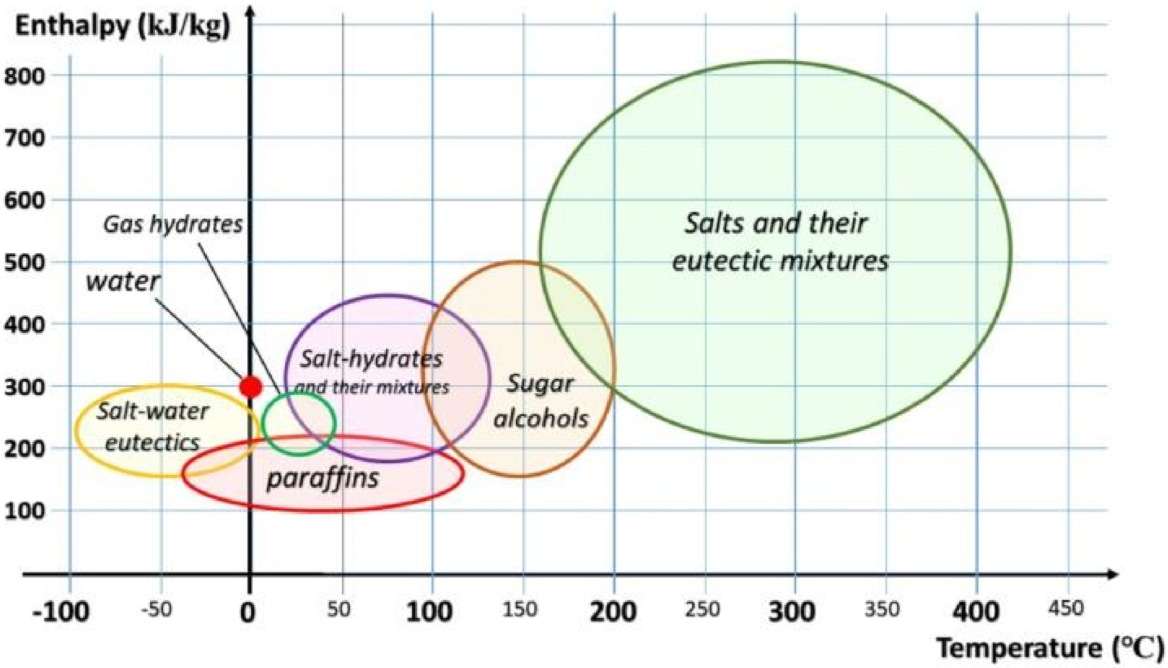


Figure I.6. Melting enthalpy versus melting temperature of various PCMs [32]

I.4.1 Organic

Organic PCMs, both paraffins and non-paraffins, exhibit congruent melting, meaning they can melt and freeze repeatedly without experiencing phase segregation. They also demonstrate self-nucleation, crystallizing with little or no super-cooling, and are typically non-corrosive[33]. Paraffins, as depicted in Figure I.6. encompass a wide temperature range, allowing for their application in diverse fields beyond those associated with construction. The latent heat is dependent on mass, and these materials show no signs of phase segregation even after undergoing multiple cycles of solid-liquid transitions. Moreover, they have low vapor pressure. However, despite these advantages, paraffins used as PCMs have certain drawbacks. They have low thermal conductivity, approximately 0.2 W/(m K), are not compatible with plastic containers, and exhibit moderate flammability [13].

I.4.2 Inorganic

Inorganic PCMs mainly comprise substances such as salt hydrates, which are the most commonly used, as well as molten salts and metals. These materials are characterized by high density and greater energy efficiency compared to their organic counterparts. Inorganic PCMs also provide a range of benefits, Including a wider range of transition temperatures., high latent heat, and high thermal conductivity. Moreover, they are non-toxic, non-flammable, and generally more cost-effective than organic PCMs [15][34]. However, these benefits are counterbalance by some severe disadvantages. Inorganic PCMs can suffer from supercooling, which prevents them from solidifying at the expected temperature, leading to inefficiencies. They also often exhibit a lack of thermal stability and phase segregation, where the material components separate, reducing effectiveness over time. Additionally, issues such as corrosion and decomposition further complicate their use, potentially limiting their long-term reliability and performance in various applications. Despite these challenges, the high energy storage capacity and safety benefits of inorganic PCMs make them a valuable option for thermal energy storage systems, provided that the associated technical issues can be effectively managed [35].

I.4.3 Eutectic

A eutectic mixture represents the specific composition of two or more components at which the mixture exhibits a consistent and uniform melting and solidification behavior. Each constituent in a eutectic mixture melts and solidifies at the same temperature, known as the eutectic point. This characteristic ensures that during the phase transition from liquid to solid, the components crystallize simultaneously, forming a homogeneous and interconnected microstructure of crystals with no phase separation. The formation of a eutectic mixture involves the careful combination of its ingredients, resulting in unique properties that are distinct from those of the individual components. The eutectic composition can consist of various combinations of substances, including organic-organic, inorganic-inorganic, and organic-inorganic mixtures. With this flexibility, eutectic systems may be modified to produce the appropriate thermal and physical properties for specific application. For instance, in thermal energy storage, eutectic mixtures can be designed to have optimal melting points and thermal conductivities that match the requirements of the application, whether it involves heating, cooling, or maintaining stable temperatures.

Eutectic mixes are advantageous when aiming for specific properties, such as a higher heat storage capacity per unit volume or a particular melting point. While eutectic PCMs have convoked substantial attention from researchers in the past decade, their application LHTES systems is not as strongly established as that of pure compound PCMs. The study of the thermos-physical properties of eutectics remains an area that requires further exploration, as numerous combinations have not yet undergone testing and validation[36][37][38][39]. Table I.1 provides a concise overview the advantages and drawbacks of the various PCM types

Table I.1. Overview of the advantages and disadvantages of three different PCM categories[32]

Organic PCM		In-organic PCM		Eutectic PCM	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
• No super-cooling • No phase segre-gation • Low vapor pressure • Large temperature range • Self-nucleating • Compatible with conventional cons-truction materials • Chemically stable • Recyclable • High heat of fusion	• Flammable • Low thermal condu-ctivity • Low volum-etric latent heat storage capacity	• Higher thermal conductivity than organics • Low cost • Not flammable • Sharp phase change • High volumetric latent heat storage capacity • Low volume change	• Corrosive to metals • Super-cooling • Phase seg-regation • Congruent melting • High volume chang	• Sharp melting point • Properties can be tailored to match specific requirements • High volumetric thermal storage density	• Limited data on thermophysical properties for many combinations • High cost

I.5. **Integration of PCM within building structures**

LHS methods are the most widely utilized among the three primary thermal energy storage systems for building applications. This popularity is largely due to the high energy storage capacity and the capability of PCMs to maintain a constant temperature throughout the storage process. These attributes make LHS methods particularly effective when integrating PCMs into building systems. However, finding materials with melting points that are within the operating range of buildings and possess the necessary thermophysical properties to be effective TES solutions is a challenge. Many materials fail to meet these criteria, making it difficult to implement efficient TES systems using a single material. To address these challenges, researchers have explored the combination of different materials in various ratios to create eutectic mixtures or composite PCMs. These engineered materials can be suitible to achieve the desired melting points and enhance thermal properties such as conductivity, stability, and specific heat capacity. Additionally, modifying the structure of the TES system itself such as by incorporating advanced heat transfer mechanisms or using encapsulation techniques can further improve the performance and reliability of the storage system. By optimizing the material composition and system design, it is possible to overcome the limitations of individual PCMs and develop effective TES solutions that can significantly enhance the energy efficiency of buildings. This approach not only maximizes the storage capacity and thermal regulation but also ensures long-term durability and operational effectiveness, making latent heat storage a highly attractive option for modern building applications.

A high enthalpy of phase change per unit mass, the ability to completely reverse the phase change, an appropriate phase change temperature, chemical stability, compatibility with the container, minimal volume changes during the phase change, non-flammability, and non-toxicity are among the desired properties that solid-liquid and solid-solid PCMs must exhibit. Additionally, the material must be affordable and readily available. Figure. I.7. illustrates the favorable characteristics of PCMs suitable for building applications [6].

PCMs can be utilized in both new buildings projects and existing buildings undergoing retrofitting [32]. PCMs can be incorporated into building walls through various methods. These methods include directly integrating shape-stabilized PCM, encapsulating PCM on a smaller scale through various physical and chemical techniques, encapsulating PCM on a larger scale using metal or plastic containers, and incorporating them into porous building materials such as bricks or blocks. In specific situations, PCM could be incorporated into brick cavities with suitable encapsulation, or it can be integrated into the wall in one or more separate PCM layers. Moreover, PCM could be integrated into building materials such as cement mortar, gypsum, and concrete. Integrating PCM into bricks or building walls could be accomplished through five different methods: direct integration, immersion, micro or macro-encapsulation, shape-stabilized PCMs, and foam-stabilized PCM composites [6].

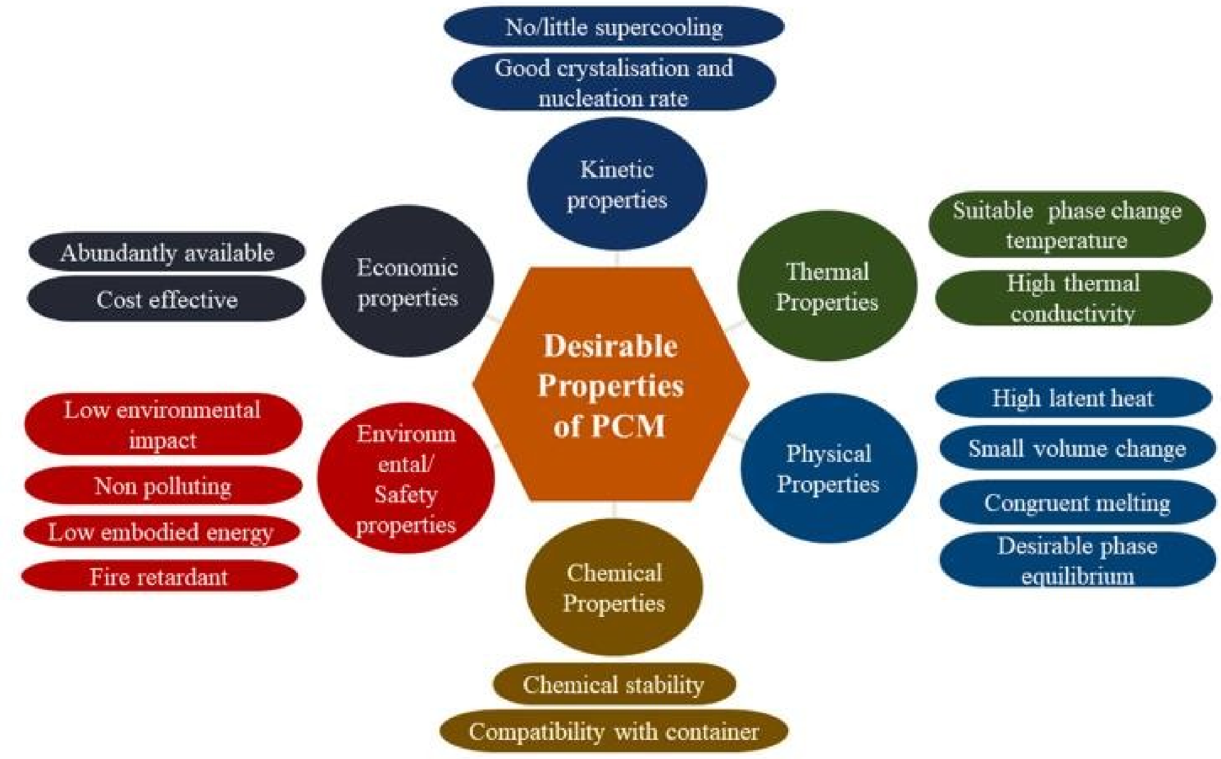


Figure. I.7. illustrates the preferred properties of PCMs for building use[6].

I.6. **Phase change materials in building applications**

PCM-TES systems can be employed for heating, cooling, or both heating and cooling, the latter being known as hybrid systems. These techniques are further categorized into four categories:

- Free cooling.
- Passive building systems.

- Active building systems.
- Peak load shifting.

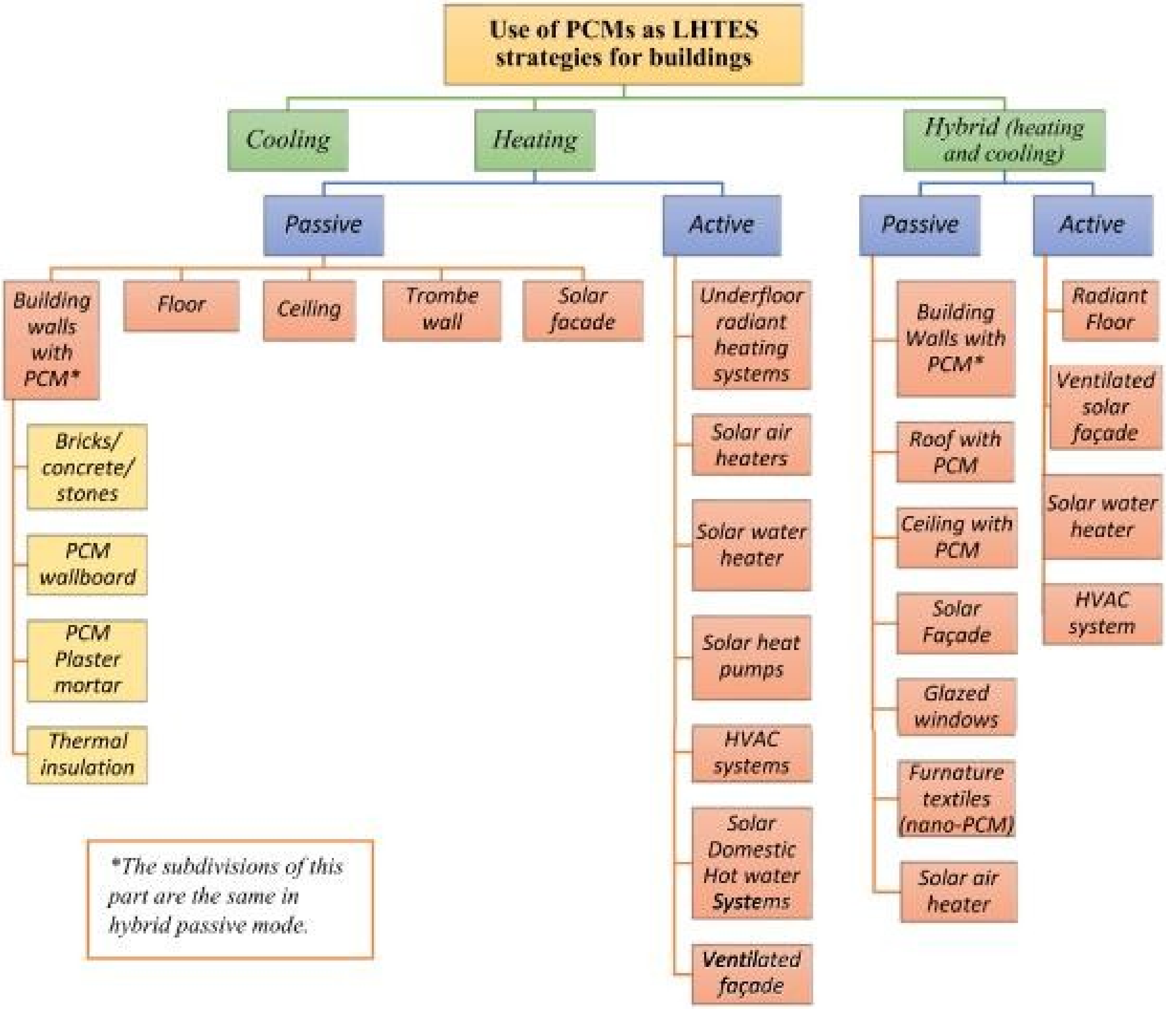


Figure. I.8. Illustration outlining the application of PCM-TES in buildings[32].

I.6.1 Free cooling

PCMs-based free cooling systems operate by storing outdoor cool air for example, during the night and subsequently releasing it indoors during the day. The PCM can be employed to extract heat from passing air within a ventilation system or from water in a pipe system. This heat is then stored as latent energy and utilized to cool the building when temperatures are higher and cooling is required. These systems function effectively provided that the ambient temperature allows the PCM to undergo freezing and melting cycles throughout the day; in other words, the outdoor temperature should be higher than the phase change temperature during the day and lower at night[40].

I.6.2 Passive building systems.

Passive heating or cooling systems are technologies or design elements that control the temperature of buildings without the need for active mechanical devices, using little to no external energy. Research on passive energy storage for greenhouse heating has been conducted in Japan, the United States, and Germany since the 1980s. Initial experiments involved the use of $CaC_{12}•6H_2O$, later succeeded by $Na_2SO_4•10H_2O$, PEG, and paraffins. Nonetheless, it was demonstrated that PCMs could serve double purposes in greenhouses by storing energy and regulating humidity. This approach proved to be effective in energy management as long as the appropriate system design was selected[11].

PCMs are incorporated into building structures for passive applications to enhance thermal mass, which is particularly beneficial since lightweight structures have lower thermal inertia. These buildings commonly face a notable problem of significant temperature fluctuations during summer, resulting from excessive overheating due to insufficient thermal mass. This is particularly evident in colder climates, where buildings are constructed in accordance with passive house standards. These standards often require substantial insulation to reduce the need for heating or cooling in both winter and summer[31].

I.6.3 Active building systems

Active PCM-TES systems, on the other hand, use mechanical devices such as pumps, fans, or heat exchangers to facilitate the transfer of thermal energy. These active systems can be more precisely controlled and are often integrated into HVAC systems to enhance their efficiency. They do this by storing additional thermal energy when it is available and releasing it when needed to assist with heating or cooling demands. This allows the HVAC systems to reduce peak loads and operate more efficiently by utilizing stored thermal energy during high demand periods. These systems include electrical heating systems, solar water heaters, solar air heaters, ventilated facades, solar heat pumps, heat exchangers, heating, as well as solar domestic hot water systems. When these systems are combined, they can achieve a reduction in peak loads. Moreover, with enhanced efficiency, they can earn additional savings by reducing the electrical demand for HVAC systems[32].

I.6.4 Peak load shifting

Peak energy demands during certain times of the day place significant stress on the electrical network and require HVAC systems to be oversized to handle higher heating or cooling loads. Ultimately, this can necessitate the construction of additional power generation facilities to meet these peak demands. Peak load shifting aims to redistribute energy consumption from high-demand periods to low-demand periods, thereby alleviating the load on the energy system during peak hours, such as hot summer afternoons or cold winter mornings. PCMs can shift peak loads away from the hours of highest electrical demand. By storing thermal energy in PCMs during off-peak periods and releasing it during peak hours, the peak load can be flattened and spread out over the course of the day. This reduces the extreme high peaks that would otherwise occur. Peak load shifting using PCMs allows for more efficient utilization of existing power generation and distribution infrastructure, potentially deferring or eliminating the need for constructing new facilities solely to meet short-duration peak demands.

Furthermore, by reducing strain on the grid during peak periods, PCM-enabled peak load shifting can improve overall energy efficiency, reduce greenhouse gas emissions from power plants, and lead to cost savings for utilities and consumers alike. It is an innovative solution that addresses the challenges posed by increasingly variable energy demands and the need for more sustainable and resilient energy systems [31]. Figure. I.9. Shows how the peak can be both reduced and shifted by the use of PCMs.

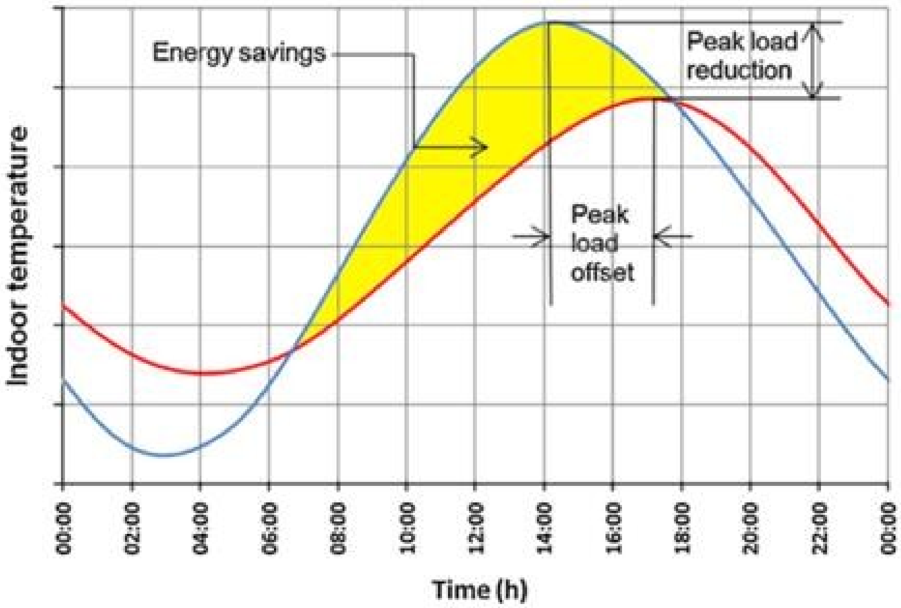


Figure. I.9. Shows how the peak can be both reduced and shifted by the use of PCMs [31].

I.7. **Effects of PCMs on thermal comfort in buildings**

Due to the difference in temperature between the interior daylight and outside nighttime especially in harsh climate conditions, using PCM offers an important advantage in reducing energy consumption. Also, they possess the capability to enhance the comfort of occupants inside a building, and they also exhibit significant heat and energy storage capacities when compared to alternative materials. For example, PCMs have the capacity to store approximately three times the amount of energy compared to water, also exhibits about six times higher energy storage capacity than concrete with an equivalent wall thickness, as shown in Figure I.10. This figure compares the energy storage capabilities of various building materials under consistent conditions of temperature variation and thickness, featuring seven different types.

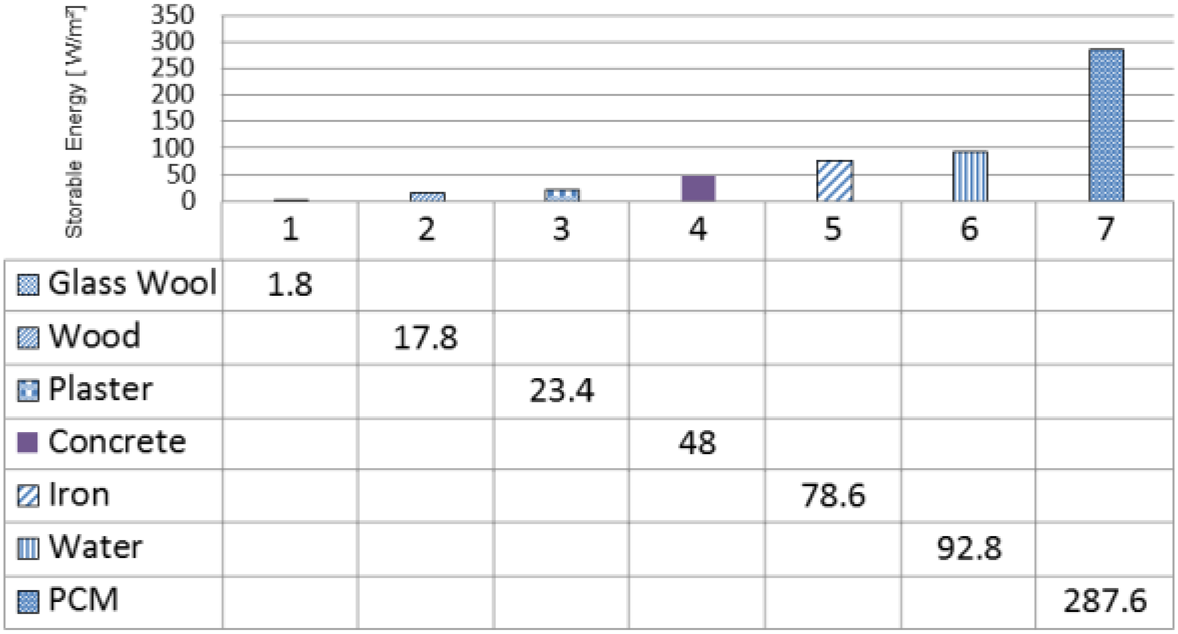


Figure. I.10. Evaluating the energy storage capability of building materials under the same conditions of temperature variation and thickness[41].

Thermal comfort is influenced by various physical factors like air temperature, relative humidity, airflow, and the temperature of nearby walls. In moderate climates, it is recommended to maintain the interior temperatures between 21°C and 26°C. Also, heat transfer coefficient depends on several factors, including the building materials, insulation levels, and the specific heat transfer mechanisms involved (conduction, convection, and radiation). It is recommended that the heat transfer coefficient range between 0.5 W/m^2K and 10 W/m^2K and a relative humidity between 30% and 60%, as the psychrometric chart shown in Figure. I.11 Ensuring thermal comfort in buildings is crucial for more than merely meeting occupants' physical comfort needs in terms of heating and cooling. It also significantly impacts human performance and concentration levels. PCMs have characteristics like thermal energy storage, which can be employed to enhance the indoor environment of buildings, leading to a significant improvement in the thermal comfort experienced by occupants. Creating a comfortable indoor environment in the majority of buildings demands a significant energy contribution, which accounts for a substantial portion of the building's operational expenses. However, the utilization of specific building materials has the potential to decrease these costs while enhancing the thermal comfort of occupants. Selecting appropriate PCMs allows to maintain the indoor temperature in a comfort level without utilizing operational costs by preventing needless heat gain in hot weather and reducing heat loss in cold weather. Consequently, integrating PCMs into buildings presents a promising strategy for achieving improved thermal comfort. It facilitates the utilization of latent heat storage to enhance thermal inertia without significantly increasing energy consumption. As a result, PCMs could enhance thermal comfort by reducing the effect of temperature fluctuations in the inner air and maintaining the desired temperature in the building environment for a longer duration [41].

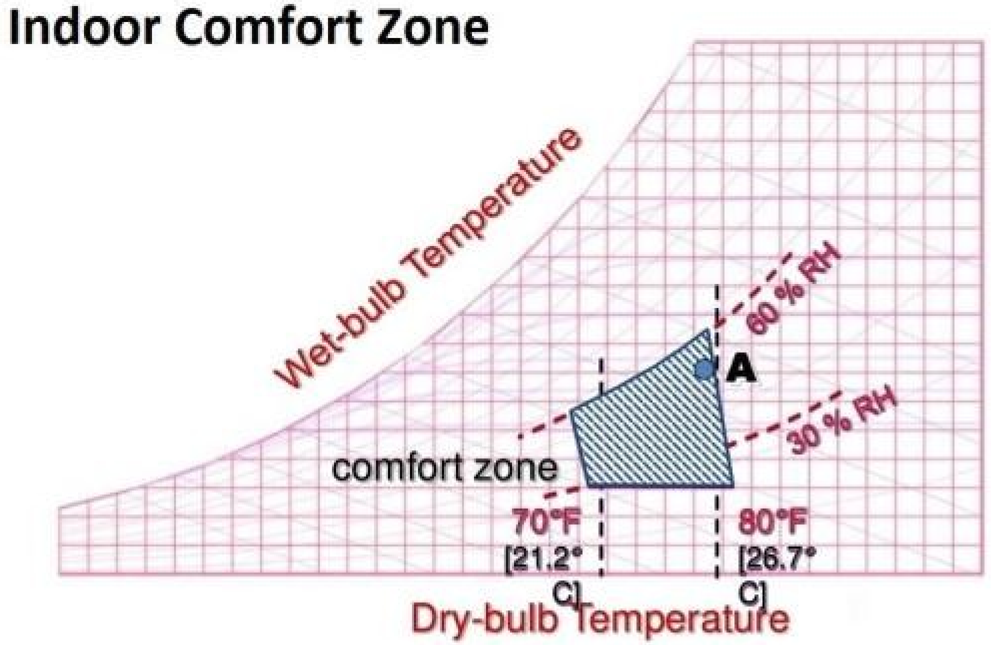


Figure. I.11. illustrates the comfort zone for thermal conditions using psychrometric data[41].

I.8. Effects of PCMs on energy saving

Heating and cooling expenses constitute a significant portion of operational costs, which can vary depending on a building's characteristics and its geographical location. PCMs offer an effective solution, reducing dependence on air-conditioning and heating energy per unit area by reducing heat transfer from the outside to the inside, or vice versa. This is especially beneficial in areas with high fluctuating temperatures between day and night. By integrating PCMs in building envelopes, this procedure can be implemented to conserve air-conditioning energy. PCMs stand out for their remarkable energy storage capabilities, which lead to decreased temperature fluctuations thanks to their high latent capacity. By capitalizing on this attribute, it becomes feasible to decrease the energy demand associated with running mechanical heating and cooling systems within buildings. This is accomplished by tactically delaying and offsetting the thermal load to the building. The integration of PCMs in building envelopes can lead to savings in cooling or heating demands. This is demonstrated by a decreased rate of heat transfer and a delay in reaching the peak indoor temperature. By incorporating PCMs with other building materials, it is possible to shift the trend of rising energy consumption in buildings. This approach addresses conservation concerns while minimizing the use of traditional energy sources[41].

