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Energy Consumption Analysis of Building Exterior Walls with Phase Change Materials under Extreme Low Temperature Conditions

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Abstract: Global energy demand is steadily increasing, and climate change is becoming more severe. In extremely cold regions, building energy consumption has gained increasing attention. Traditional materials struggle to provide sufficient insulation, leading to higher heating loads and energy costs. This study explores the use of phase change materials (PCM) in building exterior walls to improve energy efficiency and thermal regulation. This study focuses on an apartment in Yakutsk, Russia, to evaluate the impact of different PCM thicknesses on energy savings. Climate data files are modified to reflect the thermal regulation of phase change materials, and EnergyPlus software is used to simulate and analyze different PCM thicknesses. The simulation results show that PCM thickness significantly impacts energy savings. Between 0 mm and 30 mm, increasing the thickness improves energy efficiency, but the gain gradually decreases beyond this range. The simulation data indicate that a 15 mm PCM thickness is optimal, offering significant energy savings and cost benefits. Future research should focus on the long-term performance of PCM and its integration with other sustainable technologies to maximize its value in building systems.

Keywords: Phase change materials (PCMs), Energy conservation, Climate document

1. Introduction

As global energy demand continues to grow and climate change intensifies, energy consumption in the building sector will become an increasingly pressing issue. In cold climate regions, the demand for heating and cooling will be particularly pronounced, as extreme outdoor temperature fluctuations during low-temperature conditions will make it difficult to maintain comfortable indoor temperatures, further increasing heating loads [1]. However, traditional building materials will likely continue to have limited insulation performance in such conditions, struggling to store sufficient heat to counteract nighttime temperature drops, leading to greater reliance on heating systems [2]. Therefore, in response to the growing heating energy challenges in cold regions, phase change materials (PCMs) are expected to provide an effective solution for improving building energy efficiency.

PCMs are efficient latent heat storage materials made of organic or inorganic compounds. During phase change, these materials absorb or release large amounts of heat. This helps stabilize

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indoor temperatures and reduces the load on heating and cooling systems [3-4]. Studies show that PCMs applied to building exterior walls can mitigate extreme cold effects by releasing stored heat at night, improving indoor environments [5].

Most research focuses on mild or moderately cold climates, examining PCM's effects on temperature regulation, comfort, and energy savings. Studies on PCM in extreme cold climates are limited, with little analysis of energy performance at different PCM thicknesses. Existing research mainly uses static or standard climate files and rarely includes dynamic modifications to reflect the interaction between PCM and extreme cold environments. This study assesses the energy-saving performance of phase change materials (PCM) with varying thicknesses under extreme low temperatures to identify the best application strategy. It modifies climate files to reflect the impact of PCM thickness and uses EnergyPlus software for simulation. This study provides PCM thickness optimization recommendations for exterior walls in cold regions, offering useful insights for future research.

2. Methodology

2.1. Research design

This study examines an apartment building in Yakutsk, Russia. It evaluates the impact of different PCM thicknesses on the building exterior wall's energy-saving effect under extreme low temperatures. The goal is to identify the optimal material thickness. A quantitative simulation analysis is conducted using EnergyPlus software to model PCM performance at various thicknesses and analyze its energy efficiency in extreme low-temperature climates.

2.2. Material selection and thickness setting

2.2.1. Selection of phase change materials

In this study, n-Tetradecane was selected as the phase change material (PCM) for the building exterior walls. The phase change temperature of n-Tetradecane is approximately 5.9°C, allowing it to absorb and release heat near the freezing point, providing effective thermal buffering for the walls. The latent heat of n-Tetradecane is around 200-230 J/g, and it can regulate the wall temperature during temperature fluctuations, reducing the load on the heating system.

2.2.2. Thickness setting

The thickness of PCMs directly affects their thermal buffering performance (Thermo-economic evaluation of PCM layer). This study examines thicknesses of 0 mm, 5 mm, 10 mm, 15 mm, 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, and 80 mm. The range includes applications from no PCM to high-thickness insulation.

2.3. Climate file modification

2.3.1. Purpose of climate document modification

The temperature fluctuations in the standard climate file cannot reflect the actual buffering effect of the PCM. Modifying the climate file is intended to adjust the original climate data, indirectly reflecting the thermal regulation effect of n-Tetradecane PCM under extreme low-temperature conditions.

