

Improving Thermal Comfort and Reducing Peak Cooling Loads in High-Rise Buildings Through the Use of Phase Change Materials in Enhanced Building Envelopes

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Abstract

A potential remedy for the problems of peak cooling loads and thermal discomfort in high-rise buildings is the use of phase change materials (PCMs) into building envelopes. This study explores the potential of PCMs to enhance energy efficiency and occupant comfort by reducing heat gain and moderating indoor temperature fluctuations. The paper investigates various PCM types, integration methods, and their impact on building performance through simulations and experimental analysis. The findings highlight the effectiveness of PCMs in shifting peak cooling loads, reducing energy consumption, and creating a more stable and comfortable indoor environment. The study also addresses key considerations for PCM implementation, including material selection, encapsulation techniques, and optimal placement within the building envelope. By leveraging the thermal storage capabilities of PCMs, this paper contributes to the development of sustainable and resilient high-rise buildings that offer improved energy performance and occupant well-being. High-rise buildings face significant challenges in terms of energy consumption and occupant comfort, particularly in regions with hot climates. A considerable portion of energy use in these buildings is attributed to cooling systems, which are often strained to manage peak loads during hot weather. Traditional building envelope designs may not adequately address these challenges, necessitating the exploration of innovative solutions. This study investigates the potential of incorporating phase change materials (PCMs) into building envelopes to reduce peak cooling loads and enhance thermal comfort within high-rise structures.

Keywords: Phase change materials (PCMs), high-rise buildings, energy efficiency, thermal comfort, peak cooling loads, sustainable design

INTRODUCTION

As urbanization accelerates and high-rise buildings become prevalent, the demand for energy-efficient designs that ensure thermal comfort is increasingly critical. One effective strategy for

addressing these challenges is the implementation of enhanced building envelopes, particularly through the integration of phase change materials (PCMs). PCMs can absorb, store, and release thermal energy, making them invaluable in moderating indoor temperatures and reducing peak cooling loads [1]. This paper explores the role of PCMs in building envelopes, their benefits, and their impact on energy efficiency and occupant comfort in high-rise buildings.

PHASE CHANGE MATERIALS

Phase change materials are compounds that, at certain temperatures, change phases, such as from a solid to a liquid, so storing thermal energy. PCMs can regulate the indoor climate by absorbing excess

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heat at high temperatures and releasing it when the temperature drops when they are incorporated into building materials [2]. Common PCMs include paraffins, salt hydrates, and bio-based materials, each with unique thermal properties and melting points suitable for different climate conditions.

Understanding Phase Change Materials (PCMs)

A Deep Dive into Thermal Energy Storage Phase change materials (PCMs) are substances that undergo a reversible phase transition, typically between solid and liquid states, within a specific temperature range. This phase transition is accompanied by the absorption or release of a significant amount of latent heat, making PCMs ideal for thermal energy storage applications.

The Scientific Basis of PCMs: Latent Heat and Phase Transitions

Latent heat is the energy absorbed or released during a phase transition at a constant temperature, as opposed to sensible heat, which results in a change in temperature. PCMs function as thermal buffers by storing and releasing thermal energy using this latent heat (Figures 1-4). A PCM stores the absorbed energy as latent heat when it goes through a phase shift from solid to liquid. Conversely, when the PCM cools, it solidifies, releasing the stored latent heat. This reversible process allows PCMs to store and release thermal energy repeatedly, making them valuable for various applications.

Types of PCMs: Exploring the Diversity

PCMs can be broadly classified into three main categories: organic, inorganic, and eutectic (Table 1).

- *Organic PCMs*: These are typically derived from petroleum products or natural sources like fatty acids and waxes (Figures 5a-d). They are generally non-corrosive, chemically stable, and exhibit congruent melting, meaning they melt and freeze uniformly (Figure 5(d)).
- *Inorganic PCMs*: Salts that incorporate water molecules into their crystal structure are classified as salt hydrates and fall under the category of phase change materials (Figure 5(a)). They offer high latent heat storage capacity and sharp melting points but can be prone to supercooling and incongruent melting.
- *Eutectic PCMs*: These are mixtures of two or more substances that exhibit a lower melting point than their individual components. They offer the advantage of tailored melting points to suit specific applications (Figure 5(b) and (c)).

Key Properties of PCMs: Factors Influencing Performance

PCM performance in thermal energy storage systems is influenced by some important characteristics.