I.9. Problem Statement

Regardless of the advantages mentioned for PCMs in thermal management, their widespread adoption in buildings is faced with various challenges, and the current issues remain unresolved and in need of clarification. Over the past decade, significant efforts have been devoted by researchers to integrating PCMs into building envelopes. However, selecting suitable PCMs for different building envelopes exposed to different climate conditions remains a significant challenge, especially in harsh climates. Numerous efforts have been made to enhance the thermal performance of building envelopes integrated with PCM, latent heat energy absorption, and release by identifying the terminal physical proprieties, the quantity, the type, and the position of PCMs. Hamidi et al [42]. recommended exploring the option of strategically incorporating PCMs into selected locations within building blocks, rather than filling the entire brick. Their study found that PCM placed in designated locations could achieve energy savings of up to 97% compared to the energy needed to maintain a constant internal thermal comfort temperature of 26°C. This targeted approach could potentially reduce the amount of PCM required and associated costs, while still harnessing its thermal energy storage benefits. Huang et al. [43] investigated the impact of PCM layer thickness on thermal performance in buildings. Their findings indicated that increasing the thickness of the PCM layer results in a decrease in the peak temperature on the inner surface of the roof, and an increase in the time delay before heat transfer occurs. Determining the optimal thickness of the PCM layer is crucial, as it impacts both energy savings and the utilization ratio of latent heat stored within the PCM. Overly thick layers may not fully utilize the latent heat capacity, while excessively thin layers may not provide sufficient thermal mass. Clearly, there were significant variations among these studies, and they were constrained to specific scenarios, building materials, PCM types, and climatic conditions. Consequently, further research is necessary to thoroughly examine the various factors influencing the selection and optimal integration of suitable PCMs for different building elements and applications. A comprehensive understanding of these factors, including PCM thermophysical properties, melting temperature ranges, building envelope characteristics, occupancy patterns, and local climate data, would enable more effective design, sizing, and optimization of PCM systems in buildings.

Furthermore, several important factors can influence the effective utilization of the latent heat capacity of PCMs, such as the placement and the capsulation shape of the PCM, the melting points and heat of fusion of the PCM, and the quantity of integrated PCM. Previous studies, which typically focused on one or two variables, failed to comprehensively investigate the thermal behavior of structural elements, particularly under specific and realistic hot climate conditions. Moreover, there is a lack of resources demonstrating strategies to enhance the energy efficiency and the thermal comfort of building brick wall integrated with PCM based on key factors that may impact their thermal performance.

I.10. **Research Objectives**

To address the challenges and gaps identified in previous research on integrating PCMs into building envelopes, the main objectives of this thesis are as follows:

- To conduct a comprehensive investigation into the key factors influencing the thermal performance of building envelope elements, such as brick walls, when incorporated with PCMs. These factors may include, but are not limited to, the type and thermophysical properties of the PCM, the quantity and placement strategy within the building brick wall, the encapsulation or cavity shape of the brick.
- To develop an in-depth understanding of the thermal behavior and potential energy-saving capabilities of PCM-integrated into building brick components under realistic and specific hot climate scenario. Many previous studies have focused on simplified or controlled conditions, which may not accurately represent the complex and dynamic thermal loads encountered in real-world applications.
- To innovate a novel design for building brick walls incorporating PCM, EPS, and low coating emissivity tailored for challenging climate conditions.
- One of the objectives is to explore the feasibility of PCMs with other passive cooling techniques into the same configuration. The goal is to evaluate the potential for developing an energy-saving building wall assembly that could significantly reduce heat transfer across the wall. By combining PCMs' thermal energy storage capabilities with

complementary passive strategies, low coating emissivity, or insulation, the research aims to create a synergistic and highly effective solution for minimizing heat gain through the building roof. This integrated approach could lead to substantial energy savings and improved indoor thermal comfort, making it a promising avenue for innovative and high-performance building brick designs.

I.11. **Research Significance**

Building energy modeling has become a fundamental aspect of the design process, playing a crucial role in both new buildings and existing building retrofit projects. Numerous universities and companies highlight and provide support to research aimed at enhancing construction methods and reducing high energy consumption in buildings. PCMs typically show considerable promise as a strategy for managing thermal energy within buildings, particularly in the context of free cooling and heating applications. Although numerous studies have led to significant progress in incorporating PCMs into building applications, there is still a need for more comprehensive analyses to provide a fundamental understanding of the underlying working mechanisms and processes involved with PCMs. Developing this deeper comprehension of how PCMs function and interact with building components is crucial, as it can subsequently pave the way for the development of novel strategies and approaches. These innovative methods can then be employed to further enhance the energy efficiency of building brick walls and other envelope elements when integrated with PCMs. Essentially, while advancements have been made, a more thorough scientific basis is still required to unlock the full potential of PCM technology and enable its optimal implementation in energy-efficient building designs.

To achieve a profound understanding and effective utilization of PCMs in building applications, the following aspects are essential:

- Complete comprehension of the thermal dynamics of building brick walls, considering factors such as the integration location, the quantity, and the thermos-physical properties of PCM.
- Developing advanced encapsulation shape and incorporation techniques that facilitate efficient heat transfer to and from the PCMs.

- To investigating the interplay between PCMs and other passive building strategies, such as insulation, and low coating emissivity, to create synergistic and optimized solutions for energy-efficient and thermally comfortable buildings.
- An effective strategy to improve the energy efficiency of brick walls integrated with PCM.

Previous research has generated numerous short-term data sets that primarily focus on the thermal performance of entire buildings integrated with PCMs. However, these test results often exhibit significant inconsistencies, leading to a lack of comprehensive understanding of the thermal behavior of individual building elements, such as walls, floors, and roofs, when incorporating PCMs. Additionally, conducting long-term assessments of thermal performance under real-world field conditions is a time-consuming endeavor, which conflicts with the pressing need to improve building energy efficiency in the present. This disconnect between the available fragmented data, the lack of insight into component-level behavior, and the urgency to implement energy-efficient solutions highlights the need for more targeted and accelerated research efforts in this area.

While there have been considerable efforts in developing PCM technologies and integrating them into buildings, significant challenges remain. Effectively enhancing the energy efficiency benefits derived from the latent heat of PCMs for building applications continues to be a hurdle. Additionally, selecting suitable PCM types that can perform well under harsh climate conditions poses difficulties. The lack of systematic and comprehensive investigations into addressing these gaps has hindered the widespread adoption of PCM technologies in the building sector. Overcoming these obstacles through dedicated research is crucial to unlocking the full potential of PCMs for improving energy efficiency in buildings across harsh climatic regions. As a result, the aim of this thesis is to provide a numerical analysis that offers a fundamental understanding of the thermal dynamics of building brick walls incorporating PCM, which will be helpful in the development of methods for improving building efficiency under harsh climatic conditions.

I.12. **Organization of the thesis**

This thesis is constructed with five chapters:

Chapter I provides an overview of the background, classification, and usage of PCM in buildings. It discusses the current challenges associated with PCM application in buildings and then presents the research significance and objectives, as well as the organization of this thesis.

Chapter II offers an extensive review of the literature concerning PCM utilization in building envelopes and their impact on improving thermal comfort and energy saving.

Chapter III focuses on developing mathematical models to describe the heat transfer processes and phase change (solidification/melting) phenomena. It presents the governing equations for the fluid region, including the continuity equation, momentum equation, and energy conservation equation, coupled with the energy equation for the solid region. The assumptions underlying these models are also outlined. Furthermore, this chapter delves into the details of the numerical method employed to solve these equations, the validation approach used to verify the model's accuracy, and the specific geometries considered for the study. In essence, Chapter III lays out the theoretical foundation and computational framework necessary to mathematically model and analyze the intricate heat transfer and phase change behavior, providing the basis for the subsequent investigations and findings presented in the work.

Chapter IV presents the outcomes of a study organized into two sections (applications). In the first section, we conducted a numerical investigation into the impact of different brick cavity shapes on the thermal efficiency of building walls. In the second section, we examined numerically the effects of incorporating two passive measures on energy conservation and the thermal efficiency of building bricks.

Chapter V provides a comprehensive synopsis of the research's primary conclusions and significant findings. Additionally, it explores and discusses potential avenues for future investigations that could build upon the current work, highlighting promising directions and areas warranting further examination.

CHAPTER II:
Literature Review

CHPTER II: Literature Review

II.1. Introduction

A building envelope serves as a physical barrier between the interior and exterior environments. It works to shield against the entry of heat and cold, ensuring a comfortable indoor temperature. As living standards continue to rise, the need for optimal indoor thermal conditions increases. This leads to higher energy consumption by HVAC systems, particularly during harsh weather conditions in summer and winter. PCMs could be integrated into different building envelope elements, including as floors and ceilings, as well as walls, roofs, and windows. Through this integration, the building's energy efficiency is increased and indoor thermal comfort is improved [35]. In this chapter, we examine research conducted over the past twenty years that delves into the utilization of PCMs in constructions with the aim of improving their thermal efficiency. This includes investigations into the criteria for selecting PCMs for managing the thermal properties of buildings, as well as the thermos-physical characteristics of the chosen PCMs and the methods employed to integrate them into different building elements the Figure II.1. summarizing the applications of PCM into building envelopes.

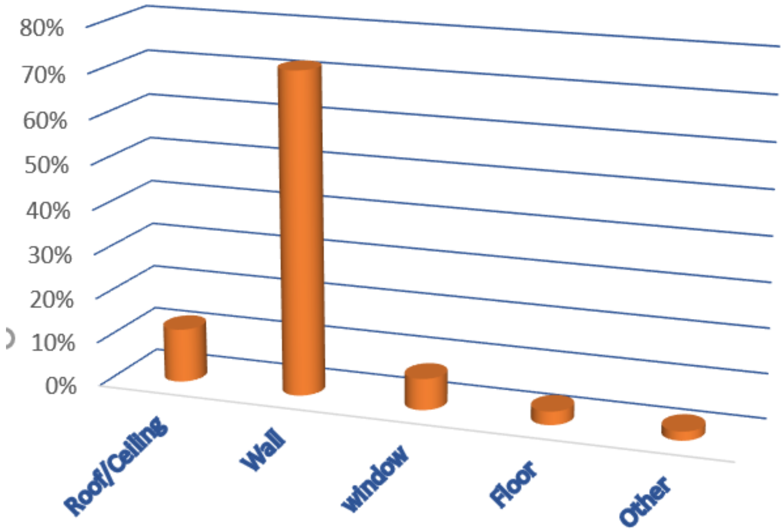


Figure II.1. Building component incorporating PCM for thermal regulation[44]

Four noticeable databases, namely Science Direct, Google Scholar, Web of Science, were referred in order to identify relevant research papers. These databases included a wide range of fields, such as materials science, energy, physics, architecture, and data science. The keyword *phase change material* was selected for publications related to energy. Furthermore, the application of PCMs to buildings was identified by the inclusion of the keywords building, *wall, brick, roof,* or *floor*, which narrowed the scope of the literature review. The aim of this chapter is to explore the integration of PCM into building envelope as discussed in recent publications, with a primary focus on five key areas. Firstly, the work provides an in-depth understanding of the phase change heat transfer model, the methods for integrating PCMs into building envelopes, and the potential enhancements in the overall performance of the building envelope. On the other hand, it comprehensively describes and evaluates the effectiveness of PCM-integrated envelopes in improving thermal performance and the indoor thermal environment of buildings. In general, the study offers a comprehensive analysis of the integration methods and fundamental theories for PCMs in building envelopes, while also providing a comprehensive analysis of the practical implications and performance benefits of such systems in terms of thermal management and indoor comfort.

Many applications of PCMs for heating and cooling in buildings focus on integrating the PCMs into the building envelope, starting with the walls. This involves incorporating PCMs into various construction materials such as building bricks, stones, concrete, and plastering mortars, with a particular emphasis on the development of PCM-enhanced wallboards. Additionally, designers aim to incorporate PCMs into floors and ceilings as part of the overall integration strategy for buildings. Further design options explore the use of PCMs in trombe walls and solar facades, using the thermal energy storage properties of the materials to successfully control interior temperature. Utilizing PCMs' latent heat storage and release capabilities is the purpose of integrating them into each of these different building envelope, thereby enhancing the thermal performance and energy efficiency of the building environment.

II.2. **Application of PCM in the walls, wallboards, floors, and ceilings**

II.2.1 **PCM incorporated building wall**

The idea of utilizing PCMs to increase the thermal mass and improve the thermal inertia of buildings dates back to the 1940s. Telkes [45] conducted research on storing solar thermal energy for building space heating using sodium sulfate decahydrate as a phase change material. Although his research didn't initially attract much attention, interest rose following the energy crisis of the late 1970s and early 1980s. In recent decades, there has been a restated interest in integrating PCMs into different building components[46]. Faraji[47] Examined a wall integrated with a PCM layer in the middle, surrounded by thick concrete on both the outside and inside. To simulate and predict the thermal behavior of this innovative wall under the particular weather conditions of Casablanca, Morocco, a method utilizing the enthalpy approach was employed. The results revealed that the wall incorporated with PCM exhibited reduced indoor temperature fluctuations and a phase shift in peak temperature compared to a conventional concrete wall without PCM. Memon et al[16]. conducted small-scale experimental evaluations of the thermal performance of lightweight aggregate concrete (LWAC) containing macro-encapsulated paraffin integrated within the lightweight aggregate (LWA), intended for use in wall constructions. Their study additionally examined the economic and environmental implications of incorporating PCM into a residential building situated in Hong Kong. The indoor test results demonstrated that the panel incorporating macro-encapsulated Paraffin–LWA successfully reduced the room center temperature and the internal surface temperature of the panel by 4.7 °C and 7.5 °C, respectively. Additionally, the Paraffin–LWA room model exhibited a reduction in indoor temperature by 2.9 °C during the test. The environmental assessment declared an annual reduction of 465 kg CO_2 equivalent. The LC–100% PCM–LWA demonstrated a recovery period of 29 years, which is below the average lifespan of a residential building in Hong Kong, standing at 60 years. Hence, economically considering, the implementation of macro-encapsulated Paraffin–LWA in LWAC building walls was shown to be practical.

Mouridet al.[48] Evaluated the thermal performance of two full-sized real prototypes in Casablanca, Morocco, which are subjected to Mediterranean weather conditions. The experimental analysis desired to measure the temperatures inside, on the wall surface, on the ceiling surface, and in the outdoor ambient environment, also heat flux through both the wall and the ceiling as shown in Figure II.2. These measurements encompassed a baseline prototype and an alternative prototype fitted with wallboards containing PCM Energain® with a thickness of 5.26 mm. It was demonstrated that the temperature in the room with PCM was high compared to the reference room, with a maximum difference of 7.3 °C. Moreover, the results led to the conclusion that the presence of PCM decreased the energy consumption of the room, and thermal losses through the ceiling were reduced by 50%. This highlights the efficiency of placing PCM in the ceiling compared to the wall.

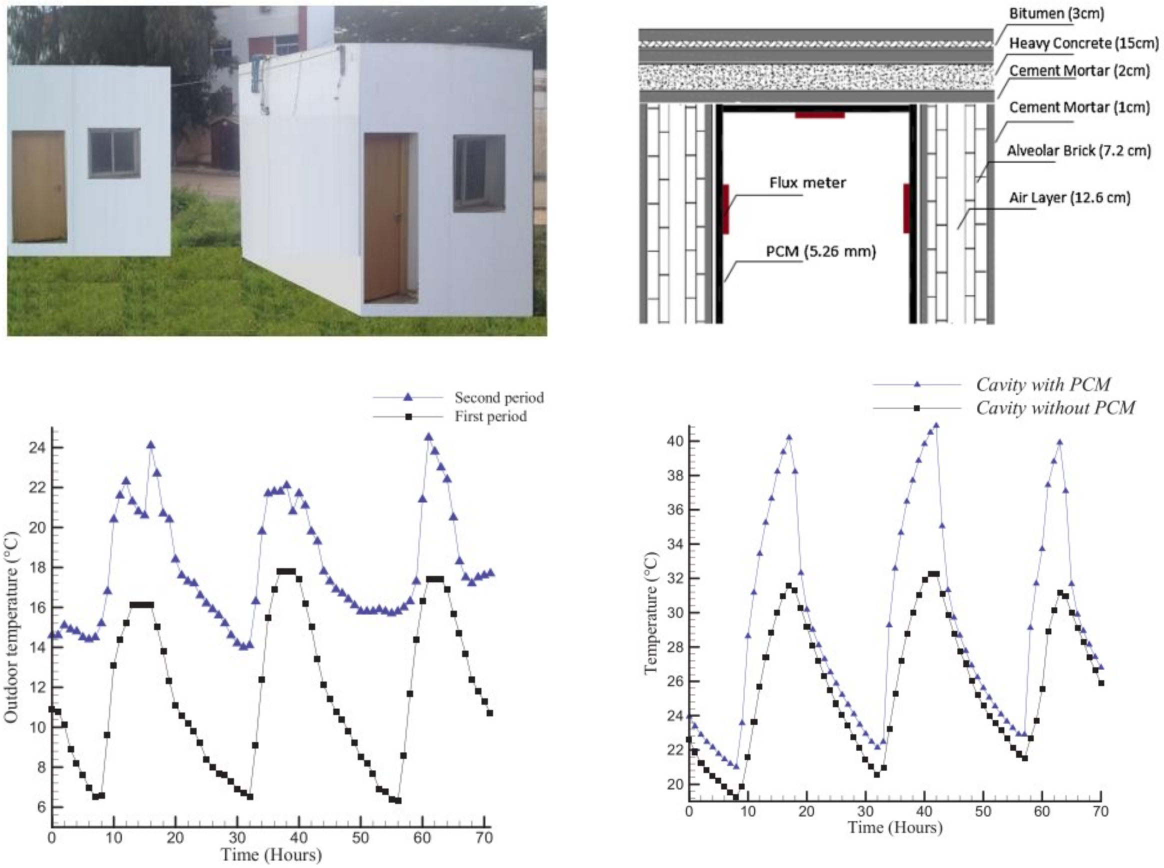


Figure II.2. Describes the full-scale prototype, including the configuration and PCM layer placement in the walls and ceilings, as well as the positioning of flux meters on the walls. It also shows ambient temperatures and temperature evolutions of the ceilings[48].

Barrientos et al[49]. Evaluated the effectiveness of PCMs applied in the outer walls of building through numerical analysis. A wall thickness of 22.5 cm was evaluated according to Spanish conventional building standards. The effectiveness of integrating the PCM layer at various positions within the wall was investigated. Studies were carried out on phase change temperatures, environmental conditions, and different wall orientations. The findings indicated a significant reduction in immediate thermal loads through the application of PCM layers in the walls. Moreover, significant reductions in temperature fluctuations were seen in the summer, but such reductions were insignificant in the winter. Li et al [50]. Evaluated the thermal performance of typical building walls in Isfahan, Iran, by integrating thirteen different types of PCMs into the wall systems. The wall structure was composed of a 2 cm layer of plaster, 15 cm of clay brick, and 3 cm of cement, as depicted in the Figure II.3. The study examined the effect of positioning PCM either closer to the interior or exterior side of the wall on the heat transfer characteristics. The results showed that the thermal conductivity, latent heat of phase change, and melting temperature of the PCM significantly influenced the performance of walls incorporated with PCM. When PCM has lower thermal conductivity, a higher latent heat of phase-change, and a phase-change temperature closer to the room temperature, It could reduce the transfer of heat into the interior space more effectively.

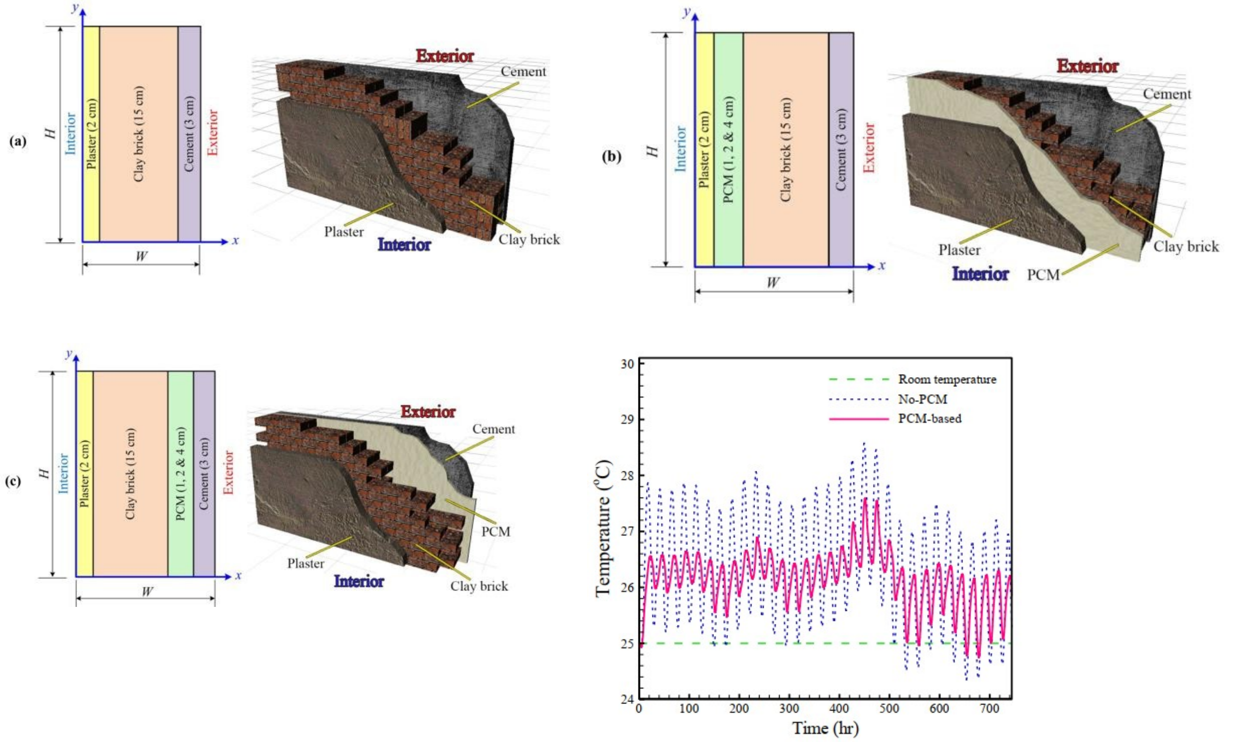


Figure II.3. Examined walls: a) without PCM b) PCM close to interior, c) PCM close to exterior, inner surface temperature of the wall with and without PCM[50]

Kong et al[51]. Evaluated the thermal performance of two innovative PCM systems integrated into building envelopes through computational simulations and full-scale experimental testing. In the experimental component, panels containing capric acid as well as a combination of capric acid and 1-dodecanol were installed on both the exterior and interior surfaces of walls and roofs. The numerical analysis, conducted using computational fluid dynamics (CFD) software, investigated the evolution of indoor temperatures, temperature fluctuations, and thermal energy savings under two ventilation regimes: free cooling and the nighttime opening of windows and doors. The study aimed to assess the efficacy of these PCM systems in improving the thermal behavior of the building envelopes. The findings indicated that the integration of PCM into the inner side wall exhibited more effective thermal performance compared to the integration into outside wall, especially when the window and door were opened at night. Nevertheless, integrating PCMIW in existing buildings necessitated an interior retrofit. Nonetheless, the installation of PCM panels in both the wall and roof assemblies demonstrated promising results. Kim et al [52]. carried out experimental tests and computer simulations to investigate the use of shape-stabilized PCM sheets installed on the floors, walls, and ceilings of various buildings under Japanese climatic conditions. Three identical test huts were constructed: type A without any PCM as a reference case, type B incorporating 4 layers of shape-stabilized PCM sheets in the floor, and type C with one PCM sheet in the floor, walls, and ceiling each. The simulation component analyzed 21 different cases, each representing a distinct building type across seven different climate zones in Japan. Compared to the reference hut A, the annual heating load was reduced by 8% to 42% for hut B and 19% to 54% for hut C when PCM sheets were incorporated into the building envelope components. Rathore and Shukla [53] aimed to assess the indoor thermal performance of a building incorporating commercially available PCM OM37 encapsulated within aluminum tubes under tropical outdoor conditions, and to quantify the associated reduction in cooling load requirements. A field experiment was conducted by constructing two cubic test cells with dimensions of 1.12 m x 1.12 m x 1.12 m. The thermal behavior observed in these cells was compared against a reference cubicle with a conventional concrete wall. The results demonstrated a notable decrease in peak temperature ranging from 7.19% to 9.18%, and a reduction in the amplitude of heat flux penetrating the walls from 40.6% to 59.79% for the cells integrated with PCM-enhanced walls. Furthermore, a maximum time lag of 2 hours in heat transfer was observed, along with a 38.76% decrease in the required cooling load when employing the PCM-enhanced wall system.

Lakhdari et al.[54] were coated the interior walls with a dual microencapsulated PCM system, as depicted in Figure II.4. To formulate this hybrid PCM, five different combinations were prepared by blending four commercially available PCMs: Rubitherm RT 21, RT 22, RT 24, and RT 25. The researchers examined the time lag performance of the hybrid PCM system and its influence on the energy efficiency of buildings. Numerical simulations were conducted using the finite volume method to analyze the hybrid PCM's behavior under various climatic conditions applied to the wall assembly. The projected outcomes indicate that incorporating dual PCMs within plaster container, in contrast to a single PCM, increases the heat storage period by 57%. The use of dual PCM also reduces the decrement factor and minimizes heat diffusion into the building during the day by over a 75% margin across various climates studied. Furthermore, the dual PCM plays a role in lowering the indoor temperature by reducing the indoor surface temperature by approximately 2 °C. Additionally, delays the peak in heat diffusion by more than 3 hours.

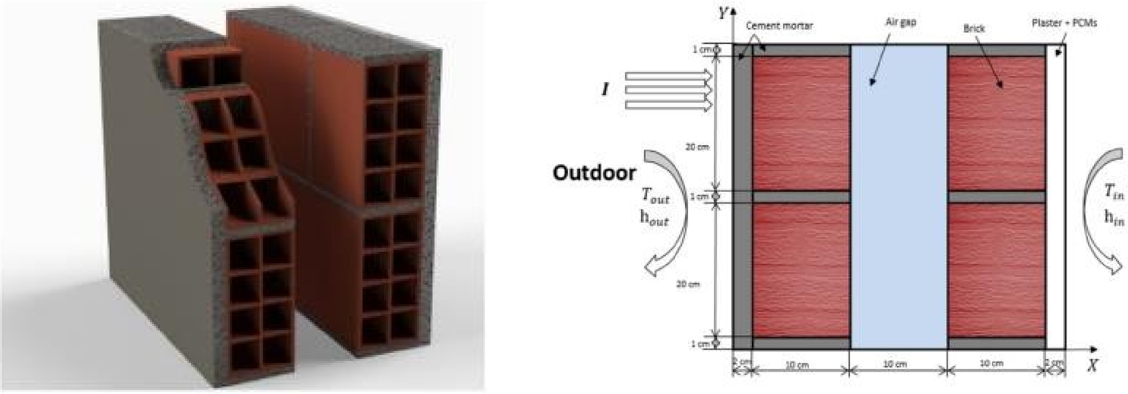


Figure II.4. The configuration of a building wall coated with a hybrid PCM with plaster[54].

Frazzica et al. [55] conducted experimental and computational studies on the incorporation of microencapsulated PCMs in cement mortar, designed especially for use in warm climates like as the Mediterranean. The investigation involved preparing cement mortar mixtures with varying compositions of two distinct microencapsulated PCMs: Micronal 5038X with a melting point of 25°C and Micronal 5040X with a melting point of 23°C. These PCM-enhanced mortar mixtures can be utilized in building components to assess thermal comfort levels and achieve energy savings. The experimental location was located in Sicily, Italy. Numerical simulations were performed using COMSOL Multiphysics software, with an optimal melting temperature of 27°C analyzed under both summer and winter climate conditions. The findings revealed that for the Sicilian climate, the ideal melting temperature was 27°C. Furthermore, incorporating 15 wt% of the optimized PCM into the mortar led to an approximately 15% improvement in thermal comfort conditions compared to conventional cement mortars without PCMs.

Li et al.[56] their study involved constructing the test box featuring with gypsum wall panels integrated with three different PCMs having melting temperatures of 12°C, 18°C, and 29°C. The experiment aimed to evaluate the energy savings potential and thermal comfort performance of these PCM-enhanced wall systems. To assess their energy-saving capabilities, a comparative test was conducted against an active heating/cooling system as a baseline. The results indicated that the hybrid PCM wall panels could effectively stabilize indoor air temperatures and maintain thermal comfort conditions throughout the year. Specifically, the mode two PCM wall panels exhibited superior performance in regulating the indoor thermal environment, releasing more heat indoors during daytime and minimizing heat loss at night during winter. The energy consumption in the test box with the hybrid PCM wallboard was approximately 30% lower compared to the box with a conventional gypsum wallboard without PCM integration.

Shi et al.[57] examined how the positioning of PCM layers, whether externally attached, encapsulated within the walls, or internally integrated, influenced humidity and temperature fluctuations inside concrete room models. The investigation concentrated on assessing how well these walls performed in regulating indoor temperature and humidity levels. The findings demonstrated that the PCM layer possesses the capacity to manage temperature and humidity, although its efficacy is significantly influenced by its placement within the wall. The model incorporating PCM coating within the concrete walls exhibited optimal temperature regulation, effectively reducing the maximum temperature by up to 4°C, but the model containing the PCM layer positioned inside the wall demonstrated enhanced humidity control performance, achieving a 16% greater reduction in relative humidity. Also, the study results showed that the use of PCM in public housing flats in Hong Kong is economically viable, with a payback period of 11 years.

