



APPLICATION OF PHASE CHANGE MATERIALS IN PASSIVE SOLAR ARCHITECTURE

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Abstract

This paper presents a review of the application of phase change materials (PCMs) in passive solar architecture, with particular emphasis on their integration into Trombe walls, building envelopes, and interior building components. The study examines the fundamental thermal properties of PCMs, their classification, thermal energy storage mechanisms, and the most common integration techniques used in buildings. Special attention is given to the role of PCMs in improving thermal comfort, enhancing energy efficiency, and increasing the utilization of solar energy through latent heat storage. The paper also discusses the advantages and limitations of different PCM types, including organic, inorganic, and eutectic materials, as well as current challenges related to thermal conductivity, long-term stability, fire safety, and economic feasibility. Furthermore, recent developments and future research directions, including bio-based PCMs, advanced encapsulation methods, and intelligent energy management systems, are reviewed. The findings indicate that PCM integration can significantly improve thermal regulation, reduce indoor temperature fluctuations, and decrease heating and cooling energy demand. Studies reviewed in this paper report energy savings of up to 30% in PCM-enhanced building systems, highlighting their considerable potential for sustainable and energy-efficient building design.

Key words: Phase Change Materials, Passive Solar Architecture, Thermal Energy Storage, Energy Efficiency, Trombe Wall

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1. INTRODUCTION

The building sector plays a key role in addressing climate change due to its high energy consumption and environmental impact. Buildings account for 36% of global energy use, while the construction industry is responsible for approximately 37% of annual CO₂ emissions [1]. Therefore, improving energy efficiency and increasing the use of renewable energy sources have become essential strategies for reducing carbon emissions and mitigating climate change [2].

Among renewable energy technologies, solar energy has attracted significant attention. However, its intermittent nature requires effective thermal energy storage (TES) systems to ensure continuous utilization. TES technologies enable the storage of excess thermal energy and its release during periods of higher demand, contributing to load balancing, improved energy efficiency, and reduced reliance on fossil fuels [3].

Phase change materials (PCMs) have emerged as one of the most promising TES solutions. These materials store and release large amounts of latent heat during phase transitions, helping to regulate indoor temperatures and reduce energy consumption [4]. Although the application of PCMs in buildings dates back to the 1970s, interest in this technology has grown considerably in recent years. PCMs can be incorporated into building envelopes, including walls, ceilings, and floors, where they increase thermal inertia, improve thermal comfort, and reduce temperature fluctuations and peak energy demand, contributing to more sustainable building operation [5].

Numerous studies have demonstrated the effectiveness of PCMs under different climatic conditions, with reported energy savings of up to 30% and further performance improvements achieved through conductivity-enhancing additives such as graphite [6,7]. Besides improving energy efficiency, PCMs contribute to sustainability by reducing dependence on mechanical heating and cooling systems and lowering greenhouse gas emissions. However, challenges related to thermal conductivity, long-term stability, fire safety, and economic feasibility still limit the widespread implementation of PCM technologies in buildings.

The aim of this paper is to review recent research on the application of phase change materials in passive solar architecture and to evaluate their potential and limitations regarding building energy efficiency and thermal comfort.

2. PHASE CHANGE MATERIALS (PCMS)

Phase change materials regulate temperature by storing and releasing latent heat during phase transitions. When temperatures rise above the phase change point, PCMs absorb heat and melt, while cooling causes them to release stored energy and solidify. If the phase change temperature corresponds to indoor comfort conditions, PCMs can stabilize indoor temperatures, improve thermal comfort, and reduce peak heating and cooling demands [8]. Their ability to enhance heat storage capacity, particularly in buildings with low thermal mass, makes them well suited for building applications.



2.1 Types of Phase Change Materials

Phase change materials are commonly classified according to their chemical composition, phase transition behavior, and application area [9]. Depending on the phase transition mechanism, PCMs may undergo solid–solid, solid–liquid, solid–gas, or liquid–gas transformations. Among these, solid–liquid PCMs are the most widely used in building applications due to their high latent heat storage capacity, effective thermal performance, and cost-effectiveness [10].