1. *Melting Point*: The temperature range at which a PCM can efficiently store, and release heat is determined by its melting point.
2. The quantity of energy stored or released per unit mass during the phase transition is represented by the latent heat of fusion.
3. The rate at which heat may move into and out of the PCM is determined by its thermal conductivity.
4. *Specific Heat Capacity*: This characteristic shows how much heat is needed to raise the PCM's temperature by a given quantity.
5. *Density*: A PCM's density influences how much volume is needed to hold a specific quantity of energy.
6. *Stability and Durability*: Throughout numerous cycles of melting and freezing, PCMs should demonstrate long-term stability and resistance to degradation.

Applications of PCMs: A Wide Range of Possibilities

PCMs have found applications in various fields, including building construction, thermal energy storage, electronics cooling, and textiles.

- *Building Construction*: To control indoor temperatures, lower energy costs, and improve thermal comfort, PCMs can be incorporated into building materials like walls, roofs, and floors.

- *Thermal Energy Storage:* By storing extra thermal energy from industrial operations or solar collectors for later use, PCMs can increase energy efficiency and lessen dependency on fossil fuels.
- *Electronics Cooling:* By distributing heat from electronic equipment, PCMs can reduce overheating and enhance functionality.
- *Textiles:* Textiles with PCM integrated in them can control body temperature, making them comfortable in a range of weather circumstances.

Table 1. Types, Characteristics and Building Components of PCMs.

S.N.	PCM Types	Advantages	Building Component
1.	Organics (Paraffin wax, fatty acids, and vegetable oils)	Availability in a wide range of temperatures <ul style="list-style-type: none"> • High heat of fusion • No subcooling • No segregation • Stable after many cycles • Chemically and physically stable • Compatibility with a wide range of containers • Corrosive materials • Environmentally safe, non-reactive • Recyclable 	Organic PCM is used as Insulation in roof
2.	Inorganic (Salt hydrates)	<ul style="list-style-type: none"> • High thermal storage capacity • Good thermal conductivity • Low cost • Available easily • Sharp melting points • Low vapor pressure • Nonflammable 	Inorganic PCM is used as insulating material in exterior glass in facade treatment.
3.	Eutectic	Sharp melting and boiling points <ul style="list-style-type: none"> • Higher volumetric storage density than the organic PCM 	Eutectic PCM can be used in false ceilings, interior walls and embedded as ceiling material

Source: Author.

Advantages of PCMs: A Sustainable Solution

PCMs offer several advantages over conventional thermal energy storage methods.

- *High Energy Storage Density:* PCMs are small and effective because they can store a large quantity of energy per unit mass or volume.
- *Isothermal Operation:* PCMs absorb and release heat at a nearly constant temperature, providing stable thermal control.
- *Reversible and Repeatable:* PCMs can undergo repeated cycles of melting and freezing without significant degradation, ensuring long-term performance.
- *Environmentally Friendly:* Many PCMs are non-toxic and environmentally benign, contributing to sustainable energy solutions.

Challenges and Future Directions

PCMs have many benefits, but they also have drawbacks that must be resolved if they are to be used more widely.

- *Cost:* The initial cost of PCMs can be higher than conventional materials, although the long-term energy savings can offset this investment.
- *Durability and Long-term Performance:* It's critical to guarantee PCMs' long-term stability and performance in a range of applications.
- *Integration with Current Systems:* It can be difficult to integrate PCMs with current building technologies and systems.
- *Thermal Conductivity:* The relatively low thermal conductivity of some PCMs can limit their heat transfer rate, requiring innovative solutions to enhance their performance.

Phase change materials have applications in many different industries and present a viable alternative for thermal energy management and storage. As research and development continue to address the challenges and unlock the full potential of PCMs, we can expect to see wider adoption of this innovative technology in the pursuit of sustainable energy solutions.

MECHANISM OF ACTION

PCMs function based on latent heat storage. When the surrounding temperature exceeds the PCM's melting point, it absorbs heat and transitions to a liquid state. Conversely, when the temperature falls below the freezing point, the material solidifies, releasing stored heat. This cyclic process effectively shifts energy demand, reducing the burden on HVAC systems during peak cooling hours.



Figure 1. Various type of building envelope design variables.

BENEFITS OF PCM-ENHANCED BUILDING ENVELOPES

Reduction in Peak Cooling Loads

One of the primary benefits of integrating PCMs into building envelopes (Figure 1) is the significant reduction in peak cooling loads. High-rise buildings often experience substantial heat gains due to their large surface areas and exposure to direct sunlight. By incorporating PCMs in walls, roofs, or windows, these buildings can effectively moderate temperature fluctuations, leading to lower cooling requirements. Studies have shown that buildings with PCM-enhanced envelopes can achieve up to a 30% reduction in peak cooling demand [3].