Arici et al.[58] carried out a comparative analysis on walls incorporating PCM and walls incorporating Phase Stabilized PCM (PSM) to reveal the enhancements created by latent heat. The study investigated the influence of PCM location, melting temperature, and layer thickness on energy savings, decrement factor, and time lag. Additionally, the aforementioned factors of two distinct wall models, one integrating PCM and the other utilizing Phase Stabilized PCM (PSM), were compared. The efficiency of walls with a PCM layer near the interior and exterior plaster was compared to that of traditional walls. The configurations of the PCM walls are provided in the study shown in Figure II.5. The monthly optimal melting temperature and PCM layer thickness ranged from 6°C to 34°C and 1 to 20 mm, respectively, in response to environmental factors across all three climatic conditions examined. The researchers recommended conducting additional optimization studies to prevent the phase change material from exhibiting behavior like to phase stabilized PCM (PSM), which could potentially limit its promised performance.

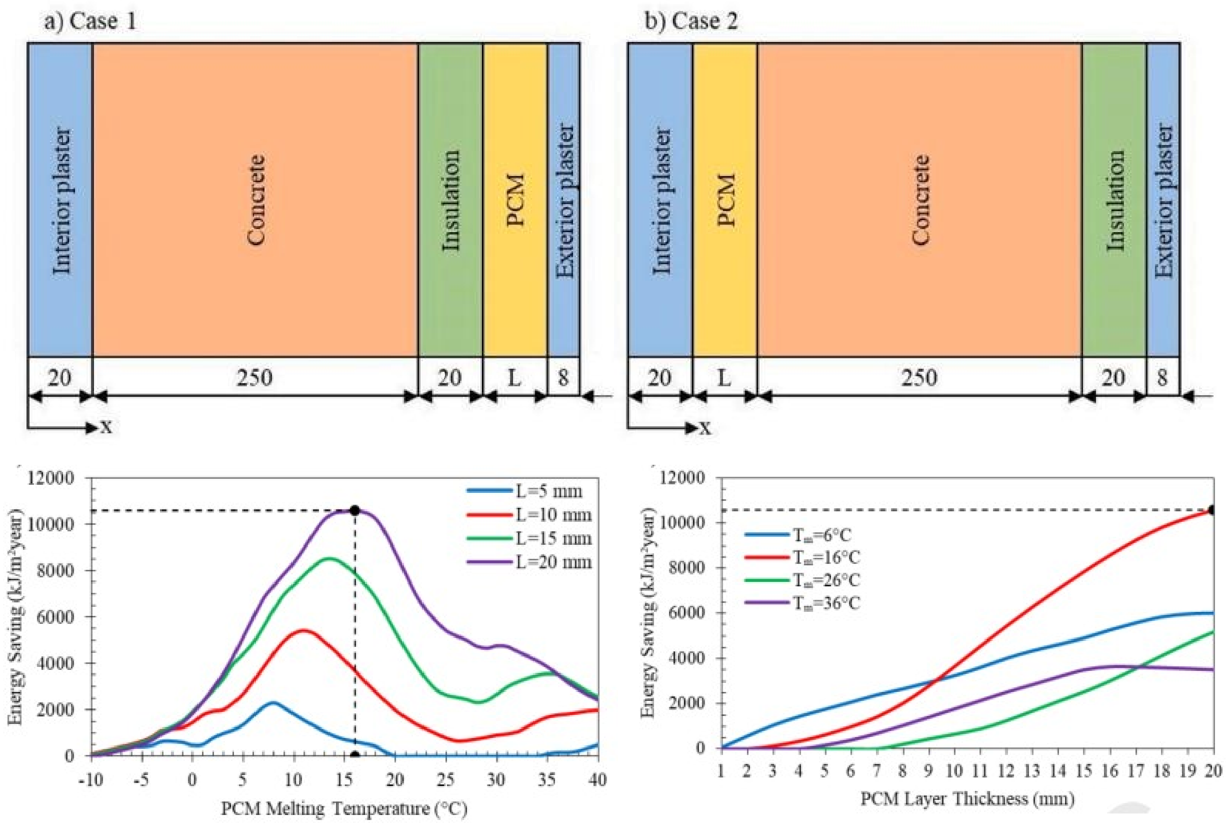
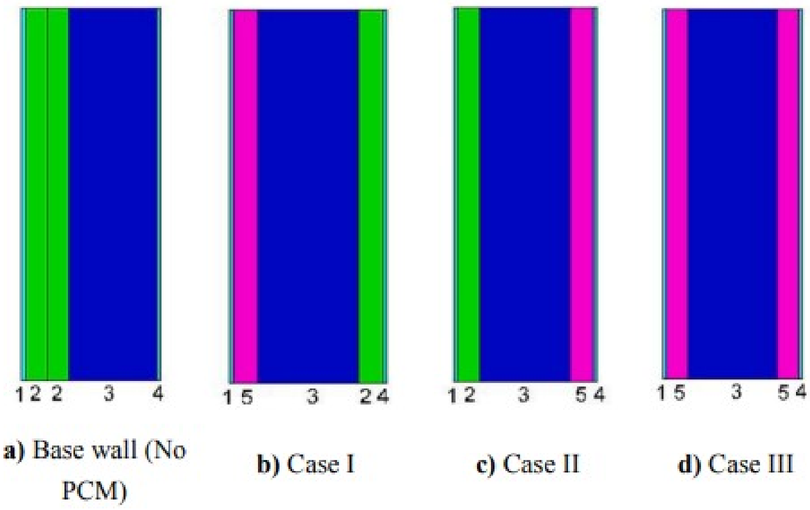


Figure II.5. Wall models consisting of composites suggested by Arici et al. [58] and the variation of annual energy saving for different cases.

Tunçbilek, et al.[59] Performed an optimization analysis for an external south-facing office wall that incorporates a PCM layer during periodic cooling operation. The optimization efforts concentrated on determining optimal parameters such as the positioning of the PCM layer within the wall assembly, the thickness of the PCM layer, and the phase change temperature of the PCM material. The goal was to maximize energy savings by effectively utilizing the latent heat storage capability of the PCM. Additionally, computational simulations were carried out for a typical week in each summer month to evaluate the influence of incorporating PCM into the wall on thermal comfort and air conditioner operation. The study compared the thermal performance of the PCM-integrated wall system against a conventional wall assembly without PCM. The results indicated that locating the PCM layer closer to the outer side of the wall did not lead to energy savings; instead, it increased energy consumption. Consequently, to enhance the energy efficiency performance, the researchers recommended positioning the PCM layer nearer to the inner surface of the wall assembly. Also, a reduction in energy consumption up to 12.8% was achieved with a

PCM layer thickness of 23 mm compared to a wall without PCM. However, energy savings were compromised when the phase change temperature above 26 °C, primarily due to the adverse effect of latent heat utilization. Murathan and Manioglu [60] evaluated the influence of the application, thickness, and position of PCMs on various building elements on the energy consumption of a building. The research investigation focused on examining the performance characteristics of a building structure comprising three floors, with dimensions of 10 m by 30 m, located in Diyarbakır within a hot-dry climatic region. Analyzed various combinations of thickness, placement, and PCM types with the aim of reducing heating and cooling loads, using the EnergyPlus software. The results showed that the energy consumption of a building is influenced by the position and thickness of PCMs in the building envelope. The most efficient energy performance in Diyarbakır was achieved by applying a 5 cm layer of PCM on the inner surface of the insulation material. This research provided a summary of different factors influencing the energy performance of buildings integrated wth PCM.

Li et al. [61] examined numerically the impact of integrating PCM walls on the heating energy consumption of a typical isolated house in northeastern China using EnergyPlus software. The study also investigated the economic and environmental impacts, particularly in terms of carbon emissions. Numerical analysis was conducted on three different configurations of the PCM layer and other wall materials. The reference case for comparison was a wall without PCM. The analysis of composite walls is illustrated in Figure II.6. The findings demonstrated that in the configuration where PCM was positioned close to the outer wall (case II), there was a 12.8% improvement in energy efficiency. Adding an additional layer of PCM resulted in higher heating energy consumption and, consequently, is not recommended for further consideration. Additionally, The results found that the most effective phase change temperature to achieve maximum energy savings was 16°C under the study's conditions, which considered an indoor temperature of 18°C. It is important to note that this optimal phase change temperature is highly dependent on the prevailing environmental conditions of the location. Furthermore, an analysis of the payback period indicated that the PCM with a melting temperature of 26°C exhibited the shortest payback duration of 1.8 years among the PCMs investigated in the study.



1:Mortar(10mm) 2:Insulation materials (60mm), 3: Clay brick (240mm), 4: Plastering (5mm), 5: PCM board (60mm)

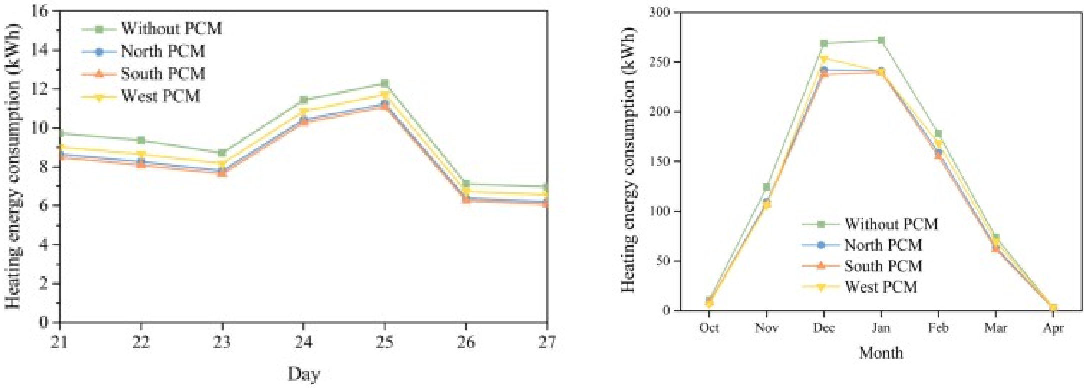


Figure II.6. Composite wall configurations used in the study, along with the daily and monthly heating energy consumption[61].

Wu et al. [62] investigated the hygrothermal performance of a multi-layer building envelope employing PCM and hemp lime concrete (HLC) through experiments analysis. HLC is a biomaterial exhibiting hygrothermal properties. The researchers utilized a controlled laboratory environment and a climate chamber to replicate the indoor and outdoor conditions that the building envelope would typically experience. The study investigated four different configurations of the building envelope. One configuration served as a reference case without PCM. The other three configurations incorporated PCM, with variations in its positioning (positioned on the outdoor side, indoor side, and in the middle of the envelope). The aim was to investigate the impact of PCM and its placement on the hygrothermal performance of the envelope. The configurations of the walls and the test arrangement are illustrated in the Figure II.6. The findings highlighted the significant impact of incorporating a PCM layer on the hygrothermal performance of HLC, characterized by a strong correlation between temperature and relative humidity variations within the envelope. The characteristic durations of temperature and relative humidity increased with the integration of PCM, indicating improved thermal and hygric inertia within the envelope. These impacts vary based on the PCM's placement, despite its role as a vapor barrier. The PCM located nearest to the exterior wall showed higher potential for heat storage/release, whereas the PCM nearest to the inner wall demonstrated a lower value. The results concluded that optimal performance is achieved when the PCM layer is positioned closer to the outer wall.

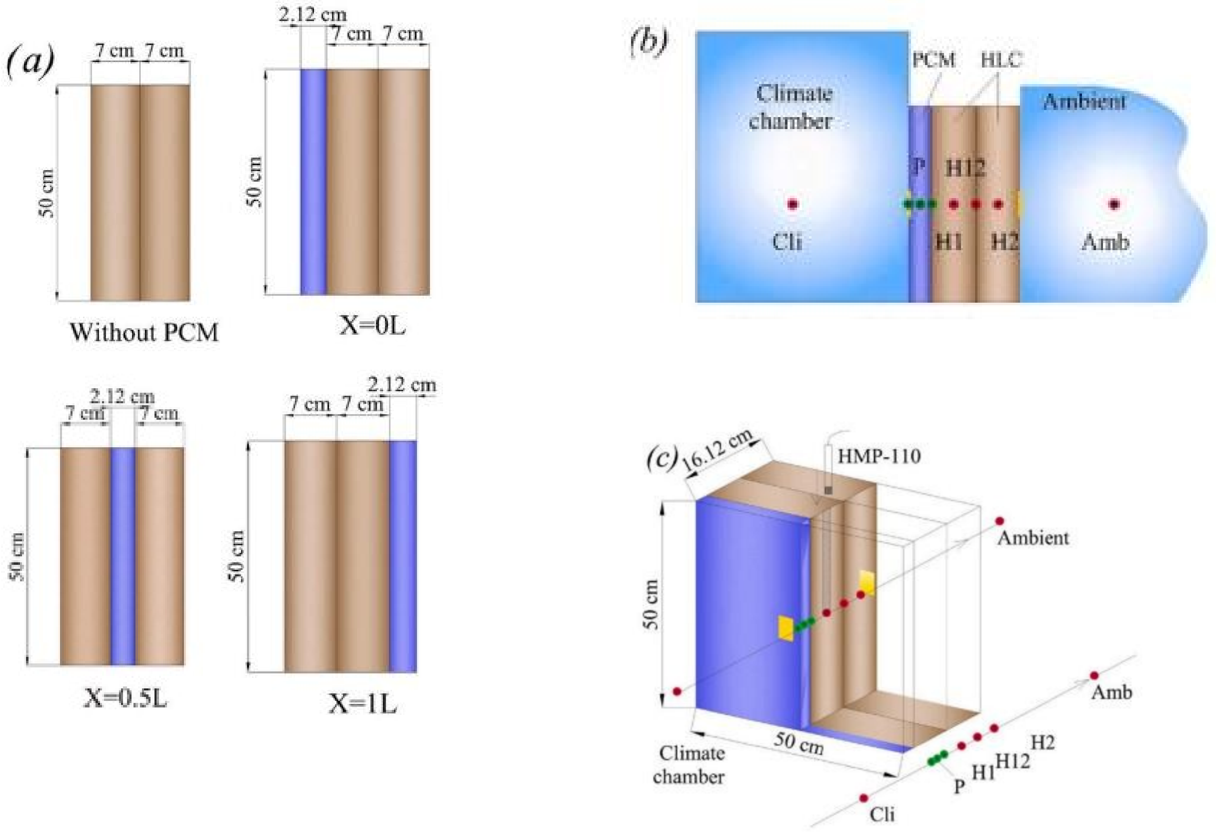
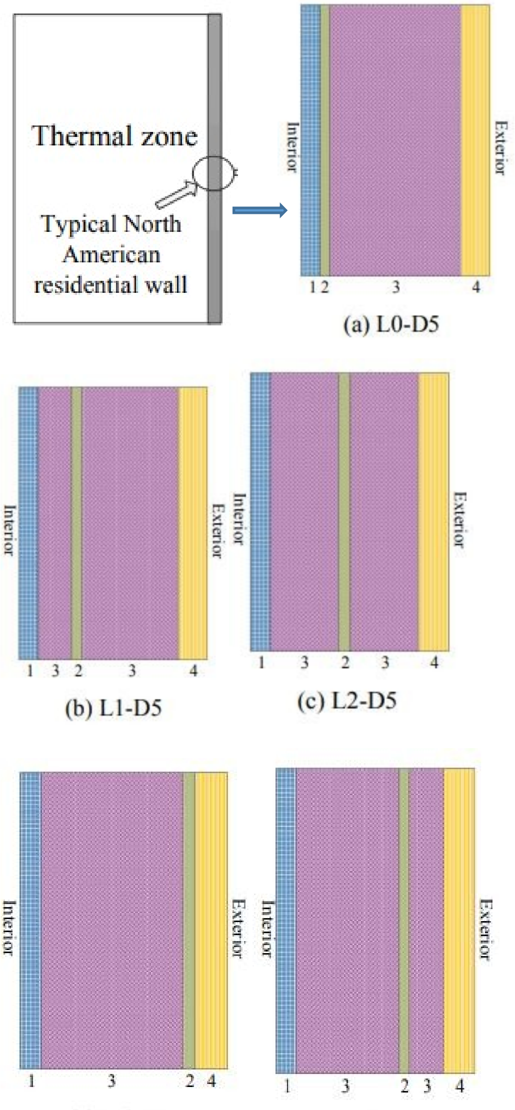


Figure II.7. (a) Various wall configurations and the reference wall, (b) locations for different sensor measurements, (c) 3D representation of the composite wall with sensors[62].

Li et al.[63] conducted a numerical study to investigate how crucial design parameters, such as the location and thickness of PCM layers, as well as the loading conditions in various climate zones across the United States, affect the optimal melting point of the PCM. Utilized COMSOL Multiphysics® software for simulating multilayer walls incorporating PCM to reveal their thermal behavior under different climate stress conditions. Figure II.8. illustrates the different integration approach of PCM in the multilayer wall. The results indicated that the location of the PCM layer in close proximity to the indoor surface of the wall is optimal. The selection of the appropriate PCM melting point for a specific building envelope is heavily dependent on the thermal loading conditions it experiences. The optimal melting point of the PCM is directly correlated with the input loading conditions, indicating that a higher melting point is required for a building envelope subjected to high input temperatures.



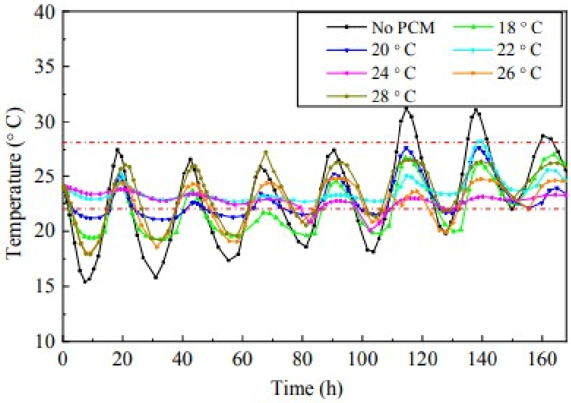
(a) L0-D5

(b) L1-D5

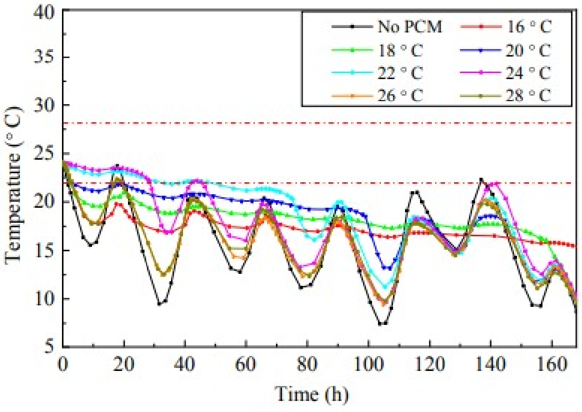
(c) L2-D5

(e) L4-D5

(d) L3-D5



(b) May



(a) January

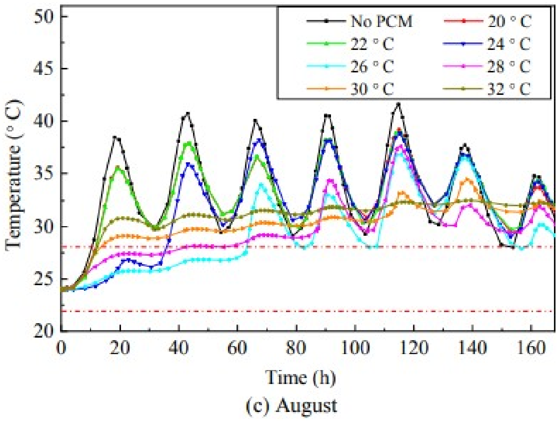


Figure II.8. Different configurations of the multilayer wall, Indoor transient temperatures during the initial week across different months in Austin[63].

Saafi and Daouas [64] performed numerical simulations using EnergyPlus to examine how several parameters, such as the phase change temperature range during summer and winter, PCM placement, wall orientation, and building material type, affect the annual energy savings. Additionally, they explored the thermal inertia advantages of PCM in relation to both wall orientation and PCM location. Results showed that incorporating PCM on the external surface of a brick wall led to a 13.4% reduction in energy consumption for south orientations. This was observed in their investigation into the application of PCMs to reduce temperature fluctuations of high-rise buildings with high window-to-wall ratios, Meng et al [65] examined the energy and economic impacts of an innovative wall system that integrated PCM with transparent insulation materials. Across the climates analyzed, this TIM-PCM wall demonstrated superior performance compared to a conventional double-glazed wall, especially when the wall was oriented towards the south. The authors highlighted the significance of considering climatic conditions, energy costs, energy conservation, the country's discount rate, and system investment costs when evaluating the economic feasibility of implementing TIM-PCM walls, the use of this wall is found economically unworkable due to the combination of low energy prices and elevated discount rates. Marin et al.[66] conducted an estimation on the efficiency of a mobile and lightweight structure equipped with PCM wallboards. They observed and analyzed how PCM influenced energy conservation. The results emphasized the ability of PCM to consistently reduce energy consumption across various seasons in Chilean climates. However, it was observed that in extremely cold and hot climates, the effectiveness of this passive thermal energy storage system was limited. The researchers recommended selecting the melting temperature of the PCM to match the specific climatic conditions, with the goal of maximizing its efficiency and effectiveness for each particular scenario or location. A numerical study examined a 20 mm thick PCM layer positioned on the inner surface of the external wall of a building was studied by Ascione et al.[67] The results indicated that it could decrease the summer cooling load by 11.7% and winter heating by 1.6%.

II.2.2 PCM applications in the building roof

Hanchiet al.[68] numerically analyzed the thermal performance of a dynamic system consisting of a multilayer roof and two layers of PCMs with different melting points. The research compared two conditioned zones, one in Casablanca and the other in Ouarzazate, Morocco, each maintained at distinct comfort temperatures of 18°C and 20°C, respectively.This involves examining scenarios with a conventional reference roof and another roof integrated with PCM. The researchers evaluated 18 different combinations, incorporating six different PCMs with melting temperatures ranging from 19°C to 34°C within the multilayer roof system. The findings indicate that incorporating PCMs into the traditional roof shows positive outcomes. The extent of energy consumption reduction in the conditioned room is dependent upon both the choice PCM and the temperature of the conditioned room. Chen et al.[69] examined the impact of PCM composite plate roofs utilizing graphite foam through numerical simulation studies on the thermal performance of buildings in different cities. The investigation aimed to assess the effectiveness of PCM and cooling paint under diverse global climatic conditions, employing the EnergyPlus software. When PCM was integrated with cooling paint (CP), the ideal phase change temperature could vary, and the impact of the phase change temperature was additionally diminished. As the thickness of the PCM increased, energy consumption consistently decreased. However, the range of peak load initially decreased and then stabilized. A practical investigation would offer greater insights into comprehending the phenomenon in real-world scenarios. Yu et al.[70] explored the thermal efficiency of an innovative ventilation roof incorporating shape-stabilized PCM in Wuhan, utilizing a dynamic heat transfer model. Experimental results validated the model, affirming that the use of PCM decreased fluctuations in room interior surface temperatures and lowered energy consumption as shown in Figure II.9. The building equipped with the PCM roof experienced a reduction in total cooling load by 19.2% compared to buildings with standard roofs. When combined with night ventilation, the cooling load was additionally reduced by 37.5%. With a PCM layer thickness of 30 mm and a phase change temperature between 36-38 °C, the utilization of PCM leads to a significant reduction in both the peak temperature of the interior air and the peak internal surface temperature of the roof, decreasing by 2.9 °C and 5.5 °C, respectively

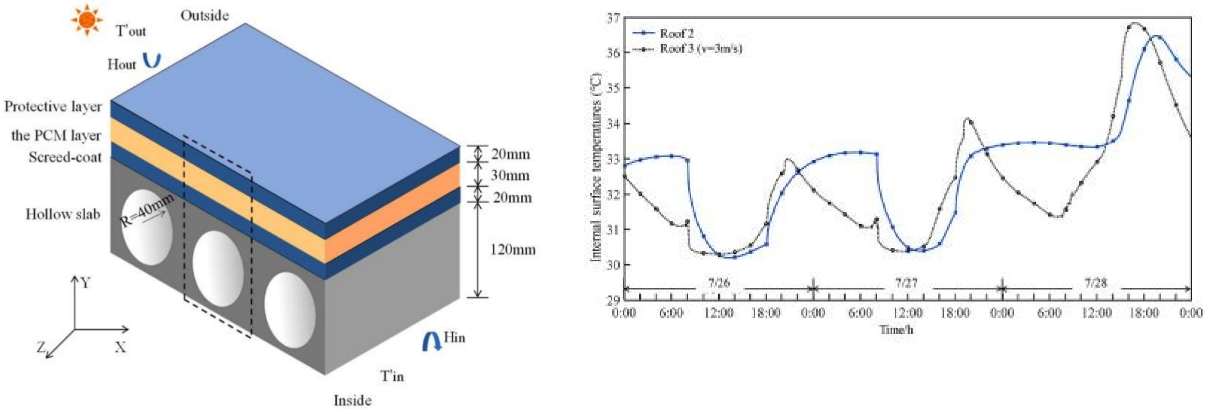


Figure II.9. Schematic of the phase change ventilation roof and the inner surface temperature[70].

Luo et al.[71] developed a numerical modeling approach using a multiple-relaxation time lattice Boltzmann method to investigate the heat transfer characteristics and evaluate the energy-saving capabilities of porous bricks roof impregnated with paraffin waxes when subjected to significant daily temperature variations. The investigation focused on a representative day in July for cities such as Shanghai, Urumqi, Hohhot, Harbin, and Xining. The scientists observed a significant influence of diurnal temperature fluctuations on the performance of PCM. Additionally, climatic parameters impose restrictions on the operational temperature range of PCM. For the cities of Urumqi, Hohhot, Harbin, and Xining, the study recommended using paraffin waxes with phase change temperatures of 28°C, 26°C, 28°C, and 24°C respectively. These specific phase change temperatures were suggested to provide optimal thermal comfort and maximize energy savings in those locations. The corresponding total heat fluxes gained through the roofs were calculated as 95.2 kJ/m², 23.0 kJ/m², 61.6 kJ/m², and 0 kJ/m² for each city.

Bhamare et al. [72] conducted experimental investigations to examine how varying the thickness of the air gap layer affects the thermal efficiency of a roof integrated with a PCM in a test room as shown in Figure II.10. An air layer with a thickness of 2 cm reduces the diurnal temperature variation in the room compared to a non-PCM test room with a higher MKR (Measure of Key Response) index (8.83). Moreover, the application of an air gap resulted in a reduction of solar heat gain, and a maximum decrease of 75% in solar heat gain was observed with a 2 cm air gap.

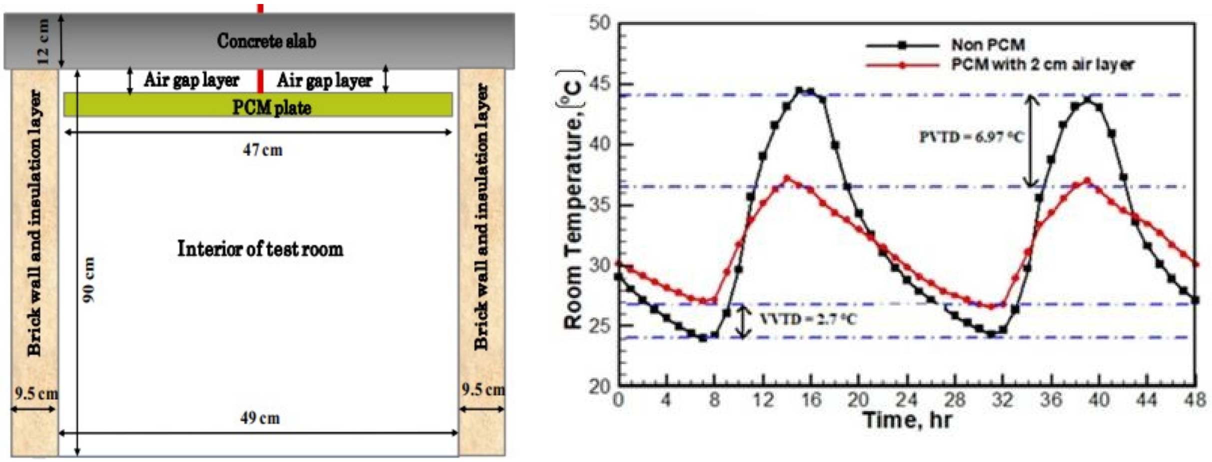


Figure II.10. Diagram and average room temperature variation of the test room[72].

Mustafa et al.[73] conducted a study on utilizing PCM to enhance the thermal efficiency of a radiant cooling ceiling in a building located in Saudi Arabia, specifically in Tabuk City as show in the Figure II.11. The study found that incorporating an air gap and optimally positioning the PCM layer led to a 57.6% reduction in heat transfer through the ceiling during the period from April to the end of October, as well as an annual decrease of 22.6% in heat transfer.

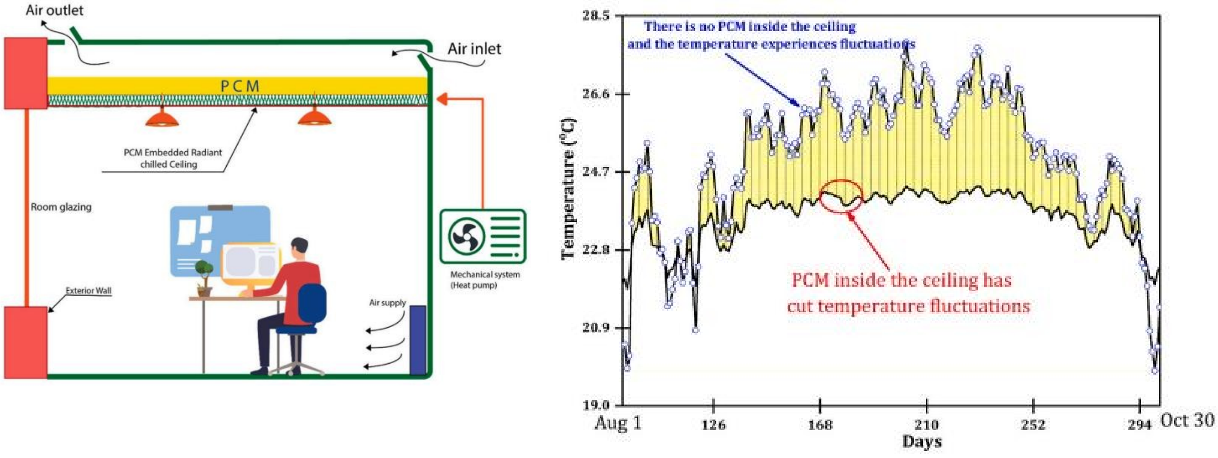


Figure II.11. Diagram of the room featuring a radiant chilled ceiling embedded with PCM, along with the temperature of the roof[73].