The selection of a suitable PCM primarily depends on its melting temperature and latent heat capacity, which should correspond to the operating conditions of the intended application. Based on their chemical composition, PCMs are generally categorized as organic, inorganic, or eutectic materials [11].

2.1.1. Organic PCMs

Organic phase change materials (PCMs) are generally divided into two categories: paraffin and non-paraffin materials. Owing to their favorable thermal and chemical characteristics, they are among the most commonly used PCMs in thermal energy storage applications. Organic PCMs possess relatively high latent heat storage capacity and suitable phase change temperature ranges, which makes them particularly effective for building applications [12]. Furthermore, they are chemically stable, non-corrosive, and typically do not experience phase segregation, while exhibiting little or no supercooling during the solidification process, contributing to reliable thermal performance [13]. However, their relatively low thermal conductivity remains one of the main limitations affecting heat transfer efficiency in building applications.

2.1.1.1. Paraffins. Paraffins are petroleum-derived saturated hydrocarbons with melting temperatures typically ranging from 20 °C to 70 °C, depending on carbon chain length [14]. They exhibit good thermal reliability, low vapor pressure, and minimal phase separation during repeated thermal cycles [15]. However, their relatively low thermal conductivity (approximately 0.2 W/(m·K)), moderate flammability, and limited compatibility with certain plastic containers represent important drawbacks [16].

2.1.1.2. Non-paraffins. Non-paraffin organic PCMs comprise a diverse group of materials, including fatty acids, esters, fatty alcohols, glycols, and other organic compounds. Among them, fatty acids have received particular attention for building thermal energy storage applications due to their renewable origin, environmental compatibility, and lower flammability compared to paraffin-based PCMs [17,18].

2.1.2. Inorganic PCMs

Inorganic PCMs are widely used in building applications due to their high latent heat storage capacity, superior thermal conductivity, and relatively low cost compared to organic PCMs. Common inorganic PCMs include salt hydrates, metallic materials, and other inorganic compounds. Despite their advantages, these materials may experience corrosion and phase separation during repeated thermal cycling, which can negatively affect their long-term performance.

2.1.2.1. Salt hydrates. Salt hydrates are the most widely used inorganic PCMs in building applications. They undergo reversible phase transitions between salt and



water during heating and cooling cycles. Owing to their high latent heat capacity and thermal conductivity, they can store larger amounts of energy and provide efficient heat transfer compared to organic PCMs [19]. In addition, their low cost, non-flammability, and environmental compatibility make them attractive materials for sustainable building applications [20]. However, their practical application may be affected by phase segregation and stability issues during long-term operation.

2.1.2.2. Metallics. Metallic PCMs are rarely used in buildings, despite their high thermal conductivity, rapid thermal response, and high energy storage density [21]. Their application is limited by high phase change temperatures, greater weight, and higher costs compared to other PCM types. Nevertheless, they remain promising for hybrid and high-temperature thermal energy storage systems [22].

2.1.3. Eutectic

Eutectic materials are mixtures of two or more components that melt and solidify simultaneously at a specific composition and temperature without phase separation. This stable phase transition behavior makes them suitable for thermal energy storage applications. Eutectic PCMs can consist of organic–organic, organic–inorganic, or inorganic–inorganic mixtures. Although they generally exhibit high thermal conductivity and density, their latent heat storage capacity is typically lower than that of other PCM types, which limits their wider application [23].

2.2 Properties of PCMs

The effectiveness of PCMs in building applications largely depends on their thermal properties, which determine their ability to store and release heat, regulate temperature fluctuations, and improve building energy performance [24].

2.2.1. Latent heat capacity

During phase transitions, PCMs absorb and release latent heat at nearly constant temperatures. Therefore, latent heat capacity is a key parameter in evaluating PCM thermal storage performance, as higher values enable greater energy storage and more effective temperature regulation in buildings.