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2.3.2. Steps for climate document modification

The climate file is adjusted based on different thicknesses of the phase change material. The key adjustment steps are as follows, aiming to simulate the energy-saving effect of various PCM thicknesses under extreme low-temperature conditions and provide data support for simulation analysis.

2.3.2.1. Dry bulb temperature

1) Reason for adjustment: The phase change material absorbs and releases heat during the phase change process, directly affecting the air temperature near the building exterior walls and altering the dry bulb temperature, a key parameter reflecting the environmental thermal conditions.

2) Derivation of dry bulb temperature adjustment formula:

a. Make basic assumptions

·It is assumed that in the process of heat absorption and release, sensible heat and latent heat work together to ensure the continuity and stability of external temperature regulation

·It is assumed that the temperature regulation amount ΔT is linearly related to the PCM thickness d.

·Based on Fourier's law of heat conduction, it is assumed that the rate of heat transfer in the system remains constant, ignoring dynamic nonlinear effects or rapid changes.

·It is assumed that the heat capacity of the wall is constant, the heat capacity of all layers is evenly distributed, and there is no significant thermal resistance difference in the heat conduction process.

b. Based on the basic principles of heat conduction and energy balance

According to Fourier's Law of Heat Conduction, heat transfer relates to the temperature gradient and the conduction path length (thickness) as follows:

$$q = -k * \frac{\Delta T}{d} \tag{1}$$

This formula shows that increasing material thickness dd reduces the rate of heat conduction.

·q: Heat flux density, unit: W/m^2

·k: Thermal conductivity of the material, unit: W/(m·K)

·ΔT : Temperature difference, unit: K

·d: Material thickness, unit: m

In PCMs, heat absorption and release involve sensible heat storage and latent heat storage.

Sensible heat storage:

$$Q_{sensible} = m * c * \Delta T \tag{2}$$

·$m = \rho * A * d$, The material mass depends on density ρ、contact area A and thickness d

·c: Specific heat capacity of the material

Substitute $m = \rho * A * d$ into Equation (2):$Q_{sensible} = \rho * A * d * c * \Delta T$

Latent heat storage:

$$Q_{latent} = m * L \tag{3}$$

·L: Latent heat of phase change

Substitute $m = \rho * A * d$ into Equation (3):$Q_{latent} = \rho * A * d * L$

c. Establishing the Temperature Adjustment Formula

The total heat of the PCM relates to external temperature regulation as:

$$Q_{total} = Q_{sensible} + Q_{latent} \tag{4}$$

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Based on the law of energy conservation, the relationship between heat storage and temperature regulation can be expressed as (Assuming that the total heat storage of the phase change material balances the external temperature fluctuations at the phase change and sensible heat stage):

$$\Delta T_{adjusted} = \frac{Q_{total}}{C_{wall}} \tag{5}$$

·C_{wall}: Wall thermal mass

·$\Delta T_{adjusted}$: Adjusted temperature variation

Substitute Q_{total} into Equation (5): $\Delta T_{adjusted} = \frac{\rho*A*d*c*\Delta T+\rho*A*d*L}{C_{wall}}$

Since the sum of A and C_{wall} is a constant, the adjustment coefficient$k$ is used to represent:

$$k = \frac{\rho*A*(c*\Delta T+L)}{C_{wall}} \tag{6}$$

Therefore:

$$\Delta T_{adjusted} = k * d \tag{7}$$

Based on the above content and assumptions, the dry bulb temperature adjustment formula is unified as:

$$T_{night,adjusted} = T_{original} + k * d \tag{8}$$

2.3.2.2. Relative humidity

1) Reason for Adjustment: Relative humidity depends on saturated and actual vapor pressure. Changes in dry-bulb and wet-bulb temperatures modify these pressures and affect relative humidity.