Ben Hamida et al.[74] conducted numerical simulations to evaluate the thermal behavior of various roof configurations that integrated with PCMs. The researchers developed and solved the governing equations for a sample unit representative of a typical roof structure. They employed a control volume-based finite element method to solve the coupled equations that describe the heat transfer through the roof as well as the movement of the PCM. The key results showed that enhancing the thermal diffusivity of the PCM relative to the building material led to improved heat transfer performance. Additionally, increasing the wall thickness did not affect the fraction of melted phase change material, but it did diminish the rate of heat transfer through the wall. The results showed that reducing the non-dimensional thickness of the solid layer from 0.5 to 0.005 could increase the heat transfer rate by up to 75%.

Pasupathy and Velraj [75] investigated theoretical and experimental the concept of a dual-layer PCM and delving into its comprehensive use for passive thermal regulation throughout the year. They concluded that employing a double-layer PCM in the roof could diminish fluctuations in internal air temperature, rendering it suitable for year-round utilization. Pasupathy et al.[76] carried out both experimental and numerical studies on the thermal performance of two identical test rooms - one without PCM on the roof, and the other incorporating a PCM panel placed between the bottom concrete slab and the rooftop slab. They performed multiple simulations to examine various factors that could impact performance, such as ambient temperature, heat transfer coefficients, thickness of the PCM panel, and the effect of water circulation through the PCM panel. The findings showed that the PCMl integrated into the roof absorbed the entire heat flow, effectively insulating the inner ceiling surface from external factors and conditions.

Meng et al.[77] compared the performance of three different roof types: one with a highly reflective surface coating, another incorporating PCMs along with high reflectivity, and a third that served as a baseline without any additional features. The goal was to evaluate the thermal insulation capabilities of these varied roof configurations. To facilitate this research, three full-scale room mockups were constructed. The findings revealed that the roof incorporating both high reflectivity and PCMs provided substantial advantages. On cloudy days, it reduced indoor air temperature fluctuations by 8.5%, while on sunny days, the reduction was 17.0%. Additionally, it decreased the inner surface roof temperature by 2.2°C and led to a 66.8% reduction in the inner surface heat flux compared to the baseline roof.

II.2.3 Glass PCM

In recent times, there has been a notable rise in the incorporation of larger glazed surfaces in building designs. These glazed surfaces serve the purpose of enhancing visibility, promoting air ventilation, and maximizing daylight exposure, all while increasing passive solar gain. Glass is commonly used in roofs, windows, and building facades. However, the energy consumption of the building increases due to the baseline thermal inefficiency of glazing materials.To reduce energy consumption, the integration of PCMs into the system proves to be an effective solution. This approach not only addresses energy consumption but also enhances the building's daylighting capabilities[35], [78]–[80]. A lot of researches were conducted to investigate the thermal efficiency of glazed units filled with PCMs.

II.2.3.1 *Windows*

Ismail and Henriquez [81] conducted the forefront research on glass windows incorporated with paraffin, numerous studies have reported that the thermal insulation and thermal storage performances of glass windows filled with paraffin are considerably improved, these improvements lead to reduced indoor temperature fluctuations, the occurrence time is delayed, ultimately resulting in an improved indoor thermal environment for the building.

Grynning et al.[82] investigated the dynamic thermal behavior of a four-pane window with an interior cavity filled with salt-hydrate PCM that had been macro-encapsulated beforehand. The system employed prismatic glass on the outer cavity for controlling transmittance. It was installed in a large-scale test hut within a sizable climate simulator in Switzerland. Additionally, it was compared against a commercially available conventional double-pane window. The findings indicated that the PCM window can enhance thermal comfort, but achieving full PCM activation necessitates high outdoor temperatures and radiation. Li et al [83][84]. Analyzed the thermal characteristics of a double-glazing window containing PCM and discovered that, in addition to the thermos-physical properties of PCM, the optical parameters of PCM play an essential role. Ismail et al.[85] also compared the thermal efficiency of two glass windows in a hot climate. One window is filled with an absorbing gas, while the other incorporates a PCM. Both windows are subjected to solar radiation during the assessment. The study revealed that the solar heat gain coefficient fluctuates between 0.65 and 0.8. Furthermore, the influence of the reflective glasses is important in the case of absorbing gases. Li et al.[86] Examined the thermal performance of glazed windows incorporating Nano-PCM experimentally and numerically across different seasons. Utilizing the experimental results, the numerical model was validated. The study demonstrated that the temperature differential between the inner glazed window surface and the indoor environment ranged from 1-4°C during summer, 5-10°C in autumn, and 14-16°C in winter conditions. However, selecting the optimal nanoparticle size resulted in only a 4% decrease in energy use.

During hot summer conditions, a photovoltaic panel integrated with PCM (PV-PCM) demonstrates superior thermal performance compared to a conventional PCM-glass panel configuration. The PV-PCM system exhibits a notable decrease in heat flow through the panel, attributable to the synergistic effects of the photovoltaic component and the PCMs. As the PV cells absorb a significant portion of the incident solar radiation and convert it into electrical energy, less thermal energy is transmitted into the building envelope. Simultaneously, the phase change materials within the PV-PCM panel undergo a phase transition from solid to liquid, effectively absorbing and storing a substantial amount of thermal energy through their latent heat capacity. [87]. Li et al. [88] similarly evaluated the efficiency of air-filled double-glazed windows versus glass panels incorporated with PCM. Additionally, Biwole et al.[87] investigated a passive solar wall made of glass bricks containing PCM, with an added layer of silica aerogel. According to their results, a building's orientation and geographic location influence how effectively PV-PCM reduces heat transmission between its interior and exterior window surfaces.

II.2.3.2 *Roof Glass*

The glazed roof, known for its better lighting performance, is extensively integrated into modern building designs. However, despite their exceptional lighting performance, glazed roofs are often criticized for their relatively poor thermal insulation properties. The inherent nature of glazing materials, which prioritizes visible light transmittance over thermal resistance, can lead to significant heat gains or losses through the roof assembly, depending on the outdoor conditions. This thermal vulnerability can potentially compromise indoor thermal comfort levels, leading to excessive cooling or heating loads to maintain desired interior temperatures. To address this, an insulating glazed roof integrated with PCM to enhance the indoor thermal environment and minimize energy usage while maintaining adequate indoor lighting. Li et al. [89] conducted experiments to investigate the influence of glazed roof-filled PCM with different melting temperatures, glazed roof slopes, and PCM layer thicknesses on the thermal performance of the building. They specifically looked into how these factors affect the thermal mass of the roof and impact energy usage and occupants' comfort levels in the indoor environment. The findings indicated a substantial decrease in energy consumption when PCM is used in the glazing unit instead of air. Additionally, by utilizing PCM with a melting temperature of 32°C, the peak temperature decreased by approximately 16.3°C, the time lag increased to about 40 minutes, and energy consumption decreased by 47.5%. Mao et al.[90] numerically investigating the thermal dynamics of a double-slope PCM glazed roof involved exploring different parameters such as the roof angle, PCM thermophysical characteristics, and glazing physical properties. The study reveals that in Wuhan's typical hot summer and cold winter climate, the optimal melting temperature ranged between 26 - 30°C. Increasing the thickness of both the PCM layer and the glazing layer effectively improves the roof's thermal insulation capabilities. Furthermore, optimizing the heat transfer performance is achievable by reducing the angle of the roof; transitioning from a 45° to a 30° demonstrates notable improvements. To assess the thermal performance and energy efficiency of an innovative roof incorporating SA-PCM glazing systems, a numerical model was developed by Zhang et al.[91] this system involves dividing the PCM layer into five cavities horizontally, for PCM and air filling. Assessment of the roof's thermal performance was carried out using indicators such as the temperature decrement factor, temperature time lag, and energy efficiency. The increased PCM content of the innovative roof is responsible for the improved thermal performance, as seen by the lower amplitude and higher phase shift of temperature waves on the inner surface. Moreover, both transmittance and absorptance of the roof exhibit significant variations throughout the day with varying PCM fill ratios, whereas reflectance changes minimally. Notably, the optimal energy efficiency of the innovative roof is achieved at an 80% fill ratio of PCM.

II.2.4 PCM integrated into bricks or block.

Clay bricks continue to be the predominant construction materials in modern buildings. Bricks crafted from cement and fire clay are frequently employed in constructing walls for different buildings. These materials offer numerous advantages, including durability, strong mechanical properties, ease of installation, and a relatively high insulation capacity due to the low thermal conductivity of the air trapped in the brick's cavities. Nevertheless, its thermal effectiveness is limited in areas with harsh climatic conditions[92][93][94]. To address this limitation, it is proposed to integrate PCM into bricks. It is acknowledged that incorporating PCM into building bricks with openings or hollow cavities presents a relatively simple and uncomplicated process. During the phase change process, liquid PCMs can easily leak, leading to a loss of their heat storage capacity. Hence, the selection of the method for incorporating PCM into bricks is important. Methods for integrating PCM into buildings encompass *direct* incorporation and *indirect* incorporation[95][96].

Numerical and experimental studies are being conducted on the integration of PCM to bricks. This section will evaluate the enhancement of PCM bricks' thermal performance, considering factors such as the external environment, filling position, heat transfer surface area, packaging shape, thickness, thermal properties, and heat transfer technology.

II.2.4.1 *The influence of PCM thermal properties*

The type of PCM, as well as its thermal properties including thermal conductivity, phase change temperature, and latent heat, influence the thermal performance of bricks. Alawadhi [97] conducted a numerical analysis of the efficiency of a brick-PCM system designed for use in hot climates. The research analyzed a brick with three cylindrical holes, which were filled both completely and partially with different PCMs. Then, a comparison was made between the thermal performance of the different configurations and the baseline case, which consisted of a brick without PCM. The findings of the study highlight the positive impact of PCM on the thermal behavior of the brick. Similarly, Kant et al.[98] investigated the thermal performance of commonly used building bricks with cylindrical cavities filled with different types of encapsulated PCM using a computational method, specifically employing the finite element method. The simulation considered convective transfer and mass within the PCM cavities. A dedicated three-day period was allocated to assess the potential effectiveness of utilizing PCM in building bricks. The study evaluated three scenarios, including the use of common bricks, air-filled bricks, and PCM-filled bricks. The findings indicated that capric acid PCM exhibited superior performance compared to RT-25 and other PCMs.

II.2.4.2 *The influence of PCM filling position and quantity*

Through simulation and experimentation, it is possible to quickly determine how the quantity and location of PCM filling affect the thermal performance of the brick wall. Furthermore, simulations facilitate the convenient optimization of factors that influence the thermal performance of PCM brick walls. Before conducting experiments, simulations can assist in selecting PCMs with appropriate phase change temperatures. This aids in maximizing the utilization of PCM latent heat in specific climatic regions and enhancing the heat storage capacity of PCMs. Zhang et al. [99] investigated the impact of PCM quantity on the temperature of the inner wall constructed using a Sierpinski carpet fractal pattern. The results indicated that increasing the quantity of PCM reduces peak temperatures and decreases temperature fluctuations. Silva et al.[100] built a comparable experimental setup using fire clay bricks containing PCM encapsulated within a steel container, as depicted in Figure II.12. For the PCM, they utilized natural paraffin (RT 18) with a melting point of 18°C. This paraffin was encapsulated in macro-capsules and placed inside the central cavity of the bricks. The results showed that incorporating the PCM led to a reduction in indoor space temperature between 5°C and 10°C, as well as delaying the time to reach maximum temperature by approximately 1 to 3 hours, when compared to the scenario without PCM.

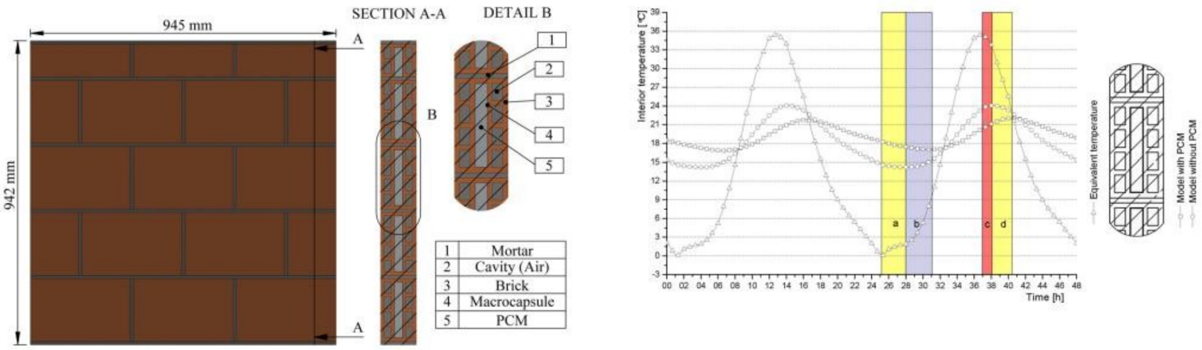


Figure II.12. depicts the configuration of the system and the fluctuation in interior temperature[100].

Hichem et al.[101] filled the cavity of hollow clay bricks with five different PCMs, each having a melting temperature, ranging from 29.9℃ to 52℃. The configurations of the bricks and outcome results are provided in Figure II.13. The hollow cavities of the bricks were filled with solid PCM encapsulated in polystyrene, and the location of the PCM was varied in the numerical investigation. $CaCl2 \cdot 6H2O$ exhibited enhanced performance when applied in the middle of the brick. Increasing the quantity of PCM resulted in more improvement in thermal performance.

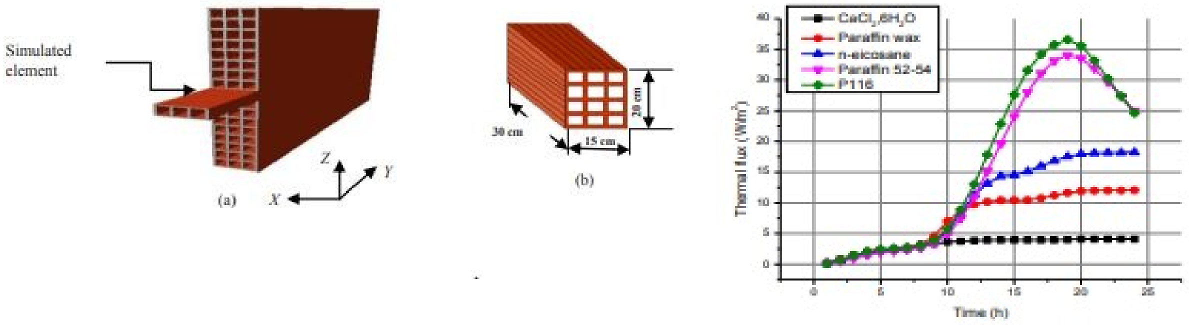


Figure II.13. The configurations of the bricks' dimensions and the hourly variation of thermal flux were observed with the PCM positioned in the middle[101].

Mukram and Daniel[102] experimentally analyzed the thermal performance of cement bricks filled with PCM encapsulated in an aluminum container within the center cavities. The experimental analysis involves constructing a model and comparing the heat transfer rate with a similar conventional brick. in this study, The phase change material HS 29, a commercially available PCM with a 29°C phase change temperature, was employed. This analysis demonstrates that placing a PCM in the middle of the brick leads to a reduction of approximately 5°C in the interior wall temperature. Moreover, by integrating PCM into the building envelope enhances the thermal comfort of the interior space and simultaneously improves the energy efficiency of the building. The thermal performance of a conventional brick integrated with PCM was studied by Tunçbilek et al.[103] The effect of bricks containing PCM on heating and cooling loads was investigated, taking into account different melting temperatures, positions, and quantities of PCM. The results demonstrated promising potential, showcasing improved thermal performance, especially when outside temperatures are high, as in the summer months. Substantial energy savings were observed when the PCM was strategically placed within the cavity closer to the interior side across all the investigated scenarios. This strategic positioning of the PCM within the bricks led to a notable 17.6% reduction in annual energy demand and a corresponding 13.2% decrease in overall energy consumption attributed to the integration of the PCM.

Elmarghany et al.[104] conducted numerical investigations into the thermal performance of bricks integrated with PCM over one year. They evaluated the impact of using different types of PCM and arrangements as shown in the Figure II.14. Through validating their computational model with experimental data, researchers discovered that the integration of PCM into brick structures improves the thermal properties of building materials by modifying the thermal storage capacity of the walls and reducing and shifting the peak loads on the building. Furthermore, PCM exhibited the ability to reduce the annual average indoor surface temperature by 1.5%.

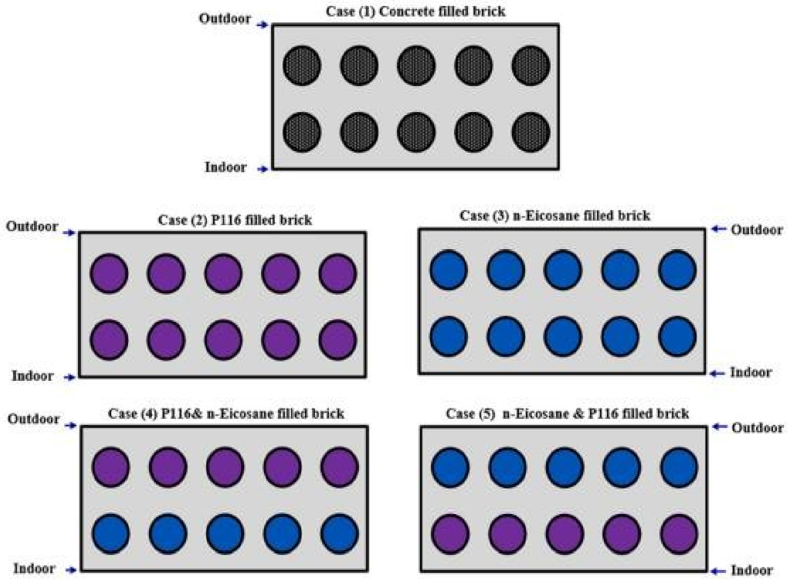


Figure II.14. represents five different cases of brick-integrated PCM utilized in the year-long simulation[104].

Chihab et al.[105] conducted a numerical investigation on integrating three passive strategies into the hollow clay brick walls commonly found in Moroccan architecture. The goal was to enhance thermal comfort and energy efficiency in buildings situated in the climate of Marrakesh. The results showed that the most significant improvement in the thermal inertia characteristics of the hollow clay brick walls was attained by filling the middle cavities with a PCM having a melting point of 32°C, combined with the application of low-emissivity paint or insulation material within both the internal and external cavities of the bricks.

Saeed. [106] numerically investigated the influence of using two PCM types within brick structures on a summer day, subjected to the climate of Medina, Saudi Arabia. Bricks containing square cavities filled with PCM are positioned on the inner sidewall. In this context, PCM types P116 and n-Eicosane are employed to fill the bricks and are compared to the case without PCM. Furthermore, the impact of varying PCM quantities is examined. The finding indicated that incorporating PCM within the brick decreases the heat flux passing through the wall. Specifically, the utilization of PCM n-Eicosane leads to a reduction in the rate of heat flux.

Hasan et al.[107] conducted a comparative study involving three concrete blocks - Block A without PCM, and Blocks B and C incorporating PCM. Blocks B and C had different configurations, with the PCM and insulation layers positioned differently within each block, as shown in Figure II.14. The integration of PCM led to a 44% reduction in indoor heat flux for Block B and a 10.5% reduction for Block C over a 24-hour energy balance period. Additionally, there was a 2.6-hour delay in reaching the peak indoor temperature. Block B consistently maintained lower temperatures than the reference Block A throughout the day and a significant portion of the night. Similarly, Block C exhibited cooler temperatures than Block A during daytime but higher temperatures during nighttime hours.

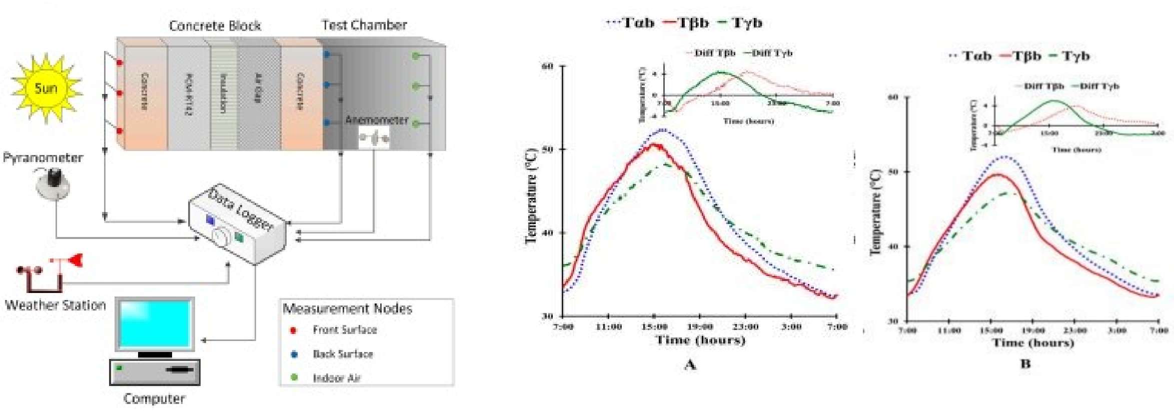


Figure II.15. Diagram outlining the experimental arrangement and progression of temperatures on the blocks surface[107].

II.2.5 The influence of outdoor conditions

Recently, several studies have been carried out to investigate the effect of external conditions on the thermal behavior of building brick walls integrated with PCM. Arunkumar et al.[108] carried out a combined numerical and experimental study on walls constructed using bricks integrated with PCM and conventional bricks. They utilized an organic PCM, OM 29, with a melting temperature of 29°C, which was assumed appropriate for the specific location under investigation. The PCM was incorporated into the central cavities of the brick blocks. The results demonstrated the effectiveness of the PCM in reducing heat transfer, leading to a 5.7% decrease in temperature and a 33% reduction in heat gain for the bricks containing the PCM compared to those without. This type of PCM brick exhibited greater thermal performance in hot and arid climatic conditions than in moderate climates. Two identical test rooms measuring 3 m × 3 m ×

3.65 m were built by Kumar et al.[109] one having a conventional clay brick wall and the other having a brick integrated with encapsulated PCM. The study employed a commercially available hydrated salt PCM, HS 29. The PCM was encapsulated within aluminum foils and positioned within the brick cavities, with experiments conducted under warm and humid weather conditions. The results confirmed that incorporating PCM into the walls led to a reduction in room temperature ranging from 2°C to 6°C. Furthermore, it was observed that walls constructed using PCM bricks exhibited improved thermal performance during the winter season, achieving a temperature decrease of up to 6°C. However, the effectiveness of the PCM was less pronounced during the summer months, with the maximum reduction in room temperature reaching only 2°C. Dabiri et al.[110] A thermal analysis was conducted utilizing a CFD model. The model was constructed by integrating PCM within steel capsules positioned centrally within a brick containing cylindrical air cavities. The objective was to investigate the thermal performance of a brick incorporating PCM and assess the role of PCM in enhancing thermal comfort. The analysis revealed that even during the coldest day in Tehran, Iran, room temperatures remained close to thermal comfort levels despite fluctuations in external temperatures over time. The conclusive findings confirmed that PCM bricks effectively regulated thermal conditions during both winter and summer seasons. However, heat storage predominantly exhibited sensible characteristics during winter and latent characteristics during summer. Hamdaoui et al.[111] numerically investigated the thermal behavior of four unique hollow clay bricks, each incorporating phase change materials within their solid matrix. Utilizing a CFD code, the physical model depicted in Figure II.16 was analyzed. The primary objective was to assess the effectiveness of bricks containing PCM in enhancing thermal comfort. The findings indicated that the thermal performance of the bricks was enhanced when PCM was incorporated, particularly on the hottest day in Marrakesh, Morocco. Mahdaoui et al. proposing the utilization of numerical analysis for evaluating the thermal behavior of hollow clay bricks incorporating PCMs embedded within a solid matrix. The computational domain is partially identical to the one analyzed in [111]. The investigation examines the influence of both indoor and outdoor conditions on the thermal response of the hollow bricks, along with the thermo-physical properties of PCM. The findings suggest that integrating PCM into walls can reduce the heat transfer rate within the walls, thereby reducing temperature fluctuations in buildings.

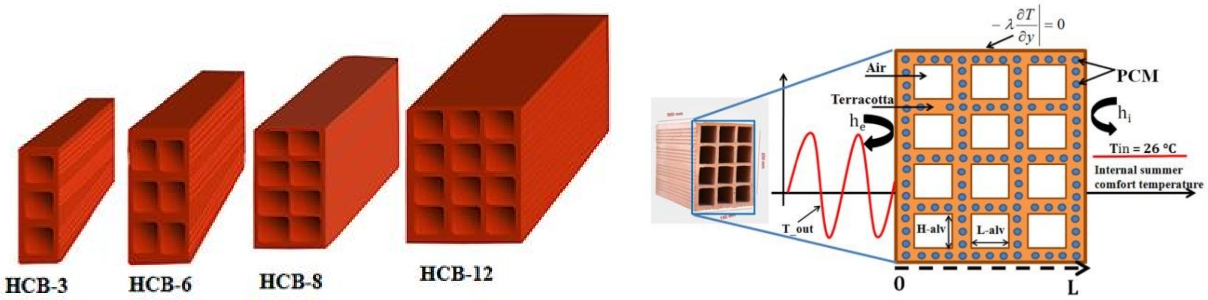
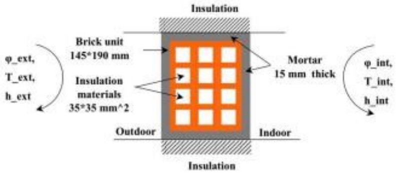
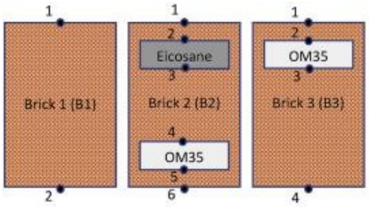
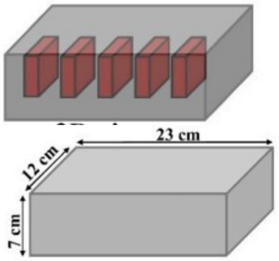
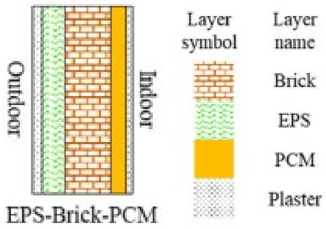
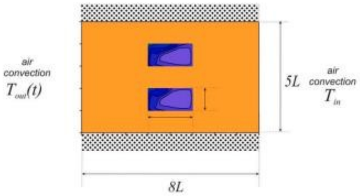
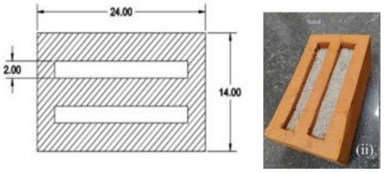
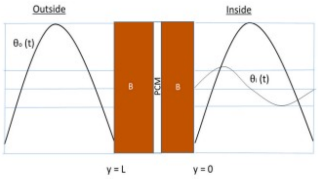
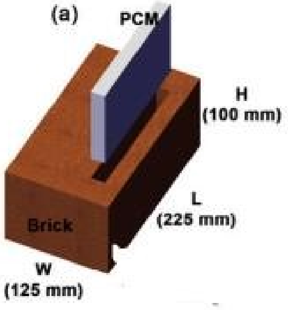


Figure II.16. The different hollow clay bricks and PCM holes studied by [111] [112]

Rehman et al.[113] conducted a numerical investigation of a novel dual-layer PCM design for brick walls in Islamabad, Pakistan, aimed at sustaining human comfort in both hot and cold climates. Utilizing Ansys Fluent, numerical simulations were conducted. Their research indicates that the dual PCM arrangement is optimal for both summer and winter conditions. The continuous charging and discharging enabled by this arrangement resulted in an interior temperature range of ±0.4°C from June to January.

Table II.1. Studies on the integration of PCMs into building bricks.

Author	Physical model	Study	Key results
Fraine et al. 2019[114]		A numerical analysis was conducted to replace the substitution of EPS insulation in Algerian buildings brick with PCHCM. The finite element method was employed to formulate and solve a coupled two-dimensional model for heat and humidity transfer.	The research revealed that using PCM in the hollow clay bricks led to a significant decrease in fluctuations of indoor temperature and humidity levels when compared to bricks containing EPS .
Saxena et al. 2020[115]		Experimental investigation was conducted on PCM bricks under real-world conditions, subsequently followed by an assessment of the impacts of various PCM brick configurations.	In comparison to conventional bricks, bricks with single and dual PCM layers decreased heat transfer by 40 to 60%.
Al-Yasiri and M Szabo 2021[116]		Experimental analysis was conducted to evaluate the thermal performance of concrete bricks incorporating macro-encapsulated PCM under the hot summer conditions of Iraq.	The thermal efficiency of concrete bricks could be significantly enhanced through the use of PCM. Among the bricks tested, those containing five macrocapsules of PCM exhibited better performance compared to others.

