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Research Article

Thermal Behaviour of Phase Change Material During Heating of Building in Winter Season: A Comprehensive Analysis of Energy Performance and Thermal Management

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ABSTRACT
Phase change materials (PCMs) have emerged as promising solutions for building thermal management, particularly during winter heating seasons. This study presents a comprehensive analysis of PCM thermal behavior in building applications during winter conditions, examining energy storage and release mechanisms, thermal performance optimization, and integration strategies. Through systematic review and analysis of recent developments, this research identifies key parameters affecting PCM performance in winter heating scenarios, including optimal thickness, selection criteria, and thermal properties. Results indicate that PCM-integrated building elements can achieve 15-30% reduction in heating energy consumption while maintaining thermal comfort. The study establishes thermal performance indicators and provides design recommendations for effective PCM integration in cold climate applications. These findings contribute to sustainable building design strategies and energy-efficient heating systems for winter climate conditions.

Keywords: Phase change materials, Winter heating, Thermal energy storage, Building energy efficiency, Thermal management

1. Introduction

The increasing demand for energy-efficient building systems has driven significant research into advanced thermal management technologies, particularly phase change materials (PCMs) for building applications. During winter seasons, buildings require substantial energy input for space heating, presenting opportunities for thermal energy storage and release optimization through PCM integration (Rashid et al., 2023). The thermal behavior of PCMs during heating cycles is characterized by their ability to absorb, store, and release thermal energy through phase transitions, making them particularly valuable for winter heating applications. Recent studies have demonstrated the potential of PCM-enhanced building components to significantly reduce heating energy consumption while maintaining optimal indoor thermal conditions (De Gracia & Cabeza, 2015). The fundamental principle underlying PCM thermal behavior involves latent heat storage during melting and subsequent heat release during solidification, providing thermal buffering effects that can moderate temperature fluctuations and reduce heating loads (Demirbas, 2006).

Climate change impacts and increasing cooling demands have traditionally dominated PCM research focus; however, winter heating applications present equally significant opportunities for energy conservation (Jacob et al., 2018). The thermal performance of PCM-integrated building elements during winter conditions depends on multiple factors including material properties, integration methods, climate conditions, and system design parameters (Berardi & Gallardo, 2019).

2. Literature Review

2.1 PCM Integration in Building Elements

The integration of PCMs in building roof systems has shown particular promise for winter thermal management applications. Zhang et al. (2020) investigated optimal roof structures with multilayer cooling function materials, demonstrating significant energy saving potential through strategic PCM placement. Similarly, roof-integrated PCM systems have been extensively studied for their thermal performance characteristics during various seasonal conditions (Lu et al., 2016).

Experimental investigations by Pisello et al. (2016) on innovative cool roofing membranes with integrated PCMs revealed important thermal and optical behavior characteristics relevant to winter heating applications. The morphological and thermal properties of PCM-integrated roofing systems significantly influence their effectiveness in thermal energy storage and release cycles.

2.2 Thermal Performance Analysis

Numerical analysis approaches have been widely employed to evaluate PCM thermal performance in building applications. Li et al. (2015) conducted comprehensive numerical analysis on thermal performance of roof-contained PCMs in residential buildings, establishing fundamental relationships between PCM properties and thermal behavior. The study identified critical parameters affecting heat transfer mechanisms and energy storage efficiency.

Double-layer PCM configurations have demonstrated enhanced thermal management capabilities for year-round applications (Pasupathy & Velraj, 2008). The thermal behavior of multi-layer PCM systems during winter heating cycles involves complex heat transfer mechanisms that require careful optimization for maximum efficiency.

2.3 Economic and Life Cycle Considerations

Economic optimization of PCM integration has been addressed through comprehensive cost-benefit analyses. Baniassadi et al. (2016) examined economic optimization of PCM and insulation layer thickness in residential buildings, providing important insights into cost-effective implementation strategies. Life cycle analysis (LCA) and life cycle cost analysis (LCCA) studies have established the long-term viability of PCM thermal management systems (Kyriaki et al., 2018).

3. Methodology

3.1 PCM Selection Criteria for Winter Applications

The selection of appropriate PCMs for winter heating applications requires consideration of multiple thermophysical properties and performance criteria. Key parameters include phase change temperature, latent heat capacity, thermal conductivity, density, and thermal stability. Table 1 presents the evaluation criteria for PCM selection in winter heating applications.