2) Derivation of the Relative Humidity Adjustment Formula

a. Definition of relative humidity:

$$RH = \frac{e}{e_s(T)} * 100\% \tag{9}$$

·e: Actual water vapor pressure (unit: kPa)

·e_s: Saturation vapor pressure, which depends on temperature T (unit: kPa)

b. Impact of Temperature Adjustment

When the temperature changes from $T_{original}$ to $T_{adjusted}$, the actual water vapor pressure e stays constant because it depends on the water vapor content in the air. The saturated water vapor pressure $e_s(T)$ changes with temperature and is calculated using the Tetens formula.

$$e_s(T) = 0.6108 * \exp(\frac{17.27*T}{T+237.3}) \tag{10}$$

When the temperature is adjusted, the new relative humidity is:

$$RH_{adjusted} = \frac{e}{e_s(T_{adjusted})} * 100\% \tag{11}$$

Since $e = RH_{original} * e_s(T_{original})$ substitute this into Equation

$$RH_{adjusted} = RH_{original} * \frac{e_s(T_{adjusted})}{e_s(T_{original})} \tag{12}$$

2.3.2.3. Wet-bulb temperature

1) Reason for Adjustment: Wet-bulb temperature directly relates to dry-bulb temperature, reflecting the balance between air humidity and temperature.

2) The wet-bulb temperature is calculated using the following approximate formula, based on engineering experience for quick estimation of moist air properties in building environments [6].

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$$T_w = T_d \arctan(0.151977 \cdot (RH + 8.313659)^{0.5}) + \arctan(T_d + RH) - \arctan(RH - 1.676331) + 0.00391838 \cdot RH^{1.5} \cdot \arctan(0.023101 \cdot RH) - 4.686035 \quad (13)$$

·T_w: Wet bulb temperature
·T_d: Dry bulb temperature
·RH: Relative humidity

2.4. Simulation process with energyplus

2.4.1. Settings of simulation parameters

According to the research objectives and methods, EnergyPlus software was used for simulation analysis. Specific parameter Settings are shown in Figure 1:

·The exterior wall consists of the following main structural parameters, from outside to inside:
·The decorative layer is made of tiles with a thickness of 10mm.
·The insulation layer is made of polystyrene foam with a thickness of 60mm.
·The structural layer is made of concrete with a thickness of 180mm.

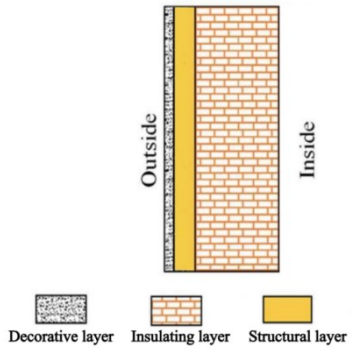


Figure 1: Wall structure

·Outdoor climate conditions: Climate data from the Yakutsk region in Russia was utilized [7]. Indoor temperature setting: Indoor temperature setting: The Heating, Ventilation, and Air Conditioning (HVAC) system maintains the indoor temperature within a comfortable range of 20°C–23°C.

·Simulation period: The heating season is from September to April, covering typical extreme low-temperature weather.

2.4.2. Simulation run and data output

2.4.2.1. Simulation workflow:

·Create the building model in SketchUp using the OpenStudio plugin and export the model as an IDF file, as shown in Figure 2.

·Load the climate file modified with the adjusted formulas.

·Configure the HVAC system to maintain indoor comfort temperatures and monitor performance data.

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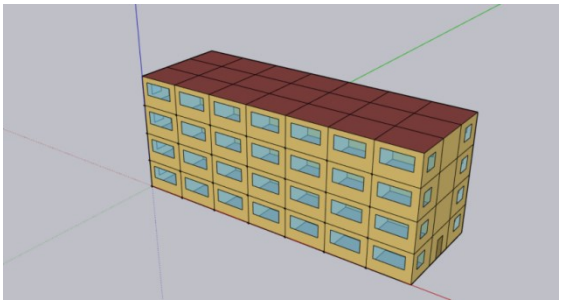


Figure 2: Apartment model

2.4.2.2. Run the simulation

Simulate each PCM thickness (0 mm, 5 mm, 10 mm, 15 mm, 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm) under the same conditions to ensure comparability. Run at least one complete simulation for each thickness to ensure stable results and record the corresponding data.