Aakash C. Rai 2021[117]		Numerical examination to evaluate the thermal behavior of various wall brick configurations that were enhanced by the incorporation of insulation materials and PCM layers.	The effectiveness of utilizing the latent heat storage capacity of the PCM was dependent on its melting temperature and its positioning within the wall. The study recommends placing the PCM layer on the interior side of the wall, combined with sufficient insulation to shield it from external environmental conditions outdoors.
Bondareva and Sheremet 2021[118]		Numerical thermal analysis was conducted on a rectangular brick block integrated with two paraffin PCMs.	The effectiveness of PCMs in reducing heat gains is greatest when their melting temperatures are high and align with very hot ambient temperatures. However, PCMs lose their thermal regulation benefits if their melting points approach or exceed the maximum outdoor temperatures.
Gupta et al. 2022[119]		Experimental investigation evaluated the thermal efficiency of clay bricks utilizing sensible, latent, and hybrid heat storage materials..	The PCM brick demonstrated superior performance, achieving a reduction in peak temperature by 3.82%, a decrease in thermal amplitude by 13.74%, and a time lag of 180 minutes compared to conventional bricks.
Shaik et al. 2022[120]		An experimental and numerical investigation on the cost-saving potential of air conditioning in houses built using PCM-integrated burnt clay bricks.	Among the different configurations studied, the duplex house design with the outer brick layers incorporating the PCM OM29 demonstrated the greatest annual reduction in energy costs.
Agarwal and Prabhakar 2023[121]		A numerical investigation conducted using MATLAB aims to explore potential energy conservation strategies for buildings in Jaipur's summer climate. This research focuses on changing the positions and thicknesses of PCM-integrated clay bricks.	PCM integration within bricks consistently reduces indoor temperature fluctuations, however, the extent of this impact depends on the placement, thickness, and characteristics of the PCM.

II.3. Numerical Simulation of Buildings with PCMs

II.3.1 Simulation of PCM-based Buildings

A solid understanding of how buildings with passive systems utilizing PCMs perform thermally is important for building researchers. It aids them in understanding the temperature behaviors of buildings and evaluating the economic feasibility of PCM usage. Regardless of the extensive experimental efforts in research, the complex and transient thermal characteristics of building components containing PCMs, along with the associated costs of experimental setups, highlight the necessity of employing numerical models for a comprehensive examination of the thermal efficiency of this system. Developing a comprehensive understanding of how building systems incorporating PCM technology function is important for devising effective strategies to optimize the utilization of PCMs. Such an in-depth knowledge is essential for maximizing the potential benefits offered by PCMs in enhancing overall building energy efficiency and improving indoor thermal comfort conditions for occupants. By fully understanding the underlying principles and behavior of PCM-based building envelopes or building element, architects, engineers, and building professionals can make informed decisions regarding the appropriate selection, integration, and control of PCM components within the building envelope design. This deeper insight enables the implementation of measures that leverage the latent heat storage capabilities of PCMs to their fullest extent, facilitating effective thermal regulation and energy management within the built environment. Ultimately, a solid By fully understanding of this technology paves the way for widespread adoption and successful implementation of PCM-based building systems, contributing to the realization of energy-efficient and thermally comfortable indoor spaces.

II.3.2 Simulation Tools

Currently, numerous simulation tools are available for evaluating the thermal performance of buildings and building elements integrated with PCM. A lot of computational analyses have been carried out to explore the impacts of integrating PCMs into building envelopes. These research studies explore a wide range of variables that impact the thermal performance of building envelopes incorporating PCMs. The factors investigated include the positioning and placement of the PCM components within the building envelope assembly, the amount or quantity of PCM utilized, the thermophysical properties of the specific PCM, the thickness of the PCM layer, as well as the outdoor and indoor environmental conditions to which the PCM-integrated envelope is exposed. All of these elements play a role in determining the effectiveness of the PCM system in regulating and improving the thermal behavior of the building envelope and element. There exist numerous numerical methods to effectively modulate the integration of PCMs into building envelopes. Enthalpy function and heat capacity methods[122][123] are extensively used for evaluating thermal performance building envelope integrated with PCM. These investigations have utilized diverse software platforms, including ANSYS Fluent[124][125], COMSOL Multiphysics[27][126], and MATLAB[127], among others. They provide an extensive range of numerical solution techniques that are not exclusively limited to building energy simulation, the table II.2. summarizes some numerical studies utilizing software for PCM integration into the building envelope. In fact, they can be used for any system with a well-structured simulation plan. Figure II.17. provides a comprehensive overview of the simulation approach methodology used to calculate thermal performance [128]. The highlighted simulation tools are recognized for their versatility and reliability. However, this dissertation also employs the ANSYS Fluent software to construct the model, simulate the thermal behavior of building bricks with PCM integration subjected to hot climate conditions, and investigate energy-saving strategies.

Table II.2. Studies using software tools on the incorporation of PCMs into building envelope.

Climate	**software**	**Application**	**Key results**	**Ref.**
Algeria	TRNSYS 17	Heating and cooling	Based on the simulation results, the office temperature increased by 4°C during winter and decreased by 7°C during summer, attributed to the integration of PCM in the hollow brick walls and concrete ceiling.	[129]
Auckland, New Zealand	EnergyPlus®	Heating	The findings indicated that there was only a modest amount of load shifting during the morning peak period. Nevertheless, the study extensively emphasized the potential of heating control in this regard. Over a ten-day period, effective control of the underfloor heating system resulted in a 42% cost reduction and a corresponding 32% decrease in energy consumption. This cost saving was achieved through both energy conservation and peak load shifting.	[130]
Latvia	COMSOL Multiphysics 5.1	Heating and Cooling	In colder regions, the utilization of a Fresnel lens, combined with PCM and insulation, has the potential to elevate interior temperatures and consequently decrease the energy consumption required for building heating.	[131]

Chiba Prefecture, Japan	EnergyPlus	Heating	Expanding the installation area of the PCM led to a larger absorption surface for solar radiation. Consequently, the melting and solidification durations of the PCM decreased while its heat storage capacity increased. This resulted in a reduction in diurnal temperature fluctuations and an enhancement in the efficiency of the PCM.	[132]
-	FLUENT 15.0	Heating	Research has demonstrated that employing an appropriate numerical model alongside accurate thermophysical properties allows for accurate predictions of PCM thermal behavior as well as air outlet temperatures. Among the numerical models, the effective heat capacity method is recommended for PCM thermal performance analysis.	[133]
Bojnourd, Iran	ANSYS Fluent 17	Heating	The appropriate quantity of paraffin significantly affects the economic considerations of the solar air heater, as well as its weight and the space occupied by the PCM. The findings indicated that utilizing 4 cm of paraffin layer thickness led to nearly optimal performance for the SAH.	[134]
Climatic Chamber	ANSYS Fluent	Heating and cooling	PCM helped decrease the need for heating and cooling to maintain thermal comfort.	[26]
Tehran, Iran	ANSYS Fluent 18.0	Heating and cooling	During both summer and winter, integrating PCM into the brick resulted in a reduction of 48.5% and 44%, respectively, in the magnitude of internal temperature fluctuations.	[110]
Chile, Spain.	EnergyPlus®	Heating and cooling	The numerical findings highlighted the potential of utilizing gypsum boards enhanced with PCM in lightweight buildings to enhance energy efficiency throughout both heating and cooling seasons in arid and warm temperate regions.	[66]
Ljubljana, Slovenia	Fluent	Heating and cooling	It is apparent that the accumulated heat or cold is relatively minor when juxtaposed with the overall heating and cooling loads experienced within a workplace. Nevertheless, there exists a potential for a yearly reduction in the energy consumption of an office by about 142 kWh.	[135]
China	MATLAB	Heating	The energy-saving rate during the heating season consistently rises with an increase in both the phase change enthalpy and thickness. Notably, the enthalpy has a greater impact than the thickness.	[136]
Wuhan, China	TRNSYS	Heating and cooling	When PCM layers are applied to both the interior and exterior surfaces of the wall, there is a reduction in energy consumption of 20.51% during winter and 0.65% during summer. Alternatively, placing PCM layers only on the interior surfaces of the wall results in a reduction of 18.75% during winter and 13.46% during summer.	[137]
Béchar, Algeria	TRNSYS	Heating and cooling	Decrease in yearly heating and cooling demands by 12.8% and 1%, respectiely.	[138]

Benguerir Morocco Sem aird	EnergyPlus	cooling	The most effective PCM for the semi-arid climate was RT-28 HC. Additionally, using double or triple layers of PCM is more efficient than using a single layer, resulting in energy consumption reductions ranging from 7.30% to 15.21%.	[139]
Anda, china cold	EnergyPlus		The optimal melting temperature for the largest energy saving is 16°C. Placing the PCM close to the inner surface within the wall results in a 12.9% energy savings.	[61]

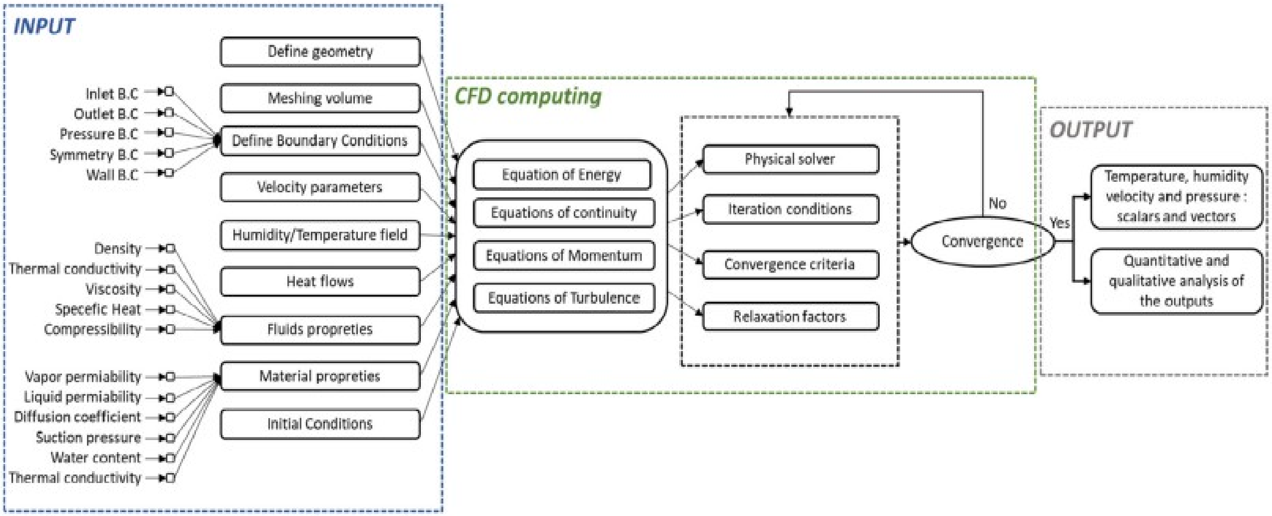


Figure II.17. illustrates a detailed schematic representation of the nodal approach employed in simulating of hygrothermal phenomena.

II.4. **Summary**

The integration of PCMs into building elements offers a transformative potential in the utilization of thermal energy. PCMs have the unique capability to store and release large amounts of energy as they undergo phase change between solid and liquid states, effectively regulating indoor temperatures. By embedding PCMs within building materials such as walls, floors, or ceilings, structures gain the ability to passively absorb and release heat, thereby reducing reliance on active heating or cooling systems. This versatility not only enhances comfort levels within buildings but also contributes to significant energy savings and environmental sustainability. Additionally, PCM integration allows for better management of peak energy demand, particularly during extreme weather conditions, ensuring more efficient operation of HVAC systems and reducing overall energy consumption. The incorporation of PCMs represents a promising avenue for improving the thermal performance of buildings and advancing towards more sustainable built environments. Within this chapter, an exhaustive literature review has been undertaken to evaluate previous research about the integration of PCMs into various building elements aimed at enhancing thermal regulation. From this review, several key findings have been synthesized and are outlined below.

Compared to conventional heating and cooling systems for buildings (1), PCMs offer significant advantages due to their high heat energy storage density and isothermal characteristics. Utilizing PCMs within building elements offers the opportunity to exploit renewable resources such as natural cooling and solar energy storage. (2) offer a versatile and efficient solution for shifting a building's energy demand from peak to off-peak periods, ultimately contributing to reduced energy costs, improved grid stability, and enhanced sustainability; (3) throught this strategy and technology, buildings can effectively mitigate temperature fluctuations, optimize energy usage, and contribute to largely energy conservation efforts, ultimately leading to a more sustainable and comfortable built environment. PCMs are categorized into three main types: eutectic, inorganic, and organic. This literature review of current research reveals that around 86% of previous studies investigating PCM applications in buildings predominantly utilize organic PCMs. This preference arises from their suitable melting points, non-corrosive properties, absence of supercooling, and compatibility with building materials. PCMs intended for use in buildings must meet safety, reliability, and thermal performance criteria. Research indicates that currently employed melting points cover a large temperature range from 16°C to 40°C. Ideally, the melting point should close to temperatures at which occupants experience optimal comfort.

Additionally, when choosing the melting temperature of PCM, it's essential to consider the environmental conditions to which a building is subjected. Due to its cost-effectiveness and ease of utilizaion, integrating PCMs into building bricks is recommended over different building elements. Moreover, the comprehensive review of existing literature reveals that a majority, around 55%, of the analyzed studies choosed to strategically position the PCM closer to the interior side of the building component or assembly. This interior placement of PCMs is favored as it allows the thermal mass to effectively regulate indoor temperatures and improve thermal comfort within the occupied spaces. In contrast, a a few studies, approximately 21%, preferred incorporating the PCM in the middle section of the building element, potentially aiming to leverage the insulative properties of the PCM for better thermal regulation. Meanwhile, around 24% of the reviewed studies favored positioning the PCM on the exterior side of the building components, likely to mitigate external heat gains before they penetrate the building envelope.

Regarding the methods employed for integrating PCMs into building materials, the review indicates a shift towards the adoption of more advanced and sophisticated methods in recent studies. Traditional methods of directly integration of PCMs into porous building materials are increasingly being replaced by modern encapsulation processes such as microencapsulation, nanoencapsulation, and shape-stabilization. These advanced techniques offer improved compatibility, stability, and durability of the PCM-enhanced building materials, addressing potential issues such as leakage or degradation of the PCM over time. Moreover, encapsulation methods facilitate better control over the phase change behavior and thermal performance of the integrated PCMs, ensuring more efficient and reliable thermal energy storage and release cycles within the building envelope.

Furthermore, it is noticed that a higher number of articles on the thermal analysis of buildings integrated with PCM have been published in recent years, with many researchers choose to use the ANSYS FLUENT software for their computational fluid dynamics simulations and numerical modeling. This trend can be attributed to the advanced capabilities of ANSYS FLUENT in handling phase change process and its ability to accurately simulate the complex heat transfer mechanisms involved in PCM-enhanced building envelopes. The software's robust meshing tools, coupled with its extensive material property database and user-defined function (UDF) capabilities, have made it a popular choice among researchers exploring the thermal performance of PCM-integrated building components under various operating conditions and climate scenarios. Additionally, the availability of comprehensive post-processing tools in ANSYS FLUENT has facilitated the detailed analysis and visualization of temperature distributions, heat flux profiles, and other relevant thermal parameters, thereby enhancing the understanding of the thermal behavior of PCM-based building systems.

CHAPTER III:

Mathematical model and numerical method

CHPTER III: Mathematical model and numerical method

III.1. Introduction

The utilization of numerical modeling in the investigation of PCMs integration into building brick walls has gained significant traction, primarily owing to its high efficiency and robust stability. Numerical simulation techniques offer several advantages over experimental approaches, including cost-effectiveness and widespread applicability. These methods allow researchers to accurately simulate complex thermal phenomena and assess the performance of PCM-integrated building systems under various conditions. Furthermore, numerical modeling enables rapid prototyping and optimization of design parameters, facilitating the exploration of a wide range of scenarios without the need for extensive physical experimentation. As computational capabilities continue to advance, numerical simulation remains a valuable tool for researchers and engineers seeking to enhance the thermal performance and energy efficiency of buildings through PCM integration. It enables a comprehensive understanding of different thermal transfer phenomena and their coupling. When investigating the thermal performance of PCM bricks, considerations must include the movement of the solid-liquid interface, heat conduction within the solid and liquid phases, and the effects of PCM flow on heat transfer. At present, predominant approaches for calculating the thermal performance of PCM involve employing mathematical models and control equations such as those derived from the enthalpy method [140], heat capacity method [141], temperature transformation model [142], heat source method [143], or alternative methodologies [144]. This study uses the enthalpy porosity approach to capture the behavior of different types of PCM integrated to building brick.

To formalize the PCM brick model, it is necessary to describe the coupling of temperature, pressure, velocity, and the melting-solidification process using the conservation equations of momentum, mass, and energy. These fundamental equations govern the complex interactions between the various physical phenomena occurring during the phase change process within the PCM-enhanced brick. The conservation of momentum equation, also known as the Navier-Stokes equation, is employed to capture the velocity field and pressure distribution within the molten PCM during the melting phase. This equation accounts for the effects of buoyancy-driven natural convection, which plays a crucial role in enhancing the heat transfer process within the liquid PCM and air inside the brick cavities. The conservation of mass equation, also referred to as the continuity equation, ensures that the mass is conserved throughout the melting and solidification cycles. This equation is essential for tracking the phase transition front and the associated density changes within the PCM as it undergoes the phase change process. The conservation of energy equation, often referred to as the heat equation, describes the temperature distribution and heat transfer mechanisms within the PCM brick. This equation incorporates the latent heat associated with the phase change process, as well as the conductive and convective heat transfer modes. The accurate modeling of the energy equation is crucial for predicting the thermal performance of the PCM brick and its impact on the overall building thermal behavior.

This chapter aims to present the mathematical models and governing equations used to analyze the cases investigated in this thesis. The modeling approach relies on the fundamental conservation laws of physics, including the conservation of mass, momentum, and energy. These conservation principles are expressed in the form of partial differential equations that describe the underlying physical processes. After formulating the necessary conservation equations, the chapter will proceed to introduce the numerical method employed to solve these coupled, non-linear equations.

III.2. **General equations**

To accurately simulate the heat transfer and phase change phenomena occurring within building bricks integrated with PCMs, it is essential to establish mathematical relationships among various parameters, such as velocity, pressure, temperature, and mass fraction. These governing equations are derived from the fundamental conservation laws of physics, including the conservation of mass, conservation of momentum, and conservation of energy. By applying these general conservation principles to the specific context of PCM-enhanced building bricks, this study can obtain a set of equations that capture the intricate coupling between fluid flow, heat transfer, and the phase transition processes involved in the melting and solidification of the PCM. These specialized equations provide a comprehensive mathematical framework for modeling the thermal behavior and phase change dynamics within the PCM-integrated brick system subjected to the real hermal condition, enabling accurate predictions and analysis of its thermal performance.

III.2.1 Continuity equation

The principle of mass conservation for a defined control volume of material is represented by this equation:

$$\frac{\partial\rho}{\partial t}+\vec{\nabla}(\rho.\vec{V})=0 \tag{III.1}$$

Where ρ is the density and V is the velocity vector.

III.2.2 The momentum conservation equation

The second law of dynamics states that the rate of change of momentum within a defined control volume *D* is equal to the sum of all external forces acting upon that control volume. This fundamental law is mathematically expressed as an equation that relates the temporal variation of momentum inside the control volume to the net force exerted on it by external sources, such as pressure, viscous stresses, and body forces like gravity. This law is expressed as follows:

$$\frac{D}{Dt}\int_D \rho.\vec{V}dV=\int_D F\,dV+\int_D \rho.\sigma\,dS \tag{III.2}$$

D represents the control volume domain *(V)*, S denotes the surface of the continuous medium, and

σ signifies the constraint vector.$\vec{V}$

The momentum conservation equation can be written as:

$$\underbrace{\frac{\partial(\rho\vec{V})}{\partial t}+\nabla.\rho\vec{V}}_{\boxed{a}}=\rho F-\underbrace{\nabla P}_{\boxed{b}}+\frac{1}{3}\underbrace{\nabla\mu(\nabla.\vec{V})}_{\boxed{c}}+\mu\underbrace{\nabla^2\vec{V}}_{\boxed{d}} \tag{III.3}$$

a: The rate of variation and transport of quantity of movement.

b: Forces due to pressure

c: Brinkman's viscous term.

d: Viscosity forces.

Where: *F* and μ are a force per unit of volume and the dynamic viscosity, respectively.

III.3. **Energy conservation equation**

The energy conservation equation is derived from the first principle of thermodynamics and can be expressed as:

$$\underbrace{\frac{D(\rho c_p T)}{Dt}}_{\boxed{a}} = \Delta\underbrace{(kT)}_{\boxed{b}} + q + \underbrace{\beta T \frac{Dp}{DT}}_{\boxed{c}} + \underbrace{\mu\varphi}_{\boxed{d}} = 0 \tag{III.4}$$

With:

a: The total variation of energy (by accumulation and convection).

b: The variation of energy by conduction.

q: Power density dissipated.

c: The energy variation due to compressibility.

d: Irreversible dissipation due to viscous friction.

c_p, k, β are the heat capacity, the conductivity thermal and the isobaric coefficient of expansion of the fluid, respectively.

III.3.1 **Boussinesq approximation**

The Boussinesq approximation is a simplified approach to the Navier-Stokes equations, which govern the behavior of incompressible fluid flows. This approximation is employed in situations where a vertical density gradient exists, leading to the absence of hydrostatic equilibrium. This approximation is credited to Boussinesq.

Boussinesq's approximation assumes all thermophysical properties of fluids are constant and uniform, except for density, which is presumed to vary linearly with temperature. This relationship is expressed mathematically as follows.

$$\rho(T) = \rho_0[1 - \beta(T - T_0)] \tag{III.5}$$

This first-order approximation applies to mixed natural and mixed convection cases, as the temperature variation within the fluid usually remains below ten degrees. In this equation, T is the fluid temperature at a given point, and T_0 is the reference temperature, often taken as the system's average operating temperature. β is the fluid's coefficient of thermal expansion, and ρ_0 is the constant fluid density.

III.4. Mathematical model for the applications studied

In this research study, we have conducted two distinct applications to investigate the thermal performance and energy efficiency of building brick walls integrated with PCMs. The first application focused on analyzing the influence of brick cavity shapes on the solidification process during melting, as well as the overall thermal performance and energy efficiency of PCM-enhanced brick wall systems. Through this analysis, we aimed to identify the optimal cavity geometries that facilitate efficient heat transfer and phase change processes within the PCM-filled cavities. The second application explored the potential benefits of combining different thermal management strategies within the brick cavities. Specifically, we investigated the synergistic effects of filling the cavities with EPS, PCM, and low emissivity coatings. This approach aimed to leverage the unique properties of each component to achieve enhanced thermal insulation, thermal energy storage, and radiation control, ultimately improving the overall energy efficiency of the brick wall system. Notably, each of these applications presented a distinct approach to enhancing the energy efficiency of the examined bricks. The first application focused on optimizing the cavity geometry for efficient phase change and heat transfer, while the second application explored the combination of multiple thermal management strategies within the cavities. These findings provide valuable insights into the impacts of various techniques that can be employed in designing new bricks with improved heat transfer characteristics and enhanced internal thermal comfort.

Ultimately, this study serves as a comprehensive reference point for the utilization of PCM-integrated bricks in hot climates. By leveraging the thermal energy storage capabilities of PCMs and implementing optimal cavity designs or incorporating additional thermal management strategies, these innovative brick systems can contribute significantly to reducing energy consumption and improving indoor thermal comfort in buildings located in hot and arid regions.

III.4.1 Mathematical model for the applications N° 1

III.4.1.1 *Description of a physical model*

The investigation combines the transient heat conduction model within the solid part of the brick with the solidification and melting model of the PCM filed in the cavities. By doing so, the model has the capability to predict the melting and solidification history of the PCM and track the melting interface. Figure III.1. displays the detailed dimensions of the brick used in the analysis. This configuration was employed to examine the efficiency of bricks with three different cavity shapes (square, circle, and polygon) containing different types of PCMs. The four PCMs used in this study are RT-24, RT-42, n-Eicosane, and Capric acid. These PCMs are suitable for construction and encapsulated in a 3 mm thick plastic container. The performance parameters of different building materials utilized in the brick structure under investigation are presented in Table III.1. The melting interface and the natural convection behavior of the melted PCM was taken into account. The modeling of the PCM was carried out using the enthalpy-porosity technique as described in reference [145]. To consider the thermal buoyancy effect of the liquid PCM, a

Boussinesq approximation was implemented. As a real-world example, it is assumed that the weather conditions outside, such as the ambient temperature and solar radiation, vary with time. The weather data in Figure III.2. were obtained from a TRANSYS weather data file (TRANSYS, 2021).

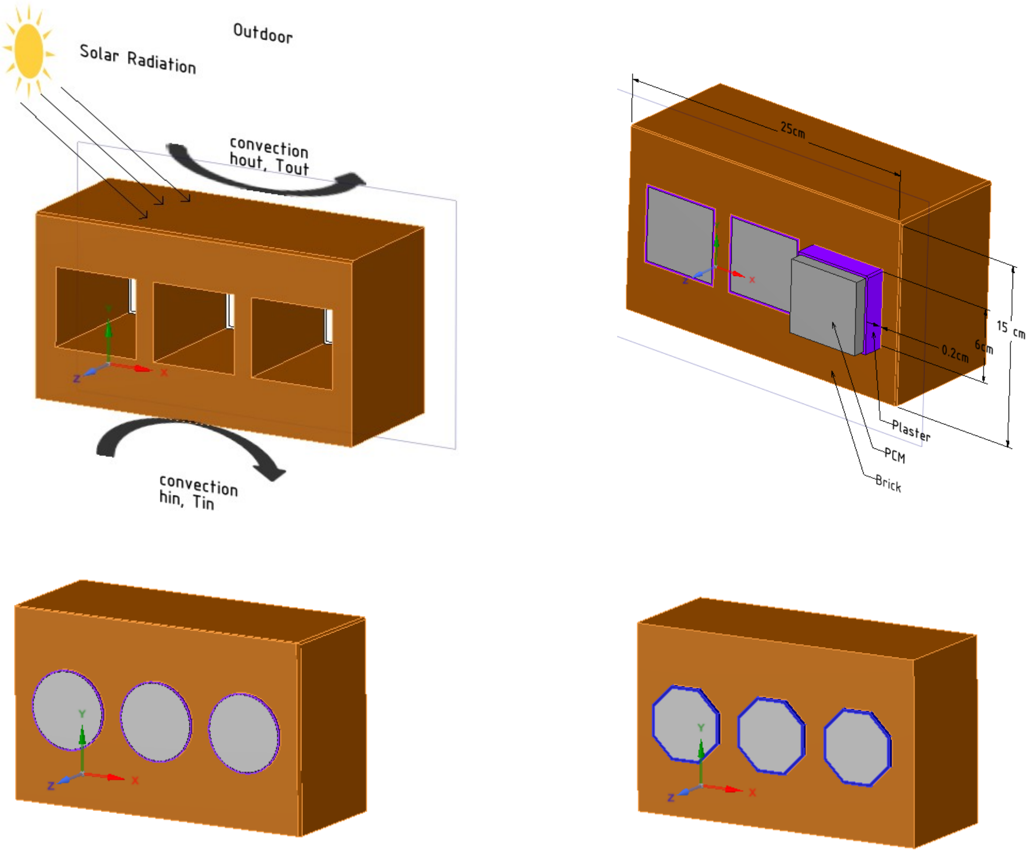


Figure III.1. The brick schematic diagram with the various cavity forms filled PCM: PCM-free brick; PCM-filled brick with square cavities; PCM-filled brick with circle cavities; PCM-filled brick with polygon cavities

Table III.1. Thermophysical properties of various simulation materials [97][98][101][146].

Material	**RT-42**	**n-Eicosane**	**Capric acid**	**RT-24**	**brick**	**Acrylic plastic**
Density, kg/m^3	885 (s) 820 (l)	885 (s) 778 (l)	1018 (s) 888 (l)	900 (s) 760 (l)	1600	1190
Specific heat capacity, J/(kg. k)	1800(s) 2400 (l)	2010 (l) 2040 (s)	1900 (s) 2400 (l)	2100(s) 2100(l)	1600	1470
Thermal conductivity	0.2	0.15	0.372 (s) 0.153 (l)	0.21	0.7	0.18
Viscosity (Pa.s)	0.02534	0.00355	0.002664	0.0254	-	
Thermal expansion coefficient (1/k)	0.001	0.001	0.001	0.001	-	
Latent heat (kJ/kg)	141.6	241	152.7	144	-	
Solidus temperature, (°C)	39	36	31	22	-	
Liquidus temperature (°C)	43	38	33	25	-	

Note: *s* and l represent the solid and liquid states, respectively.

III.4.1.2 *Assumptions of the model*

In our model, some assumptions have been made:

(1) The movement of the liquid PCM is laminar, Newtonian, and incompressible.
(2) The thermal conductivity and heat capacity of the PCM vary in a piecewise linear manner.
(3) The adiabatic wall assumption is applied to both sides of the bricks.
(4) The boundary conditions are of the no-slip type.
(5) The initial temperature of both the brick and the PCM is uniform.

This is a common assumption in recent studies, which refer to it as constrained melting [101], [147]. The governing equations for each regen in the building brick can be expressed as follows:

III.4.2 Governing equations

Initially, the equations that govern the PCM regen system are presented. Equations (III.6) - (III.14) represent the conservation of continuity, momentum, and energy in a two-dimensional, incompressible, and laminar flow.