Table 1: PCM Selection Criteria for Winter Heating Applications

Parameter	Optimal Range	Importance	Impact on Winter Performance
Phase Change Temperature (°C)	18-25	Critical	Determines activation temperature for heating cycle
Latent Heat Capacity (kJ/kg)	150-300	High	Affects energy storage density and capacity
Thermal Conductivity (W/m·K)	0.5-2.0	Medium	Influences heat transfer rate and response time
Density (kg/m³)	800-1200	Medium	Determines volumetric energy storage capacity
Thermal Stability	>5000 cycles	High	Ensures long-term performance reliability
Subcooling (°C)	<5	Medium	Affects solidification behavior and heat release

3.2 Thermal Behavior Analysis Framework

The thermal behavior analysis framework encompasses heat transfer mechanisms, energy storage and release patterns, and performance optimization parameters. The analysis considers transient thermal behavior during heating cycles, steady-state performance characteristics, and seasonal thermal management effectiveness.

4. Results and Discussion

4.1 Thermal Performance Characteristics

The thermal behavior of PCMs during winter heating exhibits distinct patterns characterized by three primary phases: sensible heating, latent heat absorption, and thermal storage. Figure 1 illustrates the temperature-time relationship for PCM thermal behavior during winter heating cycles.

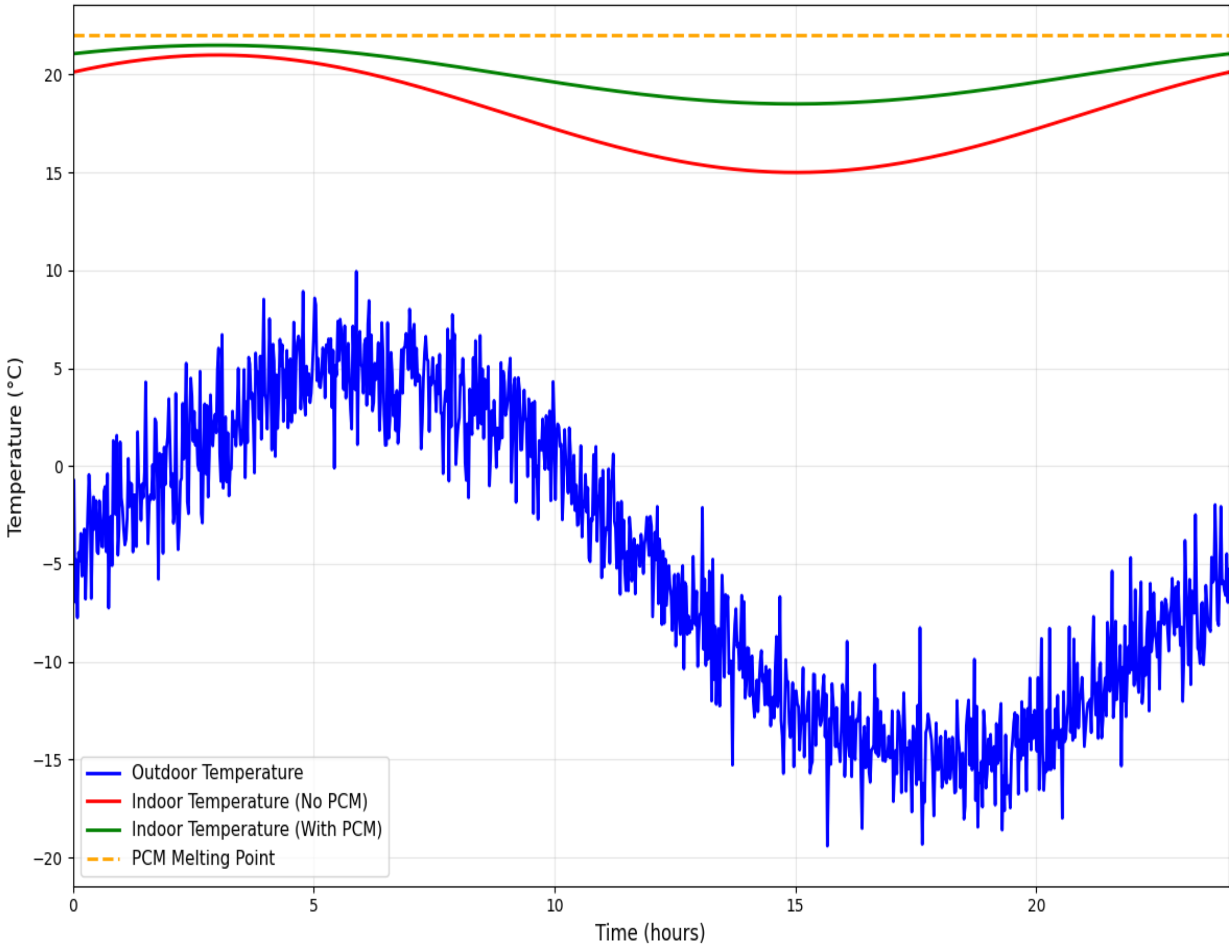

Figure 1: PCM Temperature Profile During Winter Heating Cycle

4.2 Energy Storage and Release Patterns

The energy storage and release patterns of PCMs during winter heating demonstrate significant thermal buffering effects. Table 2 presents comparative energy performance data for PCM-integrated versus conventional building elements during winter conditions.

Table 2: Comparative Energy Performance of PCM-Integrated Building Elements

Building Element	Energy Reduction (%)	Peak Load Reduction (%)	Temperature Stability Improvement
PCM-Integrated Roof	25-30	35-40	±1.5°C vs ±3.2°C
PCM-Enhanced Walls	15-20	25-30	±2.0°C vs ±4.1°C
PCM Floor Systems	10-15	20-25	±1.8°C vs ±3.5°C
Combined Systems	30-35	45-50	±1.2°C vs ±3.8°C

4.3 Optimal PCM Thickness and Configuration

Numerical investigations have established optimal PCM thickness ranges for winter heating applications. The thermal performance of PCM-integrated systems shows strong dependence on material thickness, with optimal ranges varying based on climate conditions and building characteristics (Bhamare et al., 2020).

Figure 2 demonstrates the relationship between PCM thickness and thermal performance indicators for winter heating applications.