3. Results

3.1. Comparative energy efficiency analysis

3.1.1. Comparative analysis of energy efficiency

After the simulation, the energy-saving efficiency of building exterior walls with different thicknesses of phase change materials under extreme low-temperature conditions was evaluated. The key indicator "Total Site Energy", analyzed with EnergyPlus software, was used for comparison. The energy-saving efficiency was then calculated using the formula. As shown in Table 1:

$$\text{Energy saving efficiency} = \frac{E_{baseline} - E_{PCM}}{E_{baseline}} * 100\% \quad (14)$$

Table 1: Energy saving efficiency

Phase change material thickness	Total site energy (GJ)	Energy saving efficiency
0mm	2496.93	0.00%
5mm	2258.49	9.55%
10mm	2159.08	13.53%
15mm	2101.97	15.82%
20mm	2070.29	17.09%
30mm	2019.19	19.13%
40mm	1992.16	20.22%
50mm	1974.42	20.93%
60mm	1961.80	21.43%
70mm	1952.43	21.81%
80mm	1945.14	22.18%

·$E_{baseline}$: Total energy consumption when PCM thickness is 0 mm
·E_{PCM}: Total energy consumption when using PCM of different thickness

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3.1.2. Impact of PCM thickness on energy savings

According to the data of different thicknesses and energy saving efficiency of PCM in Table 1, the relationship between PCM thickness (x-axis) and energy saving rate (y-axis) is drawn, as shown in Figure 3:

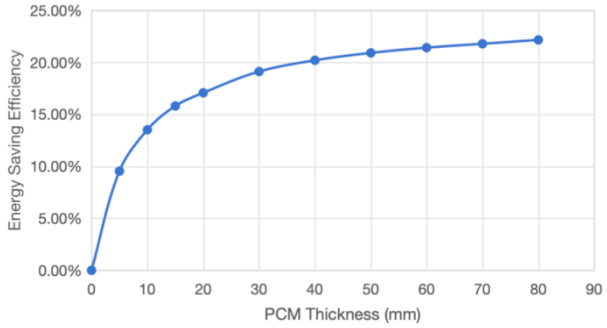


Figure 3: PCM Thickness and Energy Efficiency Graph

The detailed analysis of Figure 3 is as follows:

1) Trend of Figure 3:

·As shown in Figure 1, the energy efficiency saving rate increases significantly with the increase in PCM thickness. In the initial stage, the increase in PCM thickness (from 0mm to 20mm) results in a considerable energy saving benefit.

·When the PCM thickness reaches around 30mm, the increase in energy efficiency saving rate slows down. As the thickness increases, the energy-saving effect gradually diminishes. Above 70mm, the effect stabilizes, showing that adding more PCM thickness does not significantly improve energy savings.

2) Diminishing Marginal Returns:

·In the 0mm-30mm range, increasing PCM thickness significantly improves energy savings, and the energy efficiency saving rate rises quickly. At lower thicknesses, the thermal regulation effect of PCM is more pronounced and reduces energy consumption effectively.

·In the 30mm-80mm range, the energy-saving effect gradually diminishes as PCM thickness increases. Between 40mm and 80mm, the improvement in energy efficiency slows down, indicating diminishing marginal returns.

3) Analysis results: The trend in Figure 3 shows that increasing PCM thickness significantly improves the energy efficiency saving rate. However, when the thickness exceeds a certain critical value, the increase in energy-saving benefits becomes minimal.

3.1.3. Cost-Benefit analysis of PCM thickness

In this study, as n-Tetradecane is used as the phase change material, increasing its thickness not only improves energy efficiency but also leads to higher material and installation costs from an economic perspective. Calculate using the following formula:

Energy Saving Benefit Formula:

$$\text{Energy Saving Benefit (ESB)} = (E_{baseline} - E_{PCM}) * \text{Energy Price} \quad (15)$$

·$E_{baseline}$: Total energy consumption per unit area without PCM (kWh/m^2)

·E_{PCM}: Total energy consumption per unit area with PCM (kWh/m^2)

·Energy Price: Energy price ($/kWh)

Cost Calculation Formula:

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$$\text{Total Cost (TC)} = (C_{material} * \text{Thickness}) + C_{install} \quad (16)$$

·$C_{material}$: Cost per unit area of phase change material per millimeter ($\$/mm \cdot m^2$)
·Thickness: Thickness of PCM (mm)
·$C_{install}$: Installation cost.
Cost-Benefit Ratio Formula (CBR)

$$CBR = \frac{ESB}{TC} \quad (17)$$

Using the formulas and actual data, set the thickness of the n-tetradecane PCM as tt (in mm), the energy price as \$0.2/kWh, the material cost as \$2/mm • m^2 , and the installation cost as \$50/m^2 [8].