III.4.2.1 *Continuity equation*

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{III.6}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu\,(\frac{\partial(u_i)}{\partial x_j} + \frac{\partial(u_j)}{\partial x_i})] + \rho\beta\,(T - T_0)g + S' \tag{III.7}$$

In this context, the variables T and t represent temperature (°C) and time (s), respectively; Further u_i, ρ, P represent velocity components(m/s), density (kg/m^3), and pressure (Pa), respectively. Furthermore, g, S', and β are the Source term, gravitational acceleration (m.s^{-2}), and the coefficient of thermal expansion in degrees (1/°C), respectively.

$$S' = \frac{(1-\gamma)^2}{(\gamma^3 + \varepsilon)} A_{mush}\, u$$

Where A_{mush} is a constant that indicates how quickly the fluid velocity decreases to zero during liquid solidification. Commercial software typically recommends values for A_{mush} ranging from 10^3 to 10^8. A mush plays a crucial role in modeling direct contact melting and accurately predicting heat transfer in PCM capsules. Selecting the appropriate value depends on factors such as PCM capsule geometry, phase change dynamics, and the material properties of the PCM. This study found that using A_{mush} values of 10^3 provided better agreement with experimental results for tall and short cylinders, whereas values of 10^6 were more suitable for shapes like the RBC, tetrahedron, and pyramid. ε, a small value set at 0.001, ensures a non-zero denominator.

$$\frac{\partial(\rho H)}{\partial t} + \frac{\partial(\rho u_i H)}{\partial x_j} = \frac{\partial}{\partial x_j}(\lambda \frac{\partial T}{\partial x_j}) \tag{III.8}$$

The Boussinesq approximation is utilized, and the density can be expressed by the following expression:

$$\rho_{PCM} = \rho_{ref,PCM}\,[1 - \beta_{PCM}(T - T_{ref,PCM})] \tag{III.9}$$

For the PCM, the specific enthalpy (H) is defined by the sum of the sensible enthalpy (h_{sen}), and latent heat (*ΔH*), which is written as:

$$H = h_{sen} + \Delta H \qquad \text{(III.10)}$$

where, h_{sen} and ΔH are found by

$$h_{sen} = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT \qquad \text{(III.11)}$$

$$\Delta \mathrm{H} = \gamma L \qquad \text{(III.12)}$$

L and γ illustrate the latent heat (J/kg) and the liquid fraction during the transformation between liquid and solid phases, respectively.

The equation that follows can be utilized to express the governing equation in the brick zone:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\frac{\lambda_{brick}}{\rho_{brick}\ C_{P,brick}} \frac{\partial T}{\partial x_i}\right) \qquad \text{(III.13)}$$

III.4.2.2 ***Initial and boundary conditions of the model***

In this study, transient boundary conditions were employed, where the outdoor weather conditions change over time Figure III.2. The system's initial temperature was set to 25 °C, which was also assumed to be the temperature of the indoor air throughout the simulation. However, the outdoor weather conditions, such as ambient temperature and solar radiation, change throughout the day. As a result, the outdoor boundary conditions vary throughout the time. The left and right sides of the brick were considered to be adiabatic. The boundary conditions of the model are defined as follows:

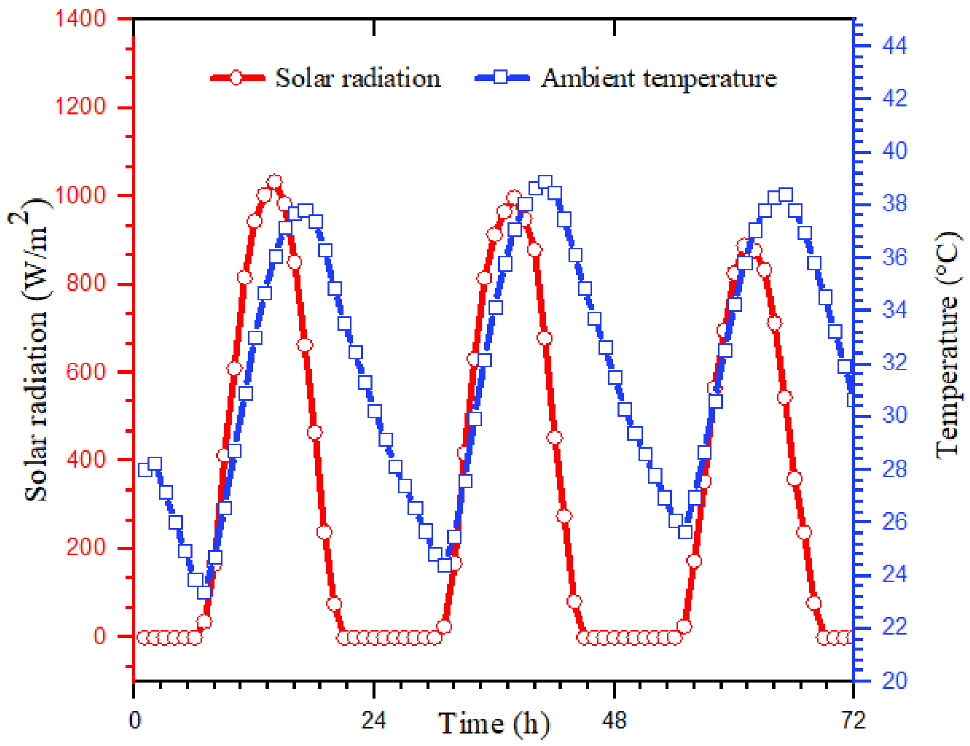


Figure III.2. Outdoor variation of temperature and global solar radiation for Bechar City.

$$-\lambda_{brick}\,\frac{\partial T}{\partial x}\Big|_{y=0} = h_i\,(T_{indoor} - T_{brick}) \qquad \text{(III.14)}$$

where, the inside convective heat transfer coefficient h_i is considered a constant value of 10 W/m^2 °C, and $T_{indoor} = 25$ °C the temperature within the indoor, specifically under summer conditions, is given by [97].

$$-\lambda_{brick}\,\frac{\partial T}{\partial x}\Big|_{y=H} = h_o\,(T_{sa} - T_{brick}) \qquad \text{(III.15)}$$

Where, the outside convective heat transfer coefficient (h_o) is taken as a constant value of 20 W/m^2 °C. The formula is shown in Eq. (III.15), where, the variable T_{sa} represents the calculated sol–air temperature for each time step, The ambient temperature and horizontal radiation are denoted by T_{amb} and I, respectively.

$$T_{sa}(t) = T_{amb} + \frac{\delta}{h_0} I(t) - \frac{\xi \Delta R}{h_o} \tag{III.16}$$

According to the guidelines provided by ASHRAE, the correction factor, $\frac{\xi\Delta R}{h_o}$, is taken equal to 4°C for horizontal surfaces facing up. The ambient temperature is assumed to change sinusoidal throughout the day and can be described by the following equation[148]:

$$T_{amb} = |\frac{T^{max} - T^{min}}{2}| \sin(\frac{2\pi t}{p} - \frac{\pi}{2}) + |\frac{T^{max} - T^{min}}{2}| + T^{min} \tag{III.17}$$

III.4.3 Performance indicators

This study monitored four key factors, namely the inner surface temperature, inner surface heat flux, and liquid fractions of PCM, in order to evaluate the energy performance of the studied brick. Daily energy consumption from the wall brick and energy saving rate were calculated as metrics to assess its energy efficiency.

III.4.3.1 *Daily energy consumption*

The total cold energy consumption on a summer day is referred to as daily energy consumption. It is computed by summing the hourly heat flux gain across the wall brick, which is expressed as:

$$Q_c(t) = 3.6 \times \sum_i^{24} (-q_i) \ , \ q_i > 0 \tag{III.18}$$

where, $Q_c(t)$ express the total energy consumption for cooling during summer days (kJ/m^2.d). q_i is the hourly heat flux from the wall brick outdoor (W/m^2).

III.4.3.2 *Energy saving rate*

To determine the energy savings rate, the total energy consumption of the new brick filled with PCM was compared to the energy consumption of the traditional brick on a typical day. This calculation was performed as follows:

$$r = \frac{Q_t - Q_n}{Q_t} \times 100\% \tag{III.19}$$

where, r expresses the energy-saving rate of a brick wall (%)Q_t and Q_n is the daily energy consumption (kJ/m^2.d) of the traditional brick wall *(t)* and that of the new brick wall (n), respectively.

III.4.3.3 *Peak temperature lag time*

The heat storage capacity of PCM is expected to cause a delay in the occurrence of the peak temperature of the day, which may vary in degree when compared to traditional wall bricks without PCM. The time difference between the expected peak temperature and the actual peak temperature caused by PCM's heat storage capacity is known as the "peak temperature lag time." This lag time can be calculated using the following formula:

$$\varphi = \tau_{n,max} - \tau_{t,max} \quad \text{(III.20)}$$

where, φ is the peak temperature lag time; $\tau_{n,max}$ is the time when the peak temperature of wall brick with PCM appears; $\tau_{t,max}$ is the time when the peak temperature of traditional wall brick appears. The larger value of φ, the better performance of wall brick with PCM.

III.4.4 Computational procedure, mesh dependency, and model validation

The governing differential equations for momentum and energy conservation subjected to initial and boundary conditions. were solved using ANSYS Fluent. The model for solidification and melting was utilized to determine the amount of latent heat generated during the melting and solidification of PCM cavities. User-defined functions (UDF) in setup and a pressure-based sequential solver for unsteady conditions were used to apply solar radiation and ambient temperature to the outside surface of the brick filled with PCM. The semi-implicit technique for the pressure-linked equations (SIMPLE) algorithm was used to decouple the pressure velocity[149]. Second-order central-differenced was used for the diffusion terms in the momentum and energy equations. To verify the model's numerical convergence, the scaled numerical residuals of all computed variables were tested at each time step. The continuity residual was set to a value of 10^{-4}. The residual energy was set to 10^{-7}. In order to obtain the temperature distribution in the 72-hour model, the maximum number of iterations was set to 27.

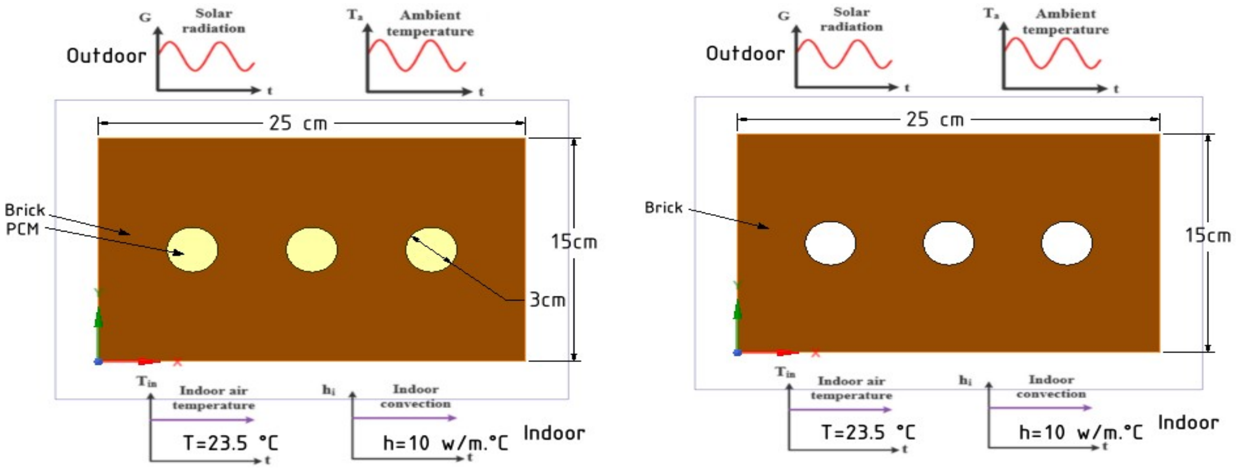


Figure III.3. The boundary conditions of a brick wall with PCM and a brick wall without PCM used to validate the results in[97].

The accuracy of the simulation results is affected by the size of the mesh and the time step used. To examine this impact, the number of elements tested ranged from 7840 to 300,500, with the predicted inner surface temperature compared as the number of elements increased. The results of mesh and time independence tests demonstrated that the number of elements above 101,400 and the time step of less than 1 s did not significantly affect the results. Therefore, these parameters were selected for the simulation. Additionally, a two-dimensional transient model was developed to validate the accuracy of the numerical model, both with and without PCM in a brick. Figure III.4. displays two cases used to validate the model. The initial case simulates a brick without PCM, while the second case involves a brick with three PCM cylinders (n-Eicosane). The outdoor weather conditions, represented by the time-dependent external solar radiation and ambient temperature shown in Figure III.4, are subject to variation over time. The physical model used was validated successfully, as shown in Figure III.5. The simulation calculation results agree with the study on the brick inner surface heat flux trends conducted by[97] in the literature. The mean error between the calculated values of brick inner heat flux and Alawadhi's [97] study in the literature is about 4.17%. As a result, the accuracy of the numerical model of the brick with and without PCM is validated.

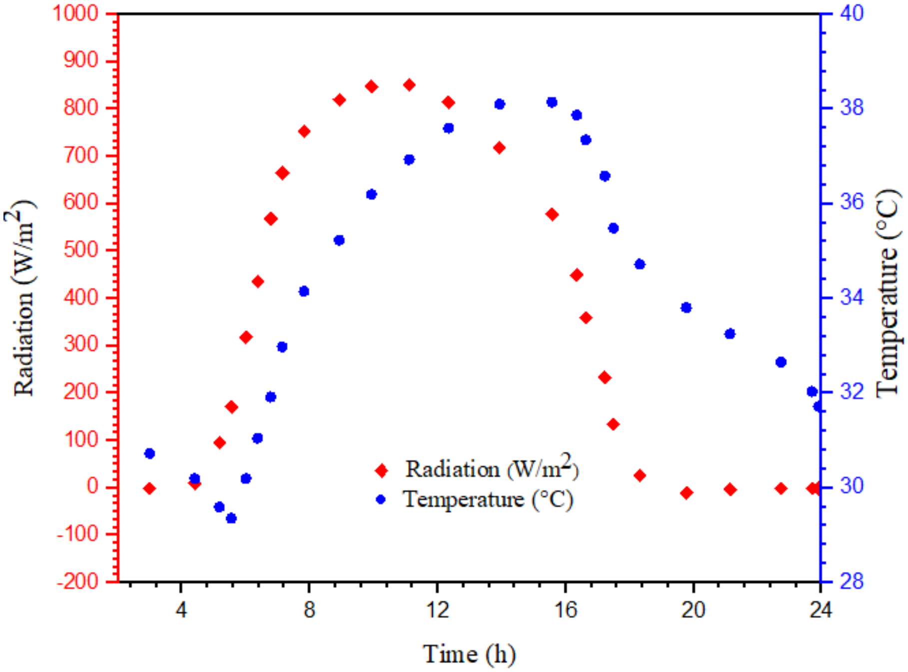


Figure III.4. Weather, ambient temperature, and solar radiation variations applied during the validation process with Alawadhi [97].

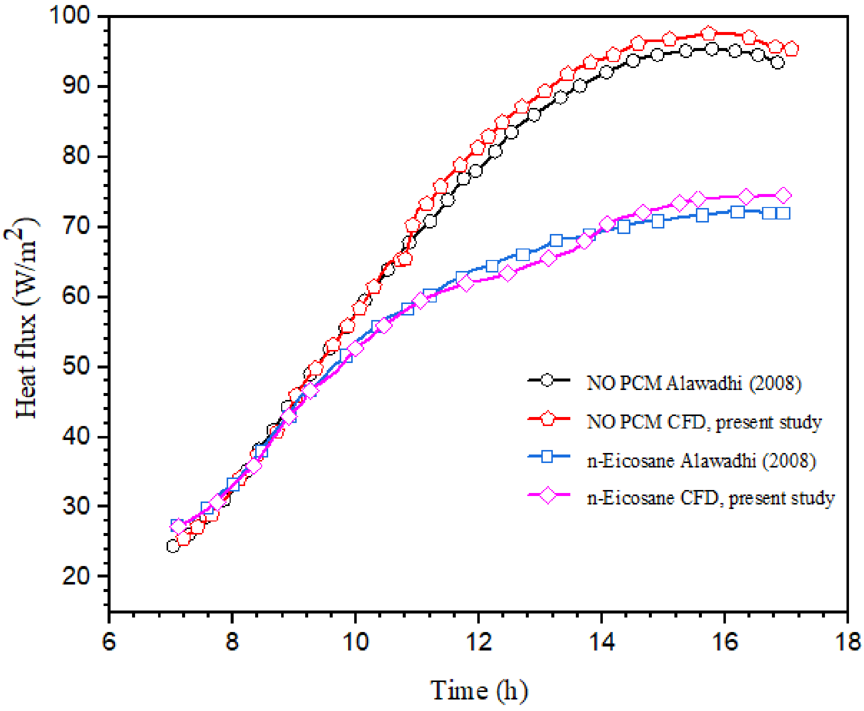


Figure III.5. Model validation with Alawadhi [97].

III.4.5 Mathematical model for the applications N° 2

III.4.5.1 *Description of a physical model*

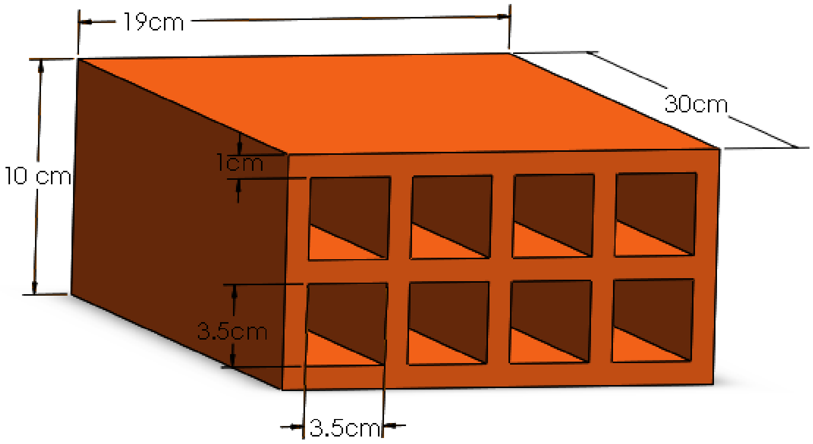


Figure III.6. Schematic of the physical model of the studied hollow clay.

To analyze the integration effect of TIM, PCM, and low coating emissivity on the thermal behavior of hollow clay brick. A traditional hollow clay brick (HCB-8) was chosen as shown in

Figure III.6. This hollow brick is the most used in the construction of walls and roofs of buildings in Algeria. Table III.2 presents the thermophysical properties of the bricks, the insolation material and the PCM. This numerical study was divided into two steps to estimate the dynamic thermal performance of hollow clay bricks used for roofing. The first step evaluated the brick integrated with a passive measurement. In the second step, we considered whether combining two measures in the same configuration was possible. Four brick structures Figure III.7 were adopted for the thermal study to compare the thermal performance of the proposed brick configurations with the traditional brick:

- **(C1)** Traditional hollow brick;
- **(C2)** Traditional hollow brick with an insulating material filling in cavities and with a low emissivity coating on the internal surfaces of the cavities (hollow brick + EPS filling cavities + low emissivity coating);
- **(C3)** Traditional hollow brick with the PCM filling in cavities and a low emissivity coating (hollow brick + PCM filling cavities + low emissivity coating);
- **(C4)** Traditional hollow brick with the PCM filling and insulating material in the cavities (hollow brick + PCM filling cavities + EPS).

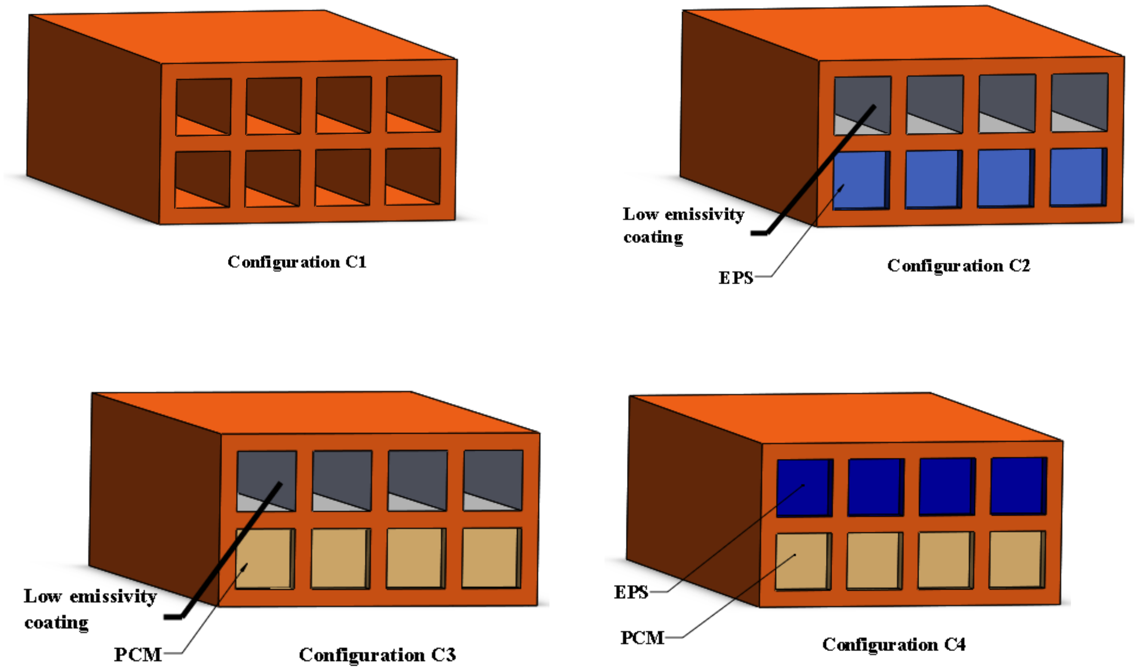


Figure III.7. Different configurations of hollow clay brick.

The following simplifying assumptions were adopted to model the conjugate heat transfer (conduction, convection and radiation) through the building bricks and the phase change processes (solidification and melting):

- The air in the cavities is modeled as a Newtonian fluid with constant physical properties except for the density in the buoyancy term for which the Boussinesq approximation is adopted.
- There are no-slip boundary conditions.
- The fluid is supposed to be perfectly transparent to radiation, and the surfaces inside cavities are assumed to be diffuse-gray with the same emissivity.
- The motion of PCM in a liquid state is incompressible, Newtonian and laminar.
- The heat capacity and thermal conductivity of the PCM vary as piecewise linear.
- The adiabatic wall assumption is adopted for the right and left sides of the bricks.
- The physical domain focuses on two-dimensional transient coupled heat transfer by conduction, convection and radiation.

Based on the above assumptions, the mathematical model of this problem can be realized using the following equations:

When the cavities inside the brick are filled with air:

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \qquad \text{(III.21)}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{air}}[-\frac{\partial p}{\partial x} + \mu_{air}\,(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2})] \qquad \text{(III.22)}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{air}}[-\frac{\partial p}{\partial y} + \mu_{air}\,(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) + (\rho\beta)_{air}\, g\Delta T] \qquad \text{(III.23)}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\lambda_{air}}{\rho_{air}\, C_{P,air}}[(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2})] \qquad \text{(III.24)}$$

where, T denotes the material temperature °C, t is the simulation time s, λ is the thermal conductivity W/(m K), and ρ denotes the density kg/m^3, C_P expresses the specific heat J/(kg K). In addition, radiative exchanges between the inner surfaces of the brick hole were calculated by the following expression:

$$q_{r,i}(r_i) = B_i(r_i) - \sum_{\substack{i=1 \\ ,j\neq i}}^{4} \int_{Sj} B_j(r_j) k(r_i, r_j) dS_j, i = 1 \ldots 4 \qquad \text{(III.25)}$$

where, $B_i(r_i)$ is the radiosity and $k(r_i, r_j)$ is the Kernel function. The following equation can be used to describe the governing equation in solid materials:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\lambda_S}{\rho_S C_{P,S}} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_S}{\rho_S C_{P,S}} \frac{\partial T}{\partial y}\right) \qquad \text{(III.26)}$$

The enthalpy porosity method was applied to simplify the melting-solidifying heat transfer through the PCM layer as described in first application.

Table III.2. Thermo-physical properties of various materials used in the simulation [146] [97] [98] [101].

Material	RT-42	n-Eicosane	Capric acid	Air	EPS	Clay brick
Density, kg/m^3	885 (s) 820 (l)	885 (s) 778 (l)	1018 (s) 888 (l)	1.225	22	664
Specific heat capacity, J/(kg. K)	1800(s) 2400 (l)	2010 (l) 2040 (s)	1900 (s) 2400 (l)	1001.43	1280	741
Thermal conductivity	0.2	0.15	0.372 (s) 0.153 (l)	0.026	0.041	0.207
Viscosity, Pa.s	0.02534	0.00355	0.002664	$1.846.10^{-5}$	-	-
Thermal expansion coefficient, (1/K)	0.001	0.001	0.001	0.00353	-	-
Latent heat,(kJ/kg)	141.6	241	152.7	-	-	-
Solidus temperature,(°C)	39	36	31	-	-	-
Liquidus temperature, (°C)	43	38	33	-	-	-

Note: *s* and *l* represent the solid and liquid states, respectively.

III.4.5.2 *Initial and boundary conditions*

The left and right sides of the hollow brick were considered adiabatic. The outside of the brick was subjected to time-dependent radiation Figure III.2. and forced convection boundary conditions, with h_o = 20 W/m K. At the indoor surface, a free convection boundary condition, with h_i = 5W/m K and T = 26 °C, was imposed. The initial temperature of the domain was 26 °C [112].

III.4.5.3 *Model validation and computational procedure*

As the fist application the governing equations of momentum and energy conservation and the PCM melting/solidification processes subjected to initial and boundary conditions were solved numerically using Ansys-Fluent software. The numerical model used in this investigation was validated against the numerical results obtained by Mahdaoui [112]. Figure III.8. compares the predicted indoor surface temperature with the same as obtained in [112] for the case of brick with PCM mass (16%). Based on the obtained results, it is evident that a good agreement was obtained during this comparison. The maximum relative deviation between the present study and the numerical results in[112] is around 1.2%.

The proposed model accurately solves the coupled energy and Navier-Stokes equations and heat transfer by conduction, convection, and radiation. The finite volume method was utilized to solve the above equations, and the coupling between the momentum and continuity equations was made with the SIMPLEC algorithm proposed by Van Doormall and Raithby [150]. The diffusion terms in the momentum and energy equations were second-order central-differenced. The convection terms were interpolated using the second-order-upwind scheme (PISO) algorithm to couple the velocity and pressure. The numerical convergence of the model was checked based on the scaled numerical residuals of all computed variables. A value of 10^{-4} was chosen for the continuity residual. the energy and radiation residuals were set to 10^{-7}. In addition, the S2S radiation model was employed to simulate radiation heat transfer in air cavities. Finally, the physical domain is discretized in a structured grid and subdivided into 76,000 elements. A time step of (1 s) was found sufficient to provide accurate results. The grid size and the time step were selected after careful analysis of the autonomy of the results to these parameters.

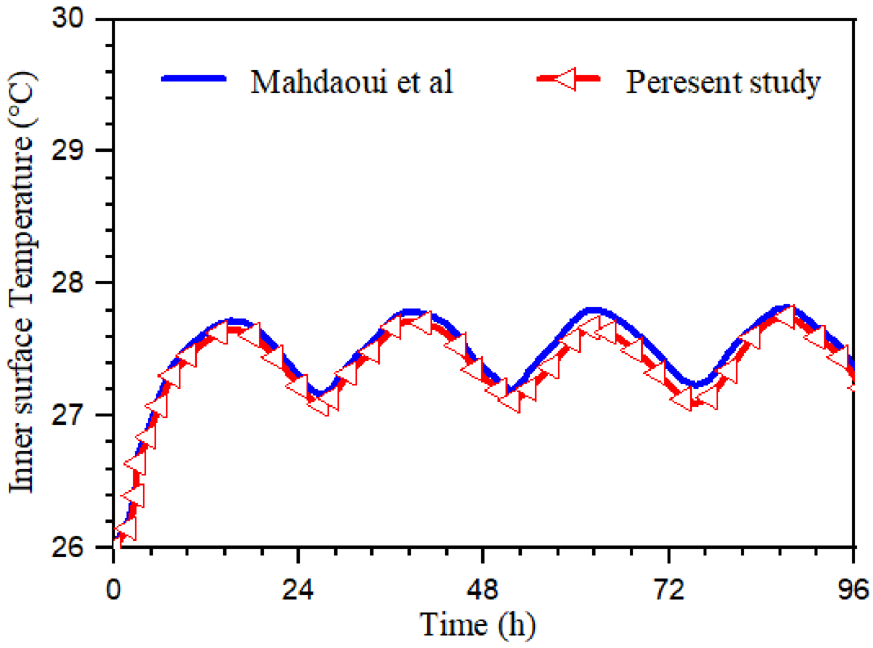


Figure III.8. Model validation with Mahdaoui [112].