Improved Thermal Comfort

Thermal comfort is a crucial aspect of occupant satisfaction in high-rise buildings. Traditional building materials can lead to uncomfortable temperature variations, especially in densely populated urban areas (Figure 2). The incorporation of PCMs helps maintain a more stable indoor temperature, minimizing the risk of overheating during the day and allowing for more consistent comfort levels throughout the day and night. In addition to increasing tenant happiness, this stability raises general well-being and productivity.

Energy Efficiency and Cost Savings

By reducing peak cooling loads, PCMs contribute to improved energy efficiency in high-rise buildings. Lower cooling demands translate to reduced energy consumption (Figure 3), which can significantly decrease utility costs. Furthermore, during peak demand periods, energy prices tend to

spike; thus, a building equipped with PCM-enhanced envelopes can avoid high operational costs associated with conventional cooling methods [4]. Life-cycle assessments indicate that buildings utilizing PCMs can achieve substantial long-term savings in energy expenditure.

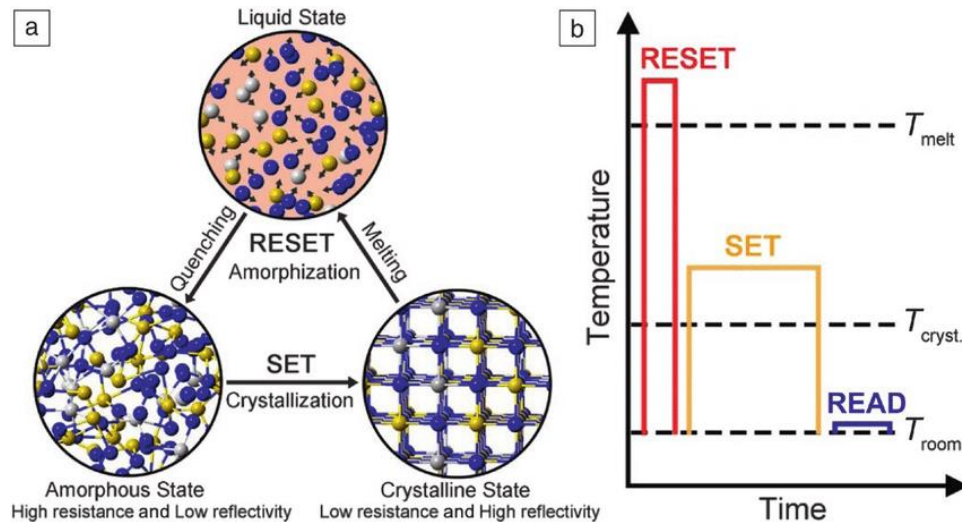


Figure 2. Various type of building envelope design variables.

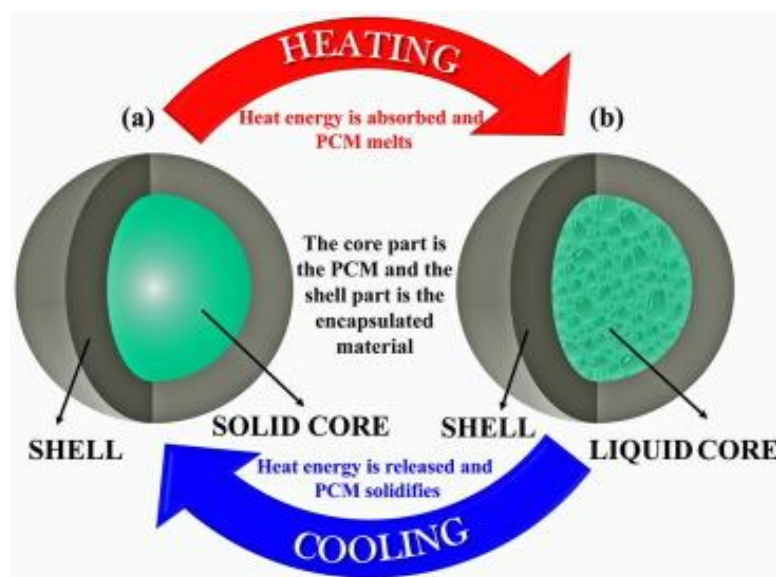


Figure 3. Solid to liquid of PCM inside encapsulated material.

ENVIRONMENTAL BENEFITS

The integration of PCMs aligns with global sustainability goals by reducing the carbon footprint of high-rise buildings. Reduced energy use results in lower greenhouse gas emissions, especially in areas where electricity is generated using fossil fuels. Furthermore, the sustainable choice of PCMs, including bio-based options, can contribute to a building’s overall eco-friendliness [5].