2.2.2. Phase transition temperature

The phase change temperature is another critical selection criterion, as it should match the building's operating temperature range. For residential applications, PCMs with phase transition temperatures between 20 °C and 30 °C are generally preferred to maintain indoor thermal comfort [25].

2.2.3. Thermal conductivity

Thermal conductivity is a key parameter affecting PCM performance, as it determines the rate of heat absorption and release during phase transitions. Higher thermal conductivity enables faster responses to temperature changes and improves efficiency under dynamic thermal conditions [26].



2.2.4. Specific heat capacity

Specific heat capacity describes the amount of heat required to increase the temperature of a material by one degree Celsius and is particularly relevant during sensible heat storage, when no phase transition occurs.

2.2.5. Thermal cycling stability

Thermal cycling stability describes the ability of a PCM to retain its thermal properties after repeated heating and cooling cycles. Since PCMs undergo numerous phase transitions during operation, long-term stability is essential for maintaining performance. Repeated cycling may cause phase separation, reduced latent heat capacity, and material degradation, making thermal stability a key criterion for assessing PCM durability and reliability in building applications [27].

3. APPLICATIONS OF PCMS IN PASSIVE SOLAR ARCHITECTURE

PCMs have attracted considerable attention in passive solar architecture due to their ability to enhance thermal energy storage and indoor thermal comfort. Their integration into Trombe walls and building envelopes improves energy efficiency and reduces indoor temperature fluctuations.

3.1 PCM-Enhanced Trombe Walls

The Trombe wall is a passive solar heating system consisting of a massive dark-colored wall covered by glazing, with an air cavity between them. Solar radiation passes through the glazing and is absorbed by the wall, where thermal energy is stored and gradually released to the indoor space through conduction and convection [28].

Despite its advantages, the traditional Trombe wall may exhibit unstable heating performance in winter and overheating during summer. To overcome these limitations, various improvements have been proposed, including the integration of phase change materials, photovoltaic systems, advanced ventilation strategies, and venetian blind technologies [29]. Among these approaches, PCM integration has attracted particular attention due to its ability to increase thermal storage capacity, regulate indoor temperatures, shift peak thermal loads, and reduce building energy consumption [30].

The performance of PCM-enhanced Trombe walls (Fig. 1) depends on factors such as solar radiation intensity, PCM properties, air gap dimensions, glazing characteristics, and indoor temperature conditions [32]. Studies reviewed in this paper reported energy savings ranging from 15% to 30%, demonstrating the potential of PCM-integrated Trombe walls to improve thermal storage performance and indoor thermal comfort. The reported performance varies considerably depending on climatic conditions, PCM characteristics, and wall configuration, which makes direct comparison between studies difficult.

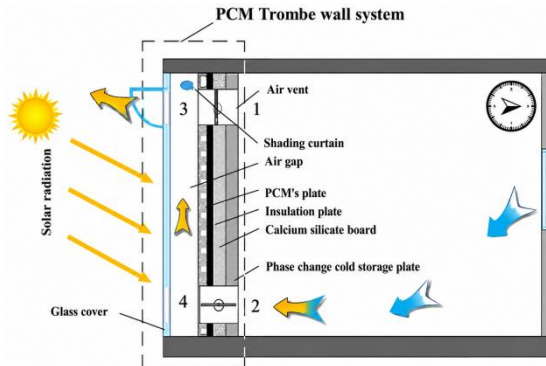


Figure 1. Trombe wall integrated with PCMs [31]

3.2 Building Envelope Integration

The integration of PCMs into building envelopes improves thermal performance, energy efficiency, and indoor thermal comfort by regulating heat transfer through walls, roofs, and facades [33]. Bio-based PCMs offer a sustainable alternative to petroleum-based materials, contributing to lower energy consumption and greenhouse gas emissions [34].