III.5. **Conclusion**

In recent years, there has been extensive utilization of Computational Fluid Dynamics (CFD) modeling building envelope integrated with PCM within the realm of addressing industrial challenges and academic research endeavors aimed at enhancing the thermal efficiency of buildings. This trend is driven by the multiple benefits offered by CFD simulations. These advantages include avoiding expensive experiments, providing quick solutions through computational algorithms with parameter adjustments, and gathering necessary data across the domain without disruption. By utilizing CFD software to simulate how phase change materials behave in thermal systems, the need for costly experimental setups is eliminated. This leads to significant savings in both time and money associated with acquiring materials, manufacturing, or building realistic systems. Additionally, CFD simulations aid in identifying operational parameters for optimizing thermal storage systems, thus boosting overall efficiency. In this chapter, we've outlined the CFD procedures utilized in our two applications, along with the modeling and validation of our results to enhance accuracy. The subsequent chapter will delve into the presentation of results and discussions

CHAPTER IV:
Results and Discussion

CHPTER IV: Results and discussion

IV.1. **Introduction**

This section assesses the effectiveness of integrating PCMs into building bricks, aiming to offer guidance to decision-makers, particularly in hot climate regions. Initially, the evaluation focuses on comparing the thermal efficiency of three distinct brick cavity designs filled with PCM. The impact of four variations in PCM thermal-physical properties on energy performance and thermal comfort is thoroughly examined. Furthermore, an energetics comparison between traditional bricks and those integrated with PCM is conducted based on estimations. In the subsequent part, the thermal analysis extends to building bricks integrated with three passive measures: low coating, material insulation, and PCM.

IV.2. **Application N°1:**

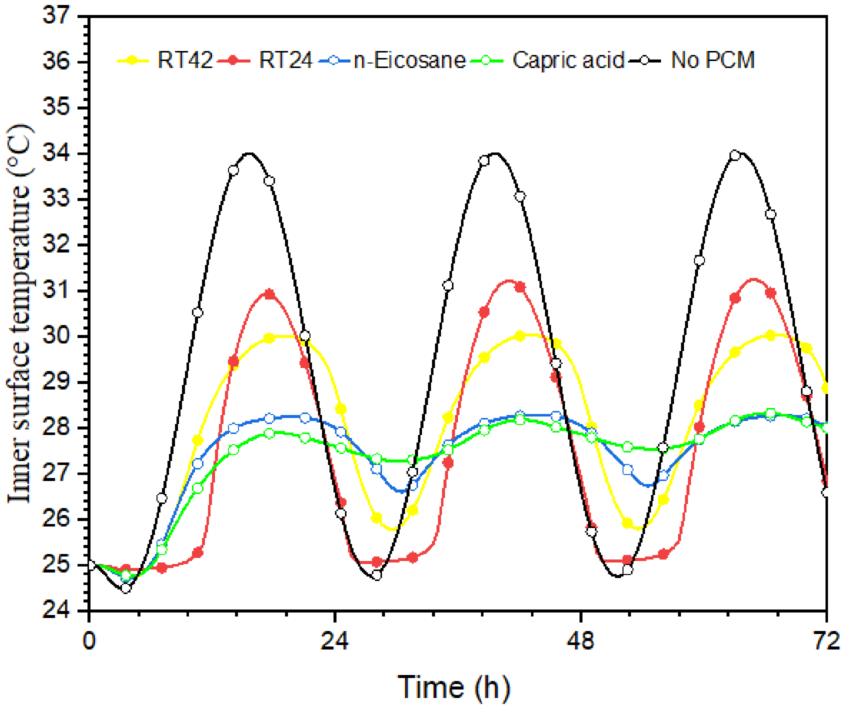
IV.2.1 Effect of PCM type

In this section, the ability of wall brick with PCM to regulate temperature in the hot climate of Algeria is investigated. The impact of four different PCMs, namely RT-24, RT-42, n-Eicosane, and capric acid, on the inner surface temperature, liquid fraction of PCM, and heat flux through the wall brick is demonstrated in Figues IV.1, IV.2, and IV.3. The integration of PCM in building bricks can enhance the thermal characteristics of construction materials by changing the wall material's thermal storage capacity. This results in a reduction of the peak load on the building while also causing it to shift. As shown in Figue IV.1, the brick with PCM can lower the inner surface temperature and shift the peak temperature when compared to a traditional brick without PCM. That is due to two factors. The first factor is that integrating PCM with low thermal conductivity reduces the thermal resistance of the brick. The second factor is that the storage of energy in the PCM cavity during melting prevents some of the heat transfer through the wall brick.

More specifically, the peak temperature on the inner surface of the wall brick without PCM appears at 15:30, approximately 34 °C, and the temperature fluctuation amplitude is approximately 10 °C. Because of the harsh outdoor environment, all PCMs undergo a phase change, and the time lag effect is noticeable. For RT-42, RT-24, capric acid, and n-Eicosane, the peak temperature on the inner surface of the brick is decreased by 3.97 °C, 3.12 °C, 6.1 °C, and 5.7 °C, respectively, with a time lag of 3.5 h, 2 h, 3 h, and 4 h. This could reduce energy consumption during the day.

The liquid fraction of four PCMs is demonstrated in Figure. IV.2, However, the difference is the time spent in the melting and solidification processes and the utilization of latent heat. In a hot climate, the minimum liquid fraction during the heat release of RT-24 is 0.85, which is caused by higher nighttime temperatures. indicates that a significant portion of the PCM has not fully solidified, which can adversely affect the next phase transition cycle. RT-42, Capric acid, and n-Eicosane have latent heat utilization rates of 28%, 54%, and 26%, respectively.

In Figure IV.3, the variations in inner surface heat flux for the four different types of PCM-filled brick cavities are shown. The current study took into account the impact of both solar radiation and ambient temperature. The inner peak heat flux is reduced regardless of which PCM is integrated into the brick. This decrease is much more pronounced when using PCM with a melting temperature close to the comfort temperature. However, when comparing brick filed the RT-24 to the traditional brick, this reduction does not reach 35%. This is because RT-24 (with a melting temperature of 24 °C) cannot solidify completely due to the outdoor temperature is always higher than its melting temperature, resulting in no latent heat capacity being produced. When RT-42, n-Eicosane, and Capric acid were used instead of brick without PCM, the inner peak heat flux reduced by 44.24%, 63.9%, and 67.84%, respectively. The energy efficiency of brick integrated with four different types of PCM is depicted in Figure IV.4. On a typical summer day, the energy consumption was determined by summing up the heat flux gain at each instant. Simultaneously, the energy-saving rate of brick with PCM was calculated using traditional brick as a baseline. According to Figure IV.4, the energy consumption of brick with RT-24 and RT-42 is the highest, with energy-saving rates of 45.79% and 35.54%, respectively, while brick with n-Eicosane comes in second, with an energy-saving rate of 54.94%. Brick-containing capric acid saves more energy, saving approximately 61.8%. The findings indicate that the PCM type significantly impacts the brick wall's dynamic thermal behavior. As a result, capric acid is the best PCM for achieving the better thermal proformance of brick walls exposed to externally hot climatic conditions.



Figue IV.1 Impact of four PCMs on the inner surface temperature of brick.

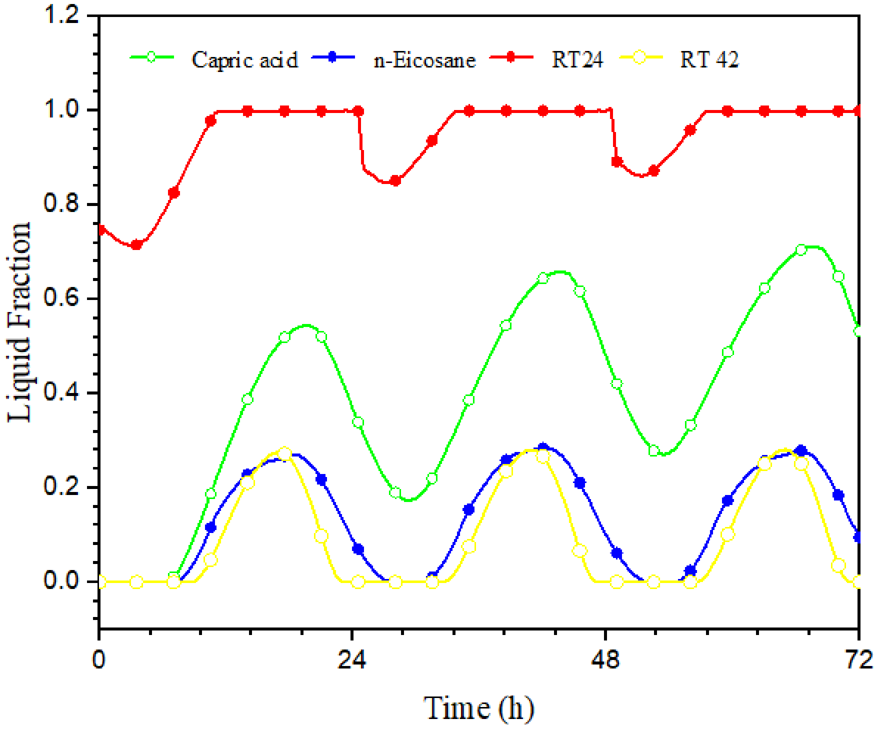


Figure IV.2. Variations of the liquid fraction of four PCMs.

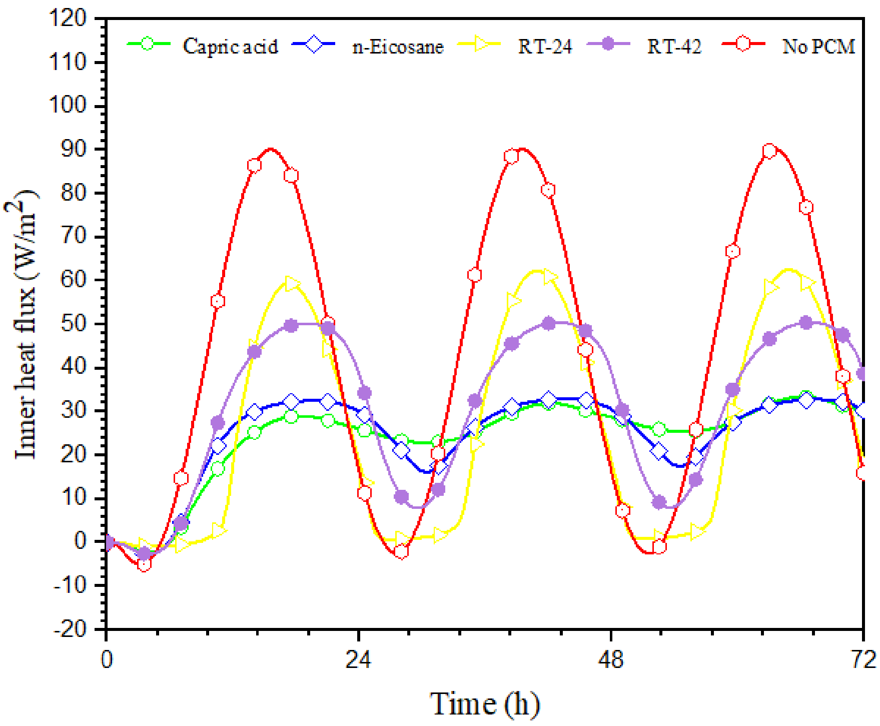


Figure IV.3. Influence of four PCMs on inner surface heat flux of brick.

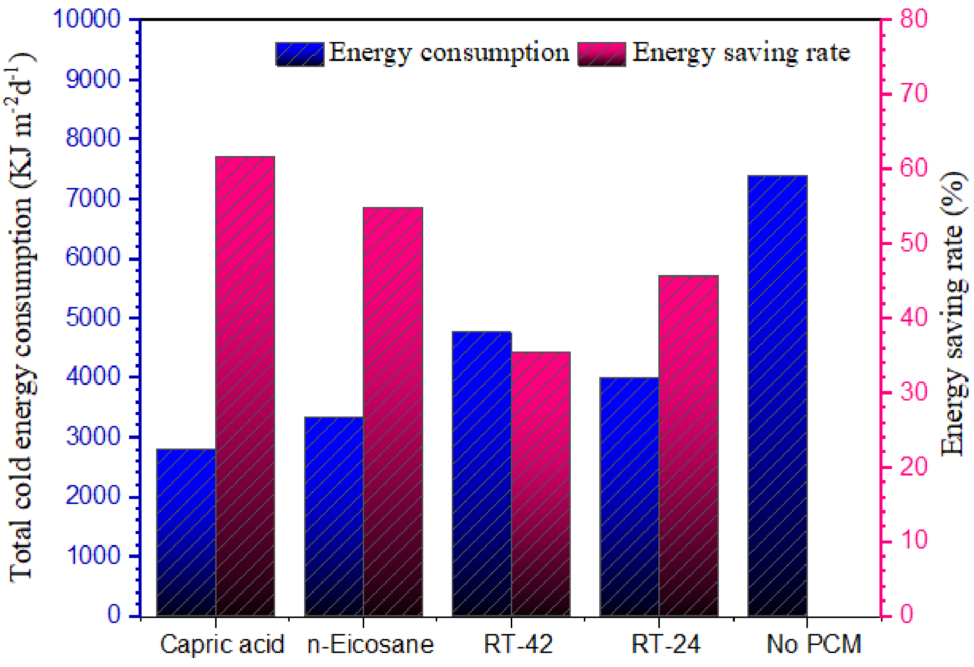


Figure IV. 4. Influence of four PCMs on energy efficiency on July 2, 2021

IV.2.2 The effect of cavity form

The effects of three cavity forms filled with PCM (capric acid) on the dynamic thermal performance of the brick wall are investigated in this section. The climate data of Algeria’s hot climate city (Bechar) on July 1-3, 2021 in summer is chosen as the simulation boundary conditions to investigate the extent to which latent heat was utilized in three different cavity forms of brick filed with PCM under real climate conditions. Within 72 h, PCM’s melting and solidification progress with various cavity forms is investigated. Figure IV.5. depicts the variations in the liquid fraction of PCM (capric acid) formed by three cavities in a hot climate.

Figure IV.6. depicts the contours of the liquid fraction of PCM inside the brick at various times. Initially, all of the PCM inside the cavities is solid until heat enters the cavities through the wall. The process of melting PCM begins when the cavities are exposed to high temperatures. First, a thin slab is melted along the upper walls’ sides. As the temperature in the PCM cavities rises, more PCM melts inside the cavities. Melting of PCM starts in the upper regions of the cavities caused by the unique thermal and physical characteristics of the PCM and the higher temperature flow within the brick compared to the PCM. Because of the small liquid fraction of PCM, there is initially weak natural convection in the cavities, and heat transfer occurs in a conductive mode. Natural convection in the cavities increases as the liquid fraction PCM in the cavities increases, and liquid fraction PCM is generated in the upper part of the cavities. Polygon and circle cavity forms require the least amount of time to partially complete the melting process. At 7:00 PM, the PCM finished melting partially. The melting daytime for the square cavity is 7:40 PM. The circle cavity’s melting rate is faster than other cavity forms early in the phase change. The cavity form has a significant impact on the melting and solidification behavior.

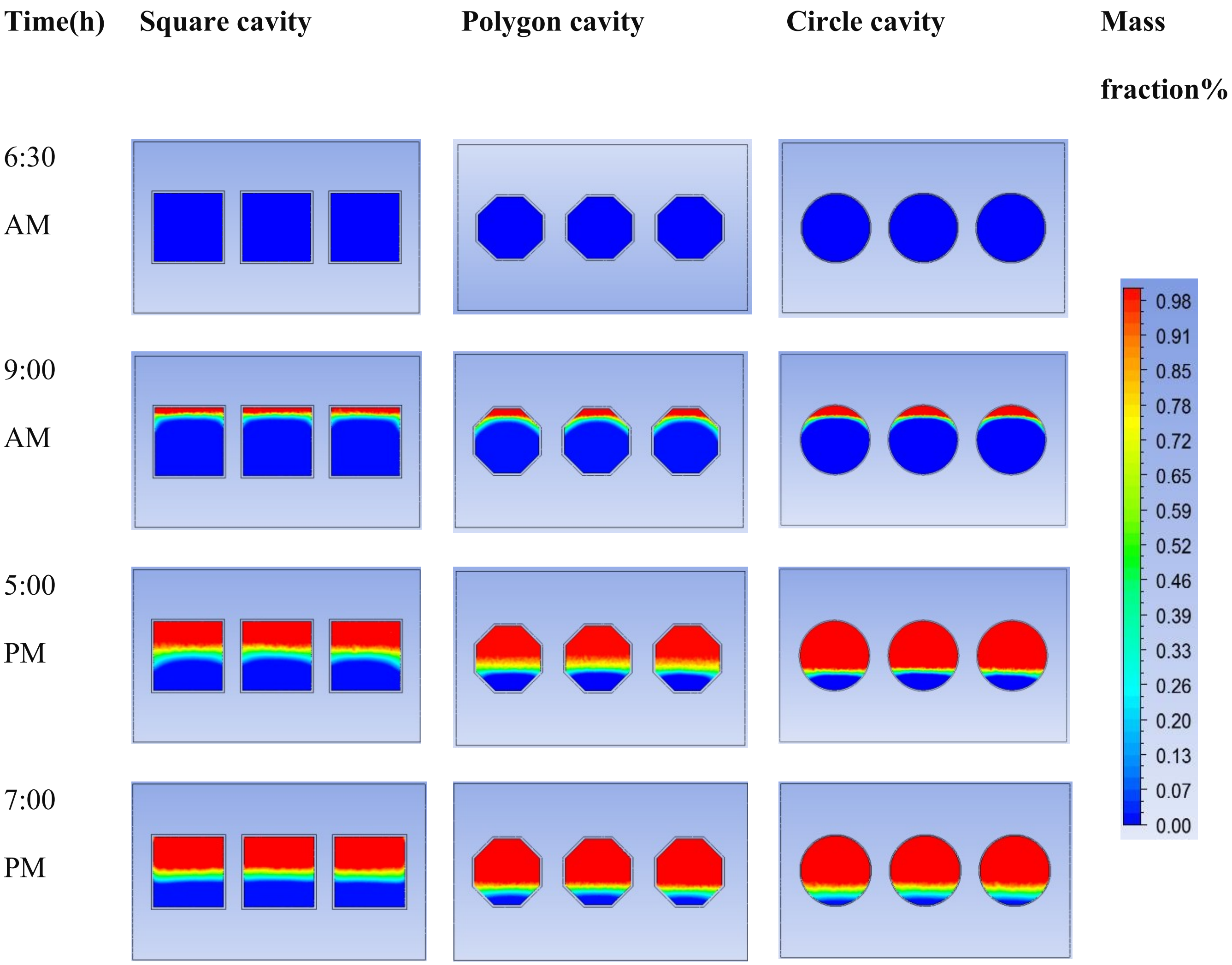


Figure IV.5. Variation of PCM liquid fraction contours under time for three different cavities (capric acid)

Figure IV.6 depicts the temperature contours of a brick filled with PCM (capric acid) for various cavity forms. The contours depict the degrees of temperature change in the brick over time. The temperature of the brick increases gradually from its initial cold temperature, which depends on the temperature set for the wall. Initially, thermal conduction heat transfer warms up the brick before it reaches to the PCM cavities. Temperature contours regularly move until the temperature reaches the cavities. When the cavity walls are exposed to high temperatures, the presence of PCM causes a decline in isothermal lines due to its unique thermo-physical properties. In the cavities, natural convection is observed. As heat transfer increases, however, the isothermal lines become curved due to the natural convection of melting PCM. The isothermal lines of building bricks with square cavities are more distorted in the PCM zone than in polygon and circle shapes. This is due to the cavity surface area and natural convection.

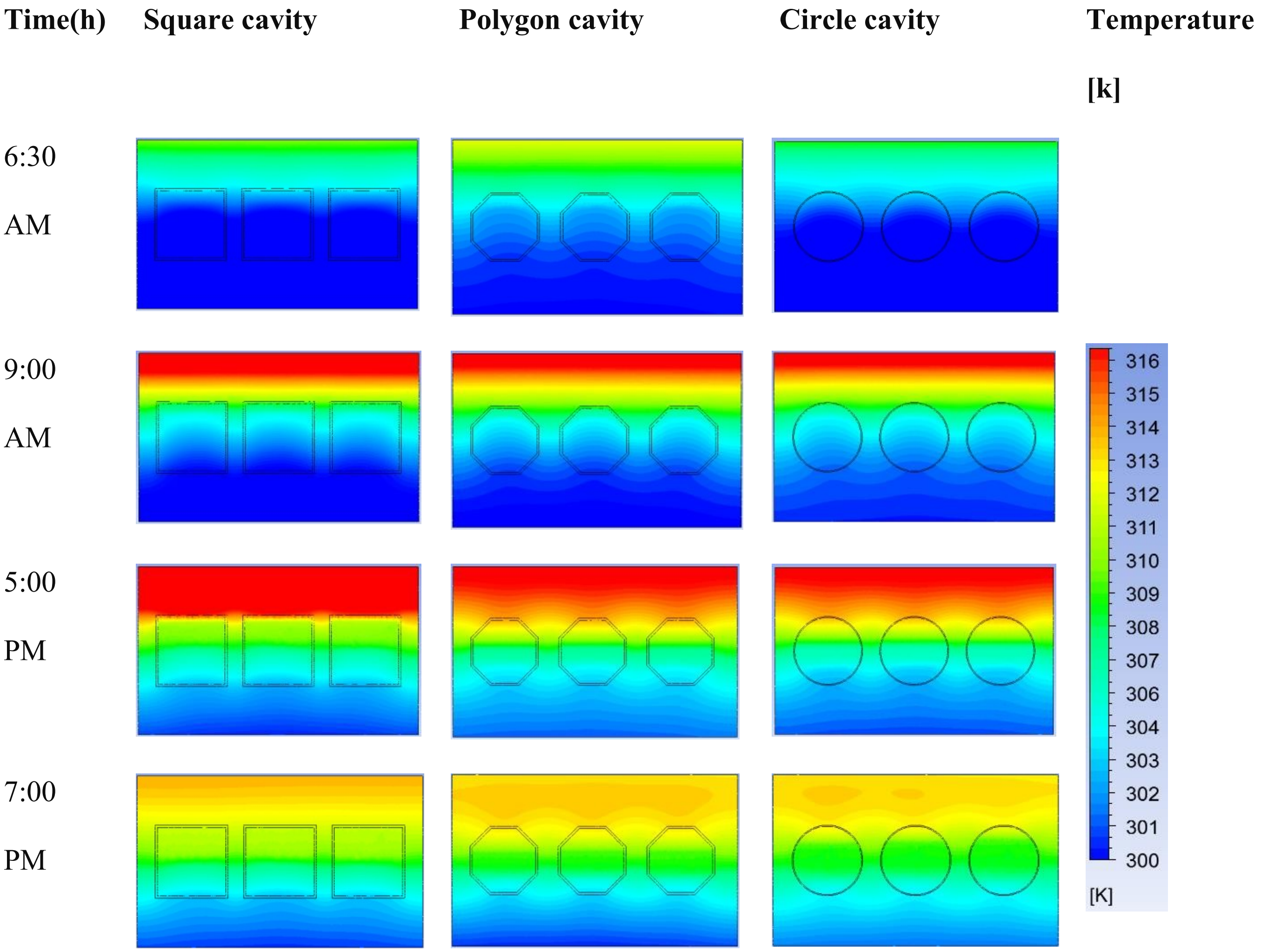


Figure IV.6. Variation of brick wall temperature contours with time for three cavities forms (capric acid).

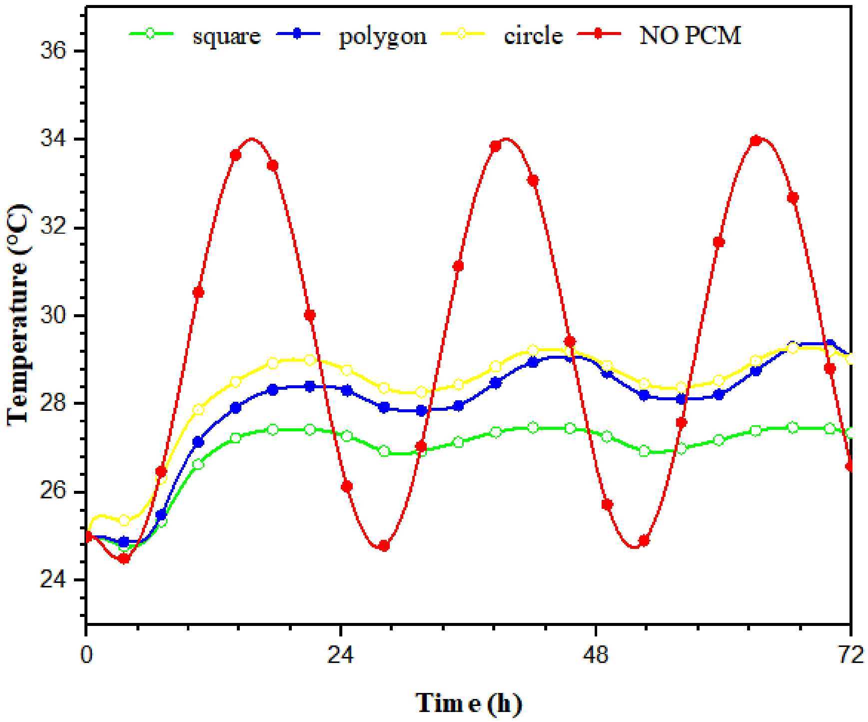


Figure IV.7. Influence of cavities forms filled with PCM on the inner surface temperature of the brick wall.

Figure IV.8. illustrates the variation in the inner heat flux of a wall brick for three different cavity shapes. It is worth mentioning that all forms of cavities filled with PCM result in lower maximum inner temperatures than traditional bricks. According to the findings, integrating PCM into brick has a beneficial impact on decreasing internal temperature fluctuations. Additionally, the square cavity shape effectively stabilizes temperature variations to a comfortable level compared to the circle and polygon cavity shapes. When a brick with square cavity filled with PCM was used instead of traditional brick, the inner peak temperature was reduced by about 6.1°C. In addition, Figure IV.8 demonstrates that incorporating PCM in brick walls leads to a significant reduction in inner surface heat flux compared to traditional brick. Furthermore, Figure IV.9 shows the percentage decrease in indoor peak heat flux for different cavity shapes compared to the traditional wall. Upon comparison of the outcomes, it can be concluded that indoor peak heat flux is reduced by approximately 31.52%, 58%, and 67.84% for the circle, polygon, and square cavity shapes, respectively, in comparison to the traditional brick.

Furthermore, the square cavity form produces the greatest improvement. As illustrated in Figure IV.9., A brick wall featuring a circle cavity shape has the highest energy consumption, resulting in an energy-saving rate of 39.1%. The polygon shape ranks second with an energy-saving rate of 53%, while the square shape saves more energy, with an approximate saving rate of 61.8%. As a result, the square cavity shape dampens the maximum inner temperature and reduces the heat flux at the inner surface of the brick wall.

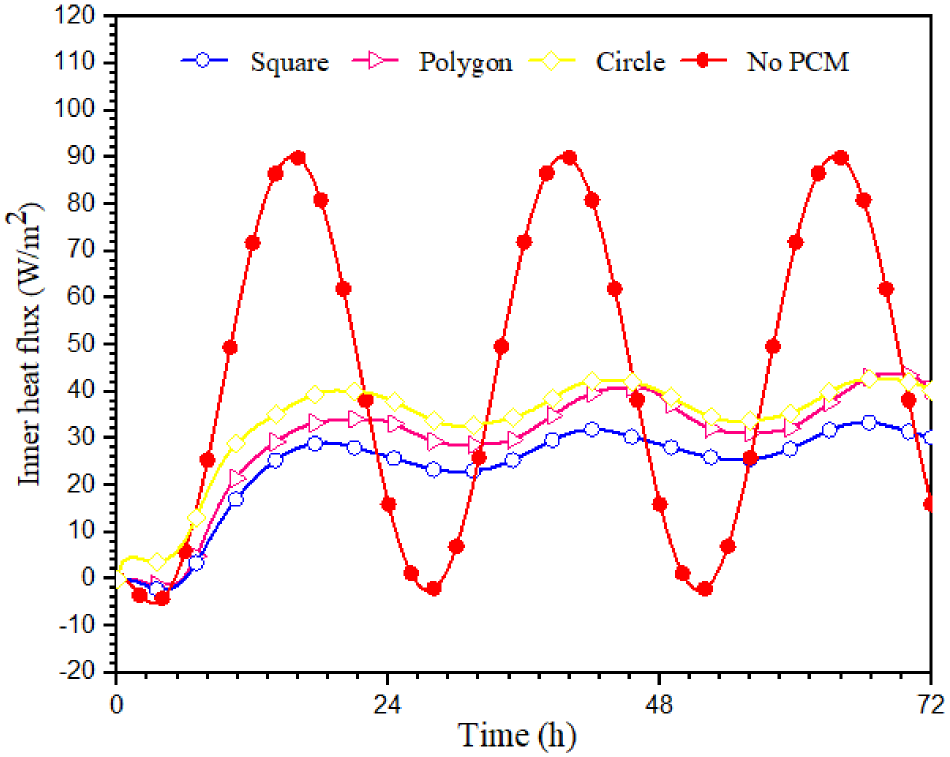


Figure. IV.8. Influence of cavities forms filled with PCM on inner heat flux of brick wall.