CHALLENGES AND CONSIDERATIONS

Despite their advantages, the implementation of PCMs in building envelopes is not without challenges [6]. The selection of appropriate PCM types and their integration into existing building materials require careful consideration of thermal properties, costs, and compatibility. Additionally, the initial investment for PCM-enhanced building envelopes may be higher than traditional methods, necessitating a thorough cost-benefit analysis (Figure 4).

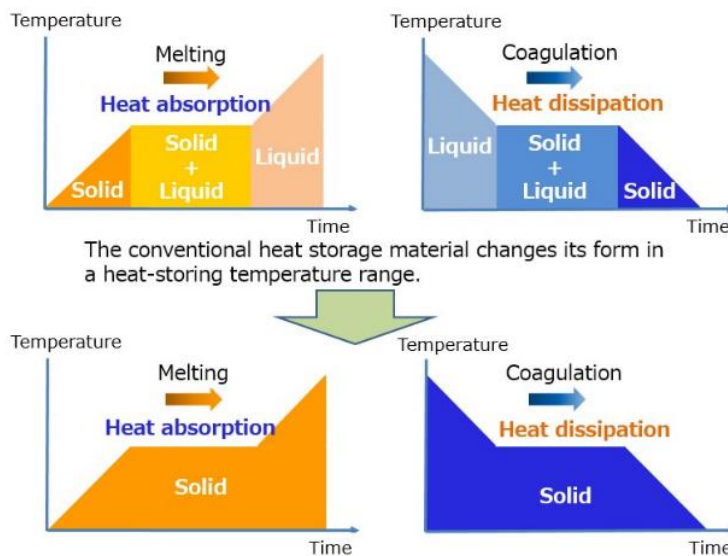


Figure 4. The Conventional Vs PCM heat storage material which changes its form in heat-storing temperature range.

Additionally, more research is required to maximize PCM performance in different building types and climates. The development of advanced PCMs that offer greater efficiency, thermal reliability, and reduced costs will be essential for broader adoption [7, 8].

System Integration and Design Considerations

The successful incorporation of PCMs into building envelopes necessitates a comprehensive design approach. To make sure that the integration does not compromise structural integrity or aesthetic concerns, engineers and architects must work together. The placement of PCMs in walls, ceilings, and facades should be strategically planned to maximize their thermal performance. Moreover, the interaction of PCMs with other building systems, such as natural ventilation and shading devices, must be evaluated to create a holistic approach to energy management.

Policy and Regulatory Frameworks

To facilitate the adoption of PCM technologies, supportive policies and regulatory frameworks are essential. Governments can encourage the adoption of sustainable materials by modifying construction codes, offering tax credits, or providing subsidies. Educational initiatives that raise awareness about the benefits of PCM integration among builders, architects, and property developers can also drive demand for these innovative materials [9].

Integration of PCM in Building Envelope

Integrating PCMs into the building envelope offers a passive strategy to enhance energy efficiency and thermal comfort by mitigating temperature fluctuations. This technology is gaining traction as a sustainable solution to reduce reliance on active heating and cooling systems.

Mechanisms and Benefits

PCMs utilize latent heat, the energy absorbed or released during a phase change, to store and release thermal energy. The PCM absorbs heat and melts when the outside temperature rises, thereby cooling the surrounding area. On the other hand, the PCM solidifies when the temperature drops, releasing the heat that has been stored and warming the environment.

1. *Reduced Energy Consumption:* PCMs decrease energy demands by reducing temperature swings and lessening the workload on HVAC systems.
2. *Improved Thermal Comfort:* By maintaining a more stable indoor temperature, PCMs enhance occupant comfort, particularly in regions with extreme temperature variations.

3. *Peak Load Shifting*: PCMs can shift peak energy demands to off-peak hours by storing excess heat during the day and releasing it at night.
4. *Sustainability*: By lowering energy use and greenhouse gas emissions, PCMs support sustainable construction practices [10].

Integration Methods

PCMs can be incorporated into various building envelope components, including walls, roofs, floors, and windows. Common integration methods include:

1. *Direct Incorporation*: PCMs can be directly embedded into building materials like concrete, gypsum, or plasterboard during the manufacturing process.
2. *Macro-encapsulation*: PCMs are encapsulated in pouches, panels, or other containers, which are then integrated into building elements.
3. *Micro-encapsulation*: PCMs are encapsulated in microscopic capsules, which can be added to building materials like paints or coatings.



Figure 5(a). Inorganic PCM that contain salt hydrants can be embedded between the glass panel which acts as thermal insulation and helps in reducing the effect of hot and cold air inside the building.