Table 2: Cost-Benefit Analysis for Different Thicknesses Over One Year.

PCM thickness	Material cost ($/m²)	Total cost ($/m²)	Energy savings ($/m²·year)	Cost performance index
0mm	0	0	0	0
5mm	10	60	47.688	0.795
10mm	20	70	67.570	0.965
15mm	30	80	78.992	0.987
20mm	40	90	85.328	0.948
30mm	60	110	95.548	0.869
40mm	80	130	100.954	0.777
50mm	100	150	104.502	0.697
60mm	120	170	107.026	0.630
70mm	140	190	108.900	0.573
80mm	160	210	110.758	0.527

Table 2 shows that energy-saving benefits increase with PCM thickness but display a diminishing marginal return effect. At lower thicknesses (0mm to 10mm), energy savings rise sharply from \$0 to \$67.570. However, at higher thicknesses (40mm to 80mm), energy savings increase only from \$100.954 to \$110.758, indicating limited improvement. The cost-effectiveness indicator is highest in the 10mm to 20mm range, peaking at 0.987 at 15mm. Further increases in thickness lead to a decline in cost-effectiveness. Considering both cost and energy savings, the optimal thickness is 15mm. Beyond 20mm, increasing thickness offers limited benefits and low cost-effectiveness.

3.2. Key findings and design implications

Based on the simulation analysis, this study provides design recommendations for applying PCM in building exterior walls under extreme cold climate conditions. After considering energy savings and cost-effectiveness, a PCM thickness of 15mm is recommended as the optimal choice. This thickness reduces energy consumption significantly while offering high cost-effectiveness and excellent performance in thermal regulation. In extreme cold climates, PCM improves energy efficiency and supports sustainability goals.

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4. Discussion

4.1. Limitations in PCM simulation

This simulation assumes the long-term stability of PCM performance, but in practical applications, PCM may experience performance degradation due to thermal cycles and prolonged use, such as phase separation or thermal fatigue [9]. These issues can reduce PCM's energy-saving effectiveness. Therefore, future research should incorporate long-term monitoring data to provide a more reliable basis for simulation analysis.

4.2. Climate file accuracy

Modifying climate files to reflect PCM's thermal regulation effects is an effective indirect method, but it relies on idealized assumptions that overlook the complexities of weather changes under extreme cold conditions. Moreover, the current climate files used differ from actual conditions, especially when accurately simulating the interaction between PCM and the external environment [10]. Future research should improve this by introducing field data to validate and further optimize the climate files.

4.3. PCM cost and feasibility

The cost of organic PCMs, such as n-tetradecane, is high, and additional installation and maintenance costs increase overall expenses. This could limit their widespread use, especially in resource-limited cold regions. Developing low-cost PCMs should be a focus of future research to enhance their economic feasibility.

5. Conclusion

This study focuses on the energy-saving efficiency of PCMs with different thicknesses in building exterior walls under extreme cold climates. The results show that a PCM thickness of 15mm reduces heating loads while providing high cost-effectiveness. Further analysis reveals that energy savings decrease as PCM thickness exceeds 30mm. Therefore, 15mm is the most cost-effective option.

However, there is room for improvement in this study. The simulation results are based on the ideal conditions of PCM. In long-term use, PCM performance may be affected by phase separation and reduced chemical stability. Additionally, material aging, humidity, and pollutant accumulation in extremely low-temperature climates may further weaken the energy-saving effects of PCM. Future research should include long-term experimental monitoring of phase change materials to evaluate the energy-saving efficiency of different PCM thicknesses. Future building energy-saving strategies can explore combining PCM with other sustainable technologies. For example, integrating photovoltaic panels with PCM can optimize the thermal environment while improving photovoltaic efficiency. PCM can also work with ground-source heat pump (GSHP) technology to enhance heating efficiency. Additionally, PCM can integrate with smart building technology to regulate the phase change process according to changing environmental conditions. Research into these technology synergies could expand PCM’s potential applications and drive sustainable building practices forward.

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