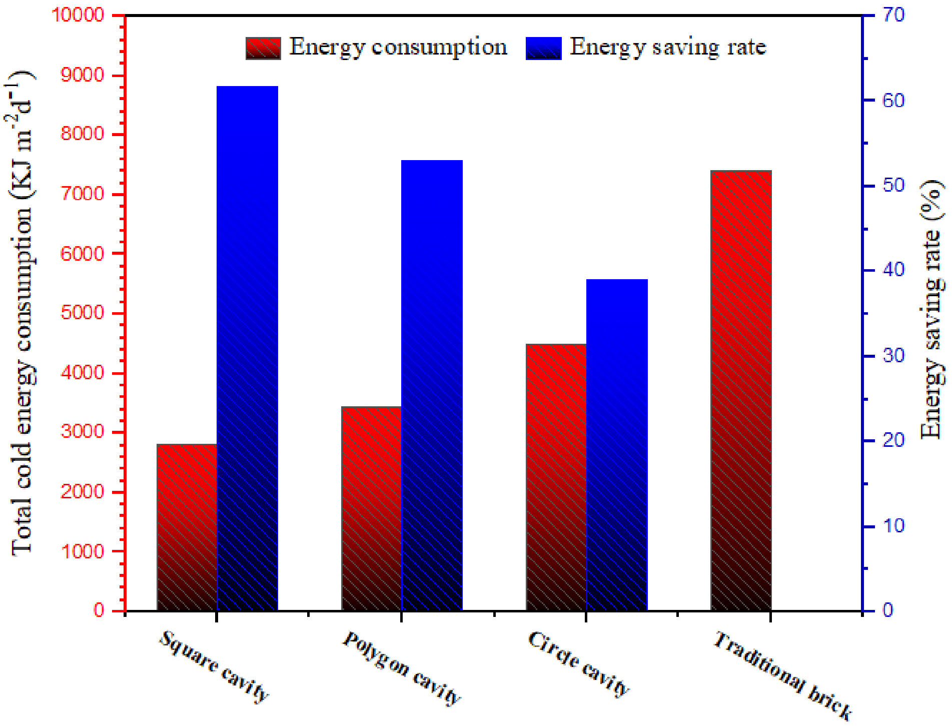


Figure IV.9. Influence of three cavities forms on energy efficiency on July 2, 2021.

IV.3. **Application N°2:**

IV.3.1 Effect of the emissivity on the dynamic thermal behavior of hollow clay bricks

We varied the emissivity of the cavities' surfaces (from 0.3 to 0.9) to examine the effect of surface emissivity on the dynamic thermal characteristics of hollow clay brick. Figure IV.10. shows the temperature variation of the inner surface of the brick for different emissivity values. The results show that emissivity significantly impacts the average values of the inner surface temperature. When the emissivity values are reduced from 0.9 to 0.3, the internal temperature peak is significantly reduced. When the emissivity of the cavity surfaces is equal to 0.3, the internal temperature peak is minimized by about 5.4 ◦C, compared to the traditional brick. Reduced emissivity minimizes radiant heat transfer into the cavities, resulting in reduced heat transfer. Therefore, covering the internal surfaces of the cavities with a low emissivity coating improves the thermal performance of hollow clay bricks.

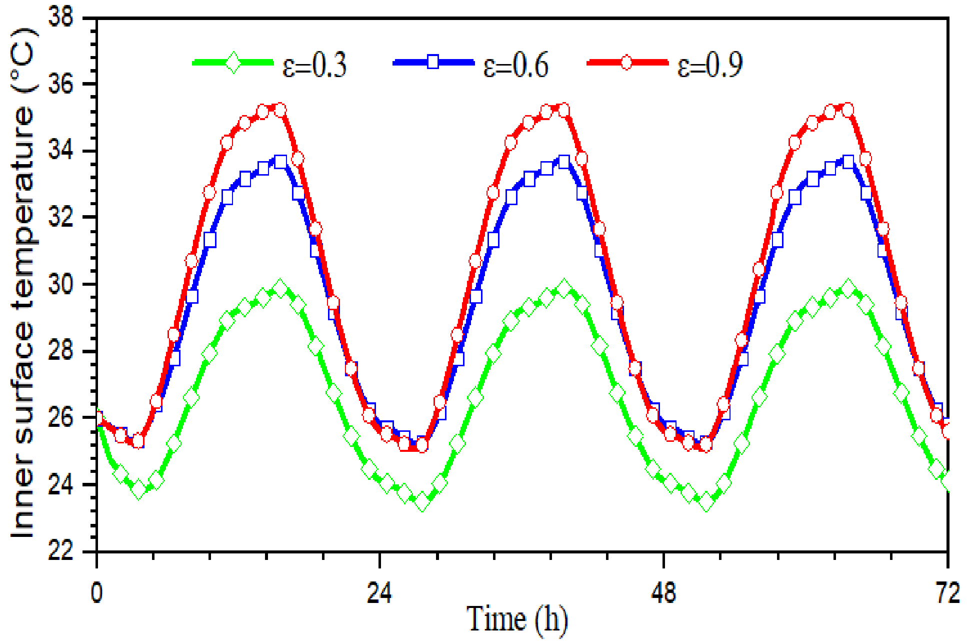


Figure IV.10. The inner surface temperature for different emissivity values.

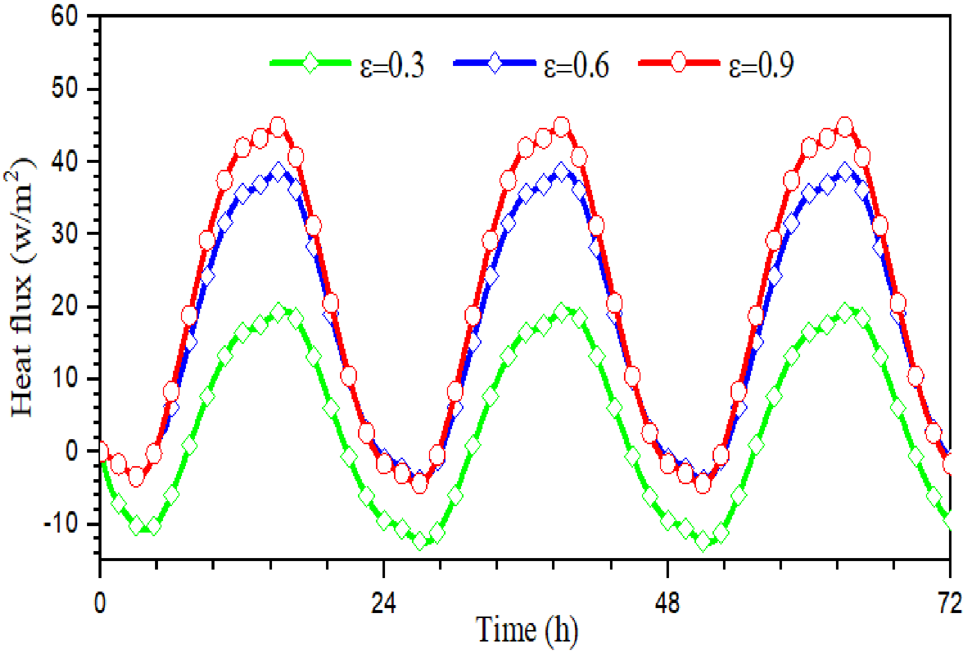


Figure IV.11. The inner surface heat flux for different emissivity coefficient values.

Figure IV.11. shows that the inner heat flux is minimized significantly by decreasing the emissivity coefficient. When the emissivity equals 0.3, the peak inner heat flux is reduced by about 55.03% compared to the traditional brick. This reduction in emissivity reduces radiant heat transfer through the holes, resulting in a decrease in overall heat transfer. In fact, for low emissivity values, the heat radiation contribution is significantly lower. Thus, the overall heat transfer through the brick is significantly reduced. Using a low emissivity coating, the total thermal load over a day is significantly reduced, thus saving energy consumption and improving buildings' internal thermal comfort level.

In addition, the low-emissivity coating is a simple and inexpensive technique to improve the thermal performance of hollow clay bricks. According to the advantages of using low emissivity coating to reduce the temperature fluctuations of the inner surface, indoor thermal comfort is not ensured. Therefore, building bricks with a low-emissivity coating must be combined with additional measures that increase clay hollow bricks' thermal inertia to achieve an appropriate thermal comfort range in summer. For this reason, the main objective of the following sections is to investigate the effectiveness of incorporating three passive measures in hollow clay bricks for improved thermal comfort and energy savings.

IV.3.2 Effect of insulation filling on the dynamic thermal behavior of hollow clay bricks

This subsection evaluates the effect of the EPS ratio on the inner heat flux and inner surface temperature. The temperature of the brick's inner surface is a key factor in assessing the thermal insulation performance of the brick. The temperature of the inner surface of the hollow clay brick is directly proportional to the thermal insulation performance. The lower the temperature of the brick's inner surface, the better the insulation performance; conversely, the higher the temperature of the brick's inner surface, the worse the insulation performance. Figures IV.12 and IV.13 show the influence of the EPS ratio on the inner heat flux and inner surface temperature, respectively. Two 50% and 100% EPS ratios were compared with HCB-8 without EPS.

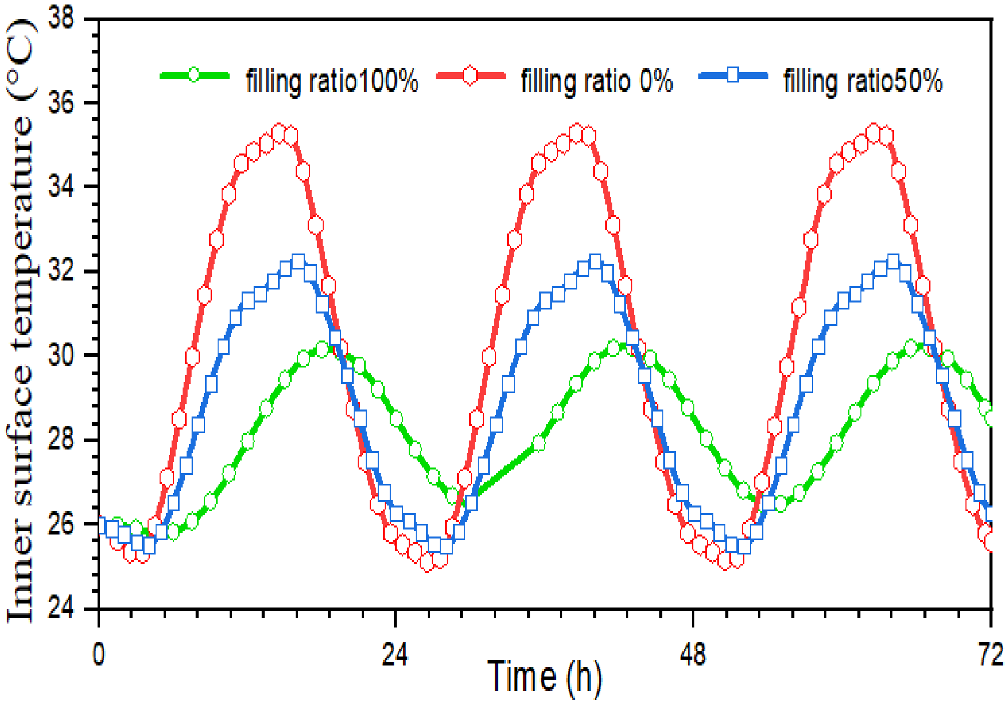


Figure IV.12. The inner surface heat flux variations for different filling insulation ratios.

The results show that increasing the fill ratio significantly reduces the brick's internal heat flow and surface temperature. Since all brick cavities are filled with the insulating material (filling ratio = 100%), the peak temperature of the inner surface decreases by about 5.2 °C, compared to the traditional hollow clay brick. Therefore, it can dampen inner thermal wave oscillations by filling the brick cavities with insulating material and reducing energy consumption.

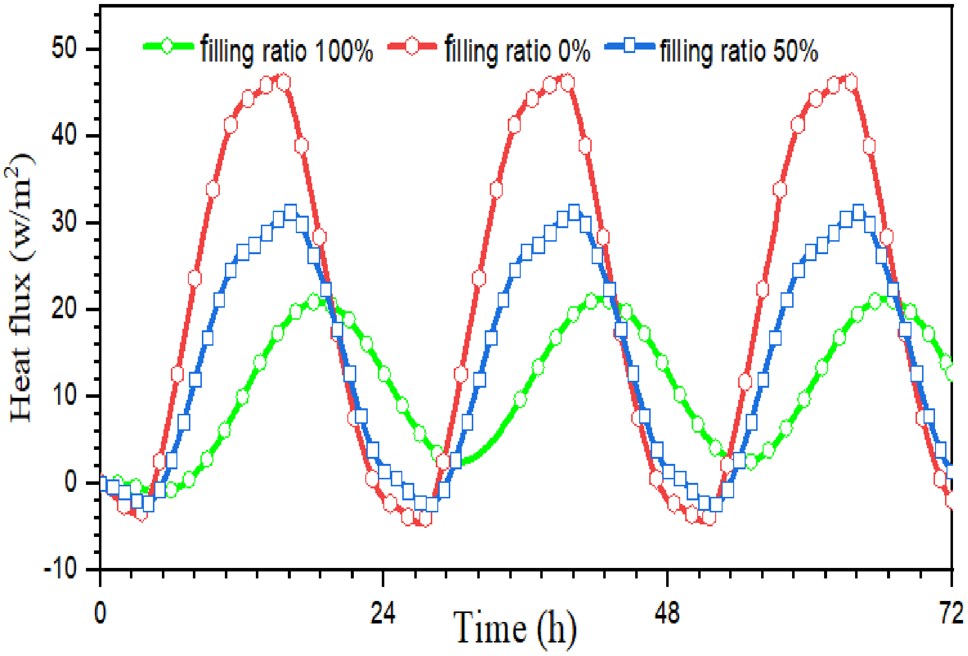


Figure IV.13. The inner surface temperature variations for different filling insulation ratios.

Figure IV.13 shows the variation in internal heat flux for different ratios of insulation fill to base brick. It can be seen that increasing the filling ratio results in a significant reduction in the internal heat flux. When 100% of the cavities are filled with insulation material, the inner surface heat flux is minimized by about 54.17% compared to the traditional hollow clay wall. In addition, the peak inner heat flux shifts from 5 h. Using insulating material to fill the brick cavities improves the thermal efficiency of the hollow clay brick. It attenuates internal heat wave variations and reduces the total heat flux through the brick. Finally, integrating this passive measure in hollow clay walls reduces the total energy consumption and extends the time needed for the external thermal wave to penetrate the indoor environment.

IV.3.3 Effect of the types of PCM on the dynamic thermal behavior of hollow clay bricks

The optimization of the type of PCM was adapted to the climatic conditions of the Bechar region. Three PCM types whose melting temperature varies between 43°C and 32°C (see Table V.2) were tested. It can be noted that the incorporation of PCM in the brick improves the building materials' thermal characteristics by changing the brick's thermal storage capacity and by decreasing and shifting the peak load of the building brick. Figure IV.14. illustrates the unsteady variation of indoor heat flow using three different PCMs. Filling the brick cavities with PCMs can shift and reduce the inner peak flux, thereby shifting the peak load hours over the day and reducing the cooling load. Specifically, the peak inner heat flux decreased by 67.14%, 46.8%, and 26.12% when capric n-Eicosane, acid, and RT-42 were used compared to the brick without PCM. This reduction is significantly more evident when PCM with a melting temperature close to the thermal comfort point is used. There are two reasons for this decrease. The first reason is the increase in thermal resistance produced by the lower thermal resistance of the PCM; the second reason is that energy is stored in the cavities of the PCM during melting, which prevents some heat from passing through the brick.

Figure IV.15. shows the variation of inner surface temperature over time for different types of PCM. When the PCM was filled into the cavities, the temperature fluctuations of the inner surfaces were reduced, which could improve indoor comfort levels. The peak temperatures in the inner surfaces were reduced by 5.9°C, 4.2 ◦C and 2.5°C, but the valley temperatures increased from 25.1°C to 27.4°C-29.8°C. This finding indicates that the PCM has a higher potential for thermal regulation. The results show that PCM significantly impacts the dynamic thermal behavior of hollow clay bricks. In conclusion, capric acid is the most suitable and leads to the best thermal efficiency of the hollow clay brick for roofs subjected to the external climatic conditions of the Bechar region.

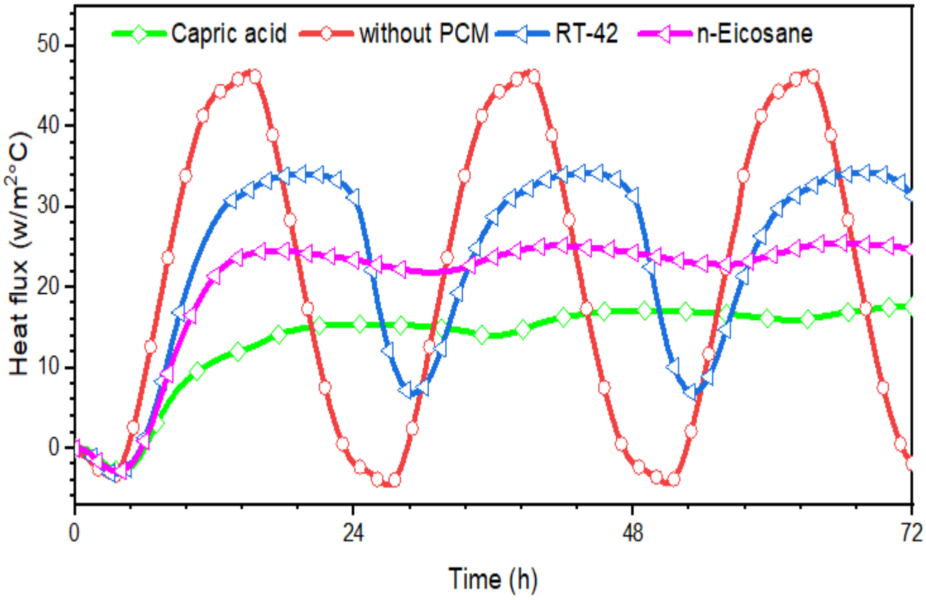


Figure IV.14. The inner heat flux variations for different PCMs filling.

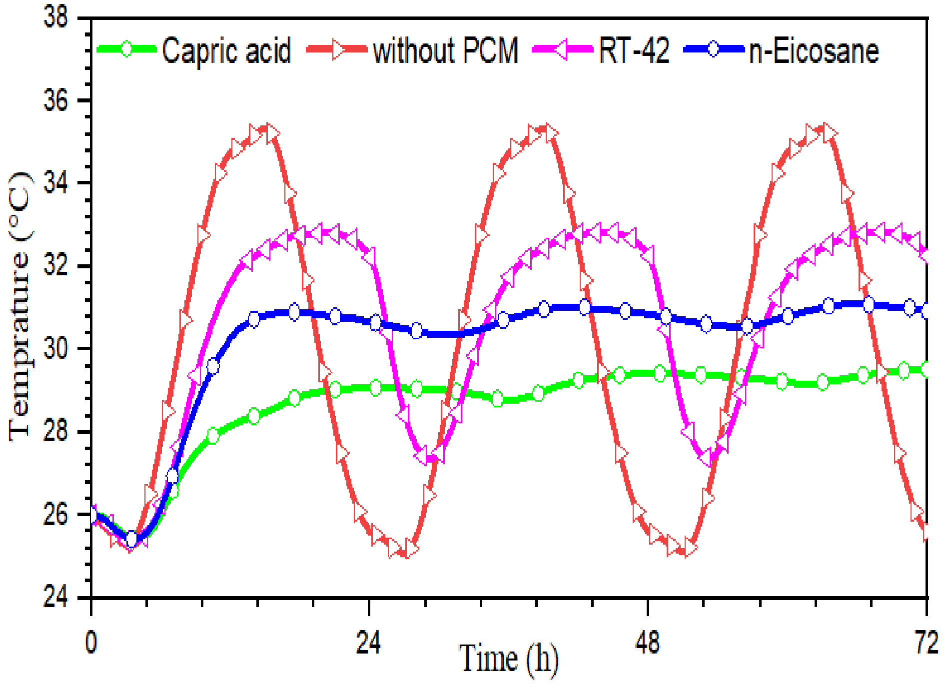


Figure IV. 15. The inner surface temperature variations for different PCMs filling.

IV.3.4 Optimization of the hollow clay brick design

The first step investigated the possibilities of increasing the thermal inertia of the hollow clay brick by using one of the three passive techniques. The second step examined the possibility of integrating two measures (low emissivity coating with ε =0.3, EPS and capric acid) in the same configuration Figure IV.7. The objective is to benefit from the advantages of each passive measurement. Figure IV.16. shows the variation of the inner surface temperature for the studied configurations. Thus, it can be noted that integrating two passive measures in the same configuration reduces the temperature fluctuations of the indoor surfaces compared to the traditional hollow brick. When both PCM and EPS measures are employed in the same configuration, the performance is better than the other configurations, followed by C3 and C2 configurations. The inner peak temperature was reduced by about 6.6 ◦C and 5°C when the inner cavities were filled with capric acid and the outer cavities with EPS or low emissivity coating, respectively (C3, C4 configuration). While in the C2 configuration, the peak temperature was reduced by about 4.3°C. The indoor heat flux shows a similar trend to the change in the inner surface temperature.

Figure.IV.17. shows the percentage reduction in heat flux. It can be noted that the maximum heat flux reduction for the different configurations is 73.7% for configuration C4, while C3 and C2 have values of 55% and 48.1%, respectively. Integrating two measurements simultaneously in the same configuration can decrease the amplitude of the thermal wave and increase the time lag. The aspect shift induced by C2, C3, and C4 is approximately 1.5 h, 6.5 h, and 5.5 h, respectively. The results demonstrate that the integration of PCM (capric acid) and EPS in the same configuration has a significant impact on the dynamic thermal behavior of the hollow clay brick. In conclusion, the PCM (capric acid) and EPS filled in the cavities is the most appropriate configuration that prospects the best thermal performance of the hollow clay brick subjected to the external climatic conditions of the Bechar region.

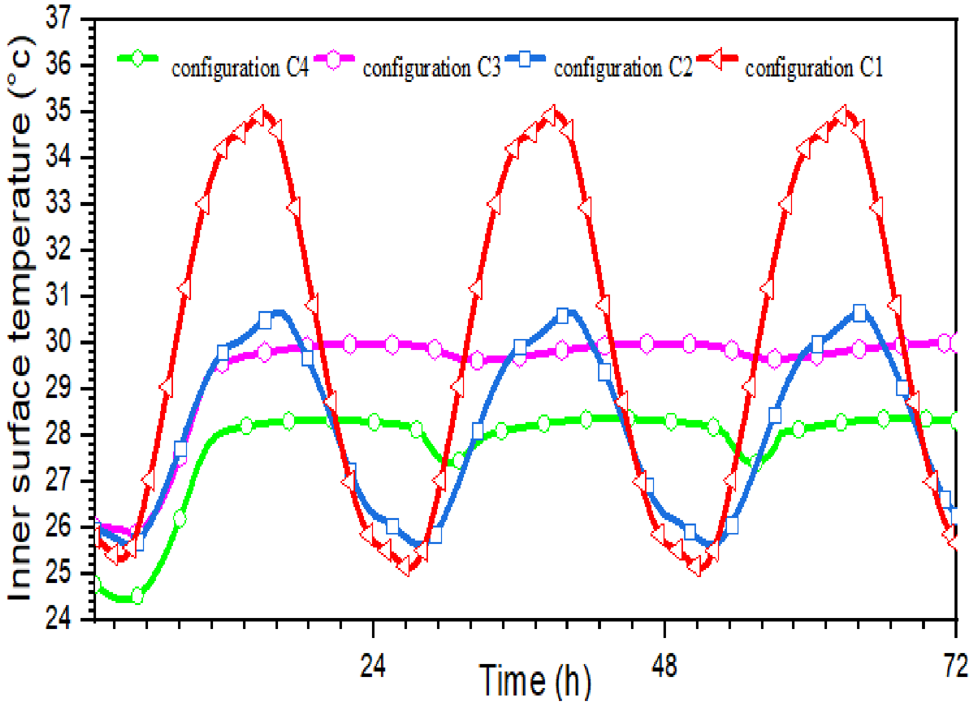


Figure IV.16. The inner surface temperature variations for configurations.

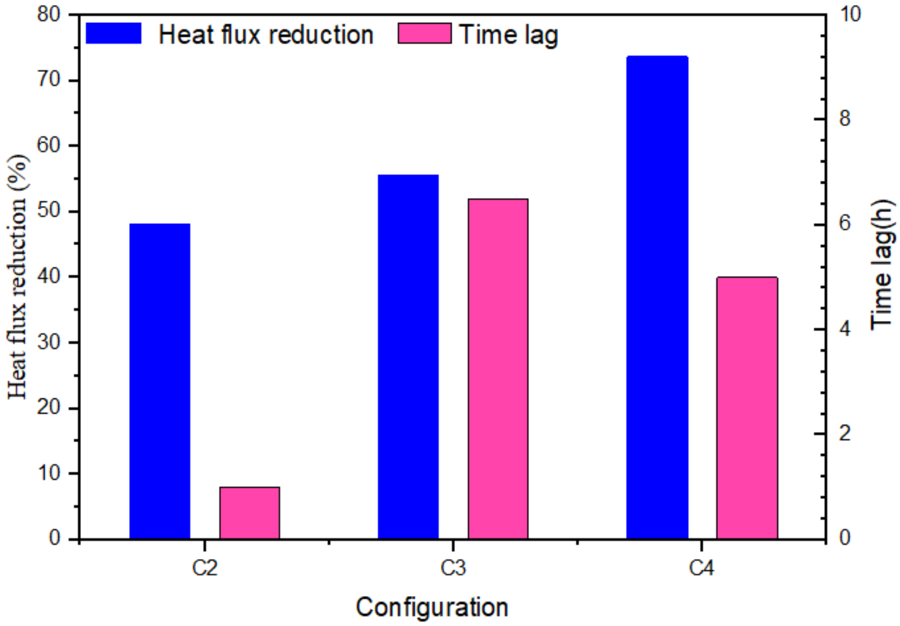


Figure IV.17. The time lag and heat reduction for the different brick configurations cases.

CHAPTHER V: General Conclusion and Future work

CHPTER V: Conclusion and future work

V.1. Conclusion

The aim of this study was to develop a systematic and comprehensive framework to deeply comprehend the operational mechanism of PCMs, along with methods for selecting suitable PCMs for building bricks and optimizing the utilization of their latent heat. This was done to effectively enhance building energy efficiency, especially in challenging climate conditions. This study investigated how different factors such as brick cavity shape, PCM location, PCM quantity, PCM type, and the combination of two passive measures (low emissivity coating, insulation materials, PCM) affected the thermal efficiency of building bricks. These investigations sought to improve the technical understanding of PCM use in building brick and highlight the impact of PCM on the thermal behavior of building bricks. The outcomes of this research and the methods suggested offer valuable understanding into the utilization of PCM in brick buildings.

A new building brick configuration with different cavity shapes containing PCM is developed to improve the service efficiency of PCM (the use of latent heat). It was found that this innovative building brick enhances thermal comfort and reduces building energy consumption in hot climate conditions. The brick thermal performance with PCM is superior to that of traditional brick. Compared to traditional wall bricks, incorporating capric acid as the filled PCM in the square brick cavities led to a 67.84 % decrease in maximum internal heat flux and a 4-h delay in the external thermal wave penetration into the indoor environment. Total energy consumption decreased from 7402.85 W/m^2/d for the wall brick without PCM to 2822.46 W/m^2/d with PCM. Utilizing bricks containing square-shaped cavities filled with capric acid PCM led to a 61.8 % decrease in total energy consumption during a typical summer day. Hence, it can be inferred that integrating phase change materials into the bricks commonly used in Algeria can enhance thermal comfort and promote energy conservation in buildings exposed to hot climatic conditions.

In order to further improve the building's brick thermal performance, this study also evaluated the benefits of filling cavities with insulating materials, phase change materials and using low emissivity coating in hollow bricks. Notably, incorporating each passive measure in hollow clay bricks has a unique mechanism for improving the energy efficiency. Therefore, combining two passive techniques in the same configuration investigated the possibility of increasing the thermal inertial of building (application N°2). A suitable configuration was determined according to the external climatic conditions. Through the comparative analysis of the inner surface temperature and heat flow of different configurations, it can be concluded that.

Thermal performance could be significantly improved by reducing the emissivity of the internal surfaces of the brick. Thus, using low emissivity coating materials on the internal surfaces of hollow bricks would contribute to improved thermal comfort in buildings, among other things.

Filling the hollow brick with EPS insulating material improves the insulation performance of the hollow brick, and the higher the EPS filling ratio, the better the insulation performance.

Heat flux is reduced when PCM is incorporated into the brick. Capric acid has the best performance among the examined PCMs.

The dynamic insulation performance of the brick roof with the low emissivity coating and EPS is much better than that of the traditional brick. It retains heat transmission through the brick.

The heat loss through the inner surface of the building brick is reduced by about 48.1 %. The time lag is shifted by about 1.5 h.

Simultaneous integration of phase change materials and insulation into the hollow clay brick shows better performance. It reduces the peak temperature of the brick’s inner surface by 6.6 ◦C. The heat flux on the inner surface of the brick after integrating these two measures is reduced by about 73.7 %, which contributes to the brick’s heat loss reduction.

Finally, this study adds value by offering comprehensive insights into potential technologies and practical guidance on PCM selection for building subjected o hot climates. It also examines the impact of factors such as brick cavity shape, PCM type and quantity, and the integration of two passive measures in the same configuration on thermal performance. The findings serve as a valuable reference for building owners, designers, and contractors looking to incorporate PCMs into building projects.

V.2. **Future Work**

PCMs have demonstrated significant promise in improving building energy efficiency and thermal comfort as a thermal management solution. Based on the findings of this study, the following suggestions emerge for future research:

Based on the computational models and numerical simulations conducted so far, more experimental testing and practical assessment of the thermal properties of the proposed building brick designs are recommended to gain a more comprehensive understanding. An outdoor experimental study could evaluate how the suggested brick configurations perform thermally over longer periods when subjected to real environmental conditions and natural forces encountered in real-world applications. Such experimental investigations have the potential to provide more comprehensive insights than simulations alone.

Using the same study to assess the efficacy of incorporating PCMs into building bricks in decreasing energy usage for heating buildings during the winter.

Utilizing nanoparticles to enhance the thermal properties of the suitable PCM (capric acid) for hat climate conditions to more use of its capacity to store latent heat, thereby expanding its applicability.

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