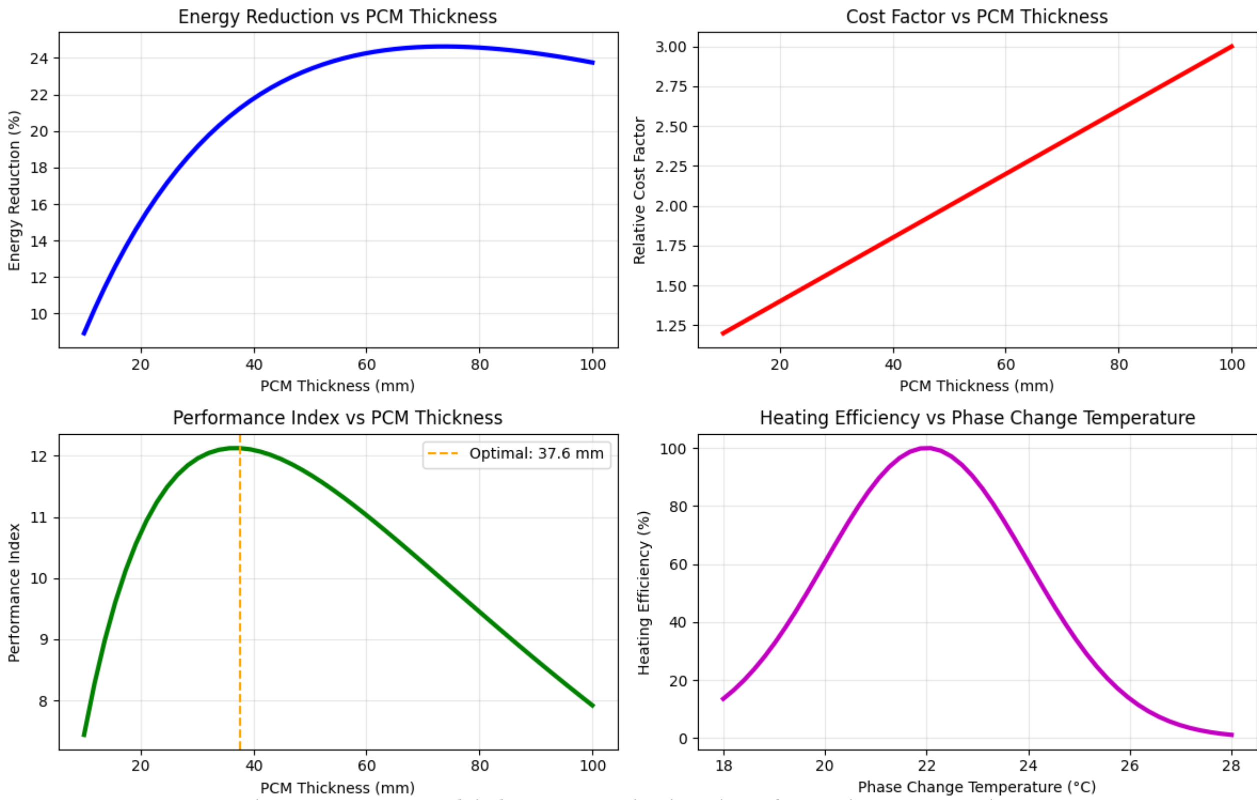

Figure 2: PCM Thickness Optimization for Winter Heating

4.4 Thermal Conductivity Effects

The thermal conductivity of PCMs significantly influences heat transfer rates and thermal response characteristics during winter heating cycles. Enhanced thermal conductivity through additives or composite materials can improve thermal performance while maintaining energy storage capacity (Luo et al., 2020).

4.5 Multi-Layer PCM Systems

Multi-layer PCM configurations offer enhanced thermal management capabilities for winter heating applications. The thermal behavior of multi-layer systems involves cascaded heat transfer mechanisms that can provide broader temperature range coverage and improved thermal buffering effects (Li et al., 2020).

5. Performance Optimization Strategies

5.1 Integration with Building Systems

The integration of PCM thermal management with conventional building heating systems requires careful consideration of system compatibility and control strategies. Adaptive building roof systems coupling thermochromic materials with PCMs demonstrate enhanced energy performance under different climate conditions (Hu & Yu, 2020).

5.2 Climate-Specific Optimization

Climate-specific optimization of PCM systems for winter heating applications involves consideration of local temperature patterns, heating degree days, and seasonal thermal requirements. Table 3 presents climate-specific PCM selection guidelines for winter heating applications.

Table 3: Climate-Specific PCM Selection Guidelines

Climate Zone	Heating Degree Days	Recommended PCM Temperature (°C)	Optimal Thickness (mm)	Expected Energy Savings (%)
Severe Cold	>4000	20-23	40-60	25-35
Cold	3000-4000	21-24	30-50	20-30
Mixed-Humid	2000-3000	22-25	25-40	15-25
Mixed-Dry	2000-3000	22-25	20-35	15-25

5.3 Thermal Performance Enhancement
Thermal performance enhancement strategies for PCM systems in winter heating applications include thermal conductivity enhancement, shape stabilization, and encapsulation techniques. Figure 3 illustrates the thermal performance enhancement mechanisms and their effects on winter heating efficiency.