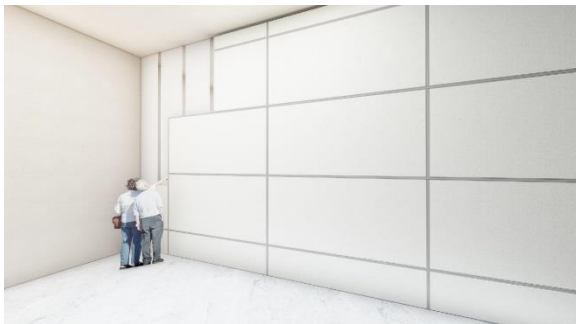


Figure 5(b). Eutectic PCM is mixed with a layer of concrete and has excellent thermal storage capacity which is useful to maintain temperature for the entire room throughout the day.



Figure 5(c). Eutectic PCM can be incorporated inside the drywall for use in interior walls which makes it less costly and has high thermal storage as compared to conventional walls.

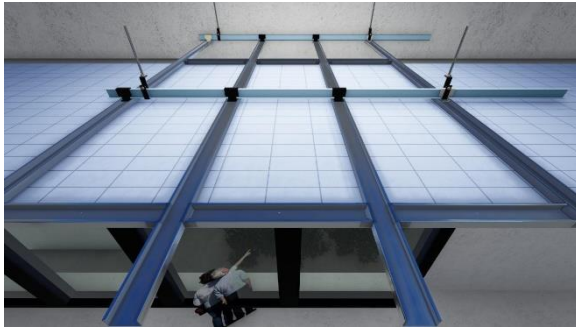


Figure 5(d). Organics PCM is embedded as ceiling material or false ceiling as it has higher thermal storage capacity.

Applications in Building Envelope

1. *Walls:* To efficiently regulate indoor temperatures, PCM-integrated walls absorb surplus heat during the day and release it at night.
2. *Roofs:* PCMs in roofs can reduce heat gain in summer and heat loss in winter, minimizing energy consumption for cooling and heating.
3. *Floors:* PCM-enhanced floors can contribute to thermal comfort by absorbing and releasing heat, particularly in spaces with high solar gains.
4. *Windows:* PCM-integrated windows can regulate solar heat gain, reducing glare and improving energy efficiency.

Factors to Consider

1. *Climate:* To guarantee best performance, the choice of PCMs should be determined on the basis of climate circumstances.
2. *Building Type:* The integration strategy should be tailored to the building's design and intended use.
3. *PCM Properties:* Factors like melting point, thermal conductivity, and durability should be considered when selecting PCMs.
4. *Cost:* Compared to standard materials, PCM integration may initially cost more, but over time, the energy savings may outweigh this expenditure.

Examples of PCM Integration

1. *PCM-enhanced plasterboard:* Plasterboard infused with micro-encapsulated PCMs can be used for interior walls and ceilings to regulate indoor temperatures.
2. *PCM-filled concrete panels:* Precast concrete panels containing macro-encapsulated PCMs can be used for exterior walls to provide thermal mass and reduce heat transfer.
3. *PCM-coated windows:* Windows coated with a thin layer of PCMs can dynamically control solar heat gain, reducing cooling loads.

CHALLENGES AND FUTURE DIRECTIONS

1. *Durability:* It is essential to guarantee PCMs' long-term performance and stability in building applications.
2. *Cost-effectiveness:* Optimizing the cost of PCM integration and demonstrating its economic viability is essential for wider adoption.
3. *Integration with Building Systems:* Energy efficiency can be further increased by integrating PCMs with other building systems, such as lighting controls and HVAC systems.

Integrating PCMs into the building envelope offers a promising passive strategy for achieving energy-efficient and comfortable buildings. As research and development continue to advance PCM technology and address its challenges, we can expect to see wider adoption of this innovative solution in the building industry.

CONCLUSIONS

One promising strategy for lowering peak cooling loads and enhancing thermal comfort in high-rise buildings is the use of phase-change materials in enhanced building envelopes. The benefits, including energy efficiency, cost savings, and environmental impact, make PCMs an attractive option for modern urban architecture. As technology advances and research continues to refine PCM applications, the integration of these materials into building designs will play a crucial role in creating sustainable, comfortable living and working environments in increasingly dense urban settings.

The transition toward PCM-enhanced envelopes not only addresses the pressing challenges of energy demand and climate control but also aligns with global sustainability efforts, marking a significant step forward in the evolution of high-rise building design. As the construction industry embraces these advancements, the potential for PCMs to revolutionize urban living becomes increasingly tangible, fostering a future where high-rise buildings are not only taller but also smarter, more energy-efficient, and better suited to the needs of their occupants [10].

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