By absorbing excess heat and releasing it when temperatures decrease, PCMs help reduce indoor temperature fluctuations and improve thermal stability [35]. They can be incorporated into various building components, including wallboards, roof tiles, and facades, where they enhance thermal performance and reduce solar heat gains [36]. The effectiveness of PCM integration depends on both the thermal properties of the selected material and the architectural characteristics of the building.

Studies have reported reductions in heating and cooling energy demand ranging from 10% to 25%, while cooling load reductions in hot climates can reach up to 30%, highlighting the potential of PCMs to improve building energy efficiency and thermal comfort. However, challenges such as limited thermal stability, relatively low latent heat capacity, and leakage during phase transitions still restrict their wider application [37]. In addition, the effectiveness of PCM-enhanced building envelopes is highly dependent on climate conditions and proper material selection, indicating that a universal solution for all building types is unlikely.

4. CHALLENGES AND LIMITATIONS

Despite significant progress in PCM development, several challenges continue to limit the large-scale implementation of PCM-based thermal energy storage systems. Low thermal conductivity, particularly in organic PCMs, reduces heat transfer efficiency, although approaches such as nanoparticle additives, graphene enhancement, and nano-encapsulation have shown promising results [38]. Long-term performance may also be affected by phase segregation, supercooling, and material degradation during repeated thermal cycles [9]. Additional concerns include the flammability of some paraffin-based PCMs, insufficient assessment of environmental impacts throughout



their life cycle [39], integration challenges within building components, and the lack of standardized performance evaluation methods. Furthermore, economic constraints remain a significant barrier to commercialization.

Although numerous technical solutions have been proposed to address these challenges, their effectiveness often depends on specific climatic conditions, building characteristics, and PCM properties, which complicates large-scale implementation and comparison of research results.

These limitations highlight the need for climate-responsive PCM system design that balances thermal performance, durability, safety, and cost-effectiveness.

5. FUTURE PERSPECTIVES

Future developments in the application of PCMs in buildings are focused on improving their heat transfer performance, expanding their operating temperature range, and ensuring long-term stability through a large number of charge-discharge cycles. In particular, enhancing thermal conductivity remains one of the primary research objectives. This can be achieved through techniques such as the use of extended surfaces, microencapsulation methods, and the incorporation of nanoparticles to improve heat transfer efficiency [40].

Further efforts are also needed to evaluate the economic and environmental impacts of PCM applications, particularly through the development of bio-based and waste-derived PCMs that can reduce costs and environmental burdens [7]. In addition, artificial intelligence, digital twin technologies, sensors, and advanced control algorithms offer new opportunities for optimizing PCM performance and supporting dynamic energy management in smart buildings [9].

Future developments should also include the establishment of standardized testing procedures and performance criteria, as well as the integration of PCM technologies into building regulations and sustainability assessment frameworks. Greater emphasis should be placed on developing climate-specific PCM solutions, since thermal performance may vary considerably under different environmental and operational conditions.

Finally, long-term field studies and large-scale demonstrations are essential for validating laboratory findings and assessing the long-term reliability and effectiveness of PCM-based systems under real operating conditions [41].

6. CONCLUSION

Phase Change Materials represent a promising solution for improving the thermal performance and energy efficiency of passive solar buildings. Their ability to store and release latent heat allows more efficient thermal regulation compared to traditional construction materials.

Applications of PCMs in Trombe walls, building envelopes, and interior elements demonstrate considerable potential for reducing energy consumption and improving indoor comfort. Although several technical and economic challenges remain, ongoing

research and technological development are expected to accelerate the adoption of PCM systems in sustainable architecture.

The findings of this review indicate that the effectiveness of PCM integration depends not only on material properties but also on climatic conditions, building characteristics, and system design. Therefore, careful selection and optimization of PCM solutions are essential for achieving the desired thermal and energy performance.

The integration of PCMs into passive solar design strategies can play an important role in achieving future energy-efficient and environmentally responsible buildings.

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