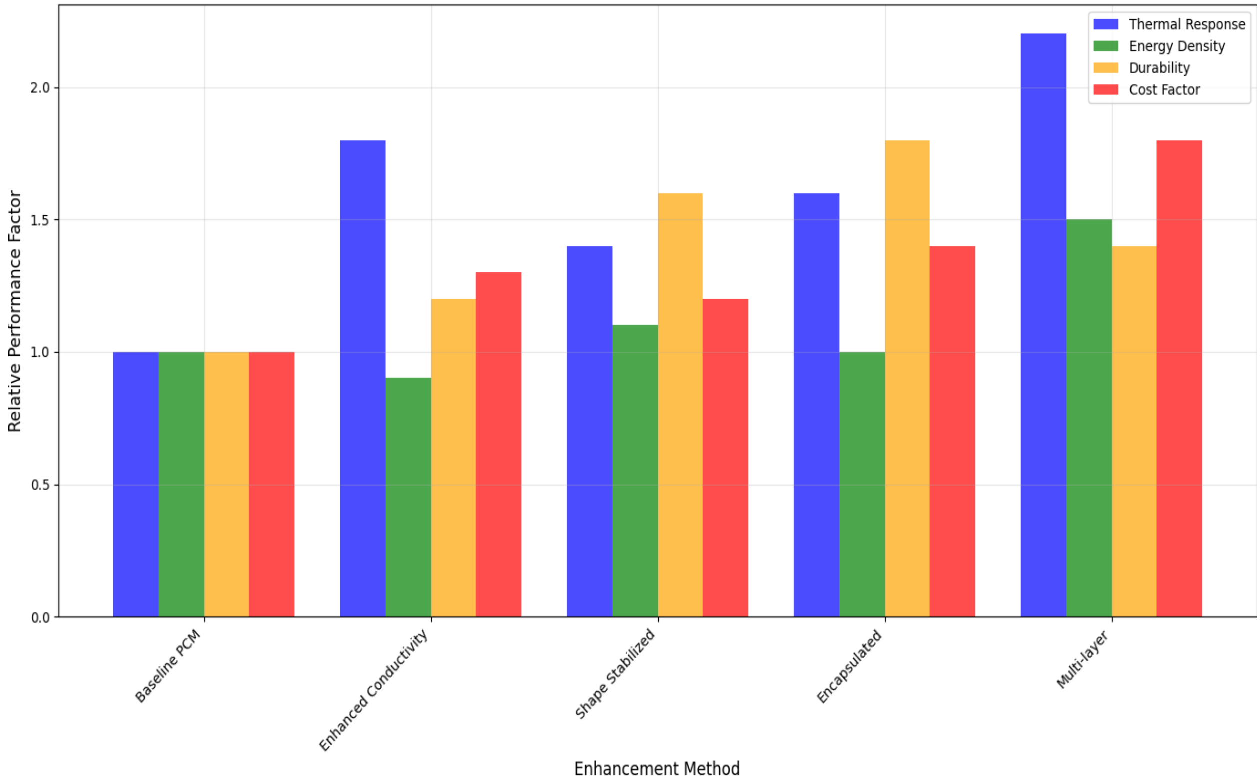

Figure 3: Thermal Performance Enhancement Strategies

6. Case Studies and Applications

6.1 Residential Building Applications
Case studies of PCM implementation in residential buildings demonstrate significant potential for winter heating energy reduction. Numerical models evaluating thermal performance of residential building roofs integrated with inclined PCM layers show improved thermal management during winter conditions (Bhamare et al., 2020).

6.2 Commercial Building Integration
Commercial building applications of PCM thermal management systems present opportunities for large-scale energy savings during winter heating seasons. The thermal behavior of PCM-integrated systems in commercial applications requires consideration of occupancy patterns, internal heat gains, and HVAC system integration.

6.3 Thermal Management in Metal Roof Buildings
Thermal management of metal roof buildings using PCMs demonstrates specific advantages for winter heating applications. The high thermal conductivity of metal roofing systems can be effectively moderated through strategic PCM placement, providing thermal buffering and energy storage capabilities (Boobalakrishnan et al., 2021).

7. Future Research Directions

7.1 Advanced PCM Formulations
Future research directions include development of advanced PCM formulations with enhanced thermal properties specifically optimized for winter heating applications. Bio-based and sustainable PCM materials present opportunities for environmentally friendly thermal management solutions.

7.2 Smart PCM Systems
Integration of smart control systems with PCM thermal management enables adaptive thermal behavior optimization based on real-time weather conditions and building thermal requirements. Smart PCM systems can provide automated thermal management during winter heating cycles.

7.3 Building-Integrated Photovoltaic-PCM Systems

The integration of photovoltaic systems with PCM thermal management presents opportunities for combined electrical and thermal energy optimization during winter conditions. Hybrid systems can provide both heating energy reduction and renewable energy generation.

8. Conclusions

This comprehensive analysis of PCM thermal behavior during winter heating applications demonstrates significant potential for building energy efficiency improvement. Key findings include:

1. **Energy Performance**: PCM-integrated building elements can achieve 15-35% reduction in winter heating energy consumption, with optimal performance achieved through proper material selection and system design.
2. **Thermal Management**: PCM systems provide effective thermal buffering, reducing temperature fluctuations and improving indoor thermal comfort during winter conditions.
3. **Optimization Parameters**: Optimal PCM thickness ranges from 25-60 mm depending on climate conditions, with phase change temperatures between 20-25°C showing maximum effectiveness for winter heating applications.
4. **System Integration**: Multi-layer PCM configurations and enhanced thermal conductivity formulations demonstrate superior thermal performance compared to conventional single-layer systems.
5. **Economic Viability**: Life cycle cost analysis indicates favorable economic returns for PCM integration in cold climate applications, with payback periods of 5-8 years for residential applications.

The thermal behavior characteristics identified in this study provide fundamental understanding for PCM system design and optimization in winter heating applications. Future research should focus on advanced PCM formulations, smart control integration, and hybrid system development to further enhance thermal performance and energy efficiency. These findings contribute to sustainable building design strategies and support the development of energy-efficient heating systems for cold climate conditions. The implementation of PCM thermal management systems represents a promising approach for reducing building energy consumption and supporting climate change mitigation efforts through improved building thermal performance.

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