

RESEARCH ARTICLE



Climate-Adaptive Dual-Temperature Composite Phase Change Wall Design for Energy-Flexible Buildings in Smart Cities

Wei Wu¹, Haibin Han¹, Wenzheng Li² , Zhengyu Chen¹, Haoyu Li¹, Minfen Gu³, Yahui Sun¹, Yunjun Wang¹, Xing Jin⁴ and Chong Zhai^{1,*}

¹*School of Energy Science and Engineering, Nanjing Normal University, China*

²*College of Astronautics, Nanjing University of Aeronautics & Astronautics, China*

³*Center for Analysis and Testing, Nanjing Normal University, China*

⁴*School of Architecture and Urban Planning, Nanjing University, China*

Abstract: Buildings in cities with pronounced seasonal variations require envelope systems capable of responding to both summer cooling and winter heating demands. This study proposes a climate-adaptive wall incorporating a single layer of composite phase change material (CPCM) with two phase change temperatures (PCTs), thereby avoiding the structural complexity of conventional multilayer phase change material (PCM) walls. A three-dimensional heat transfer model was established and validated to optimize the PCM layer position, thickness, and target PCTs under the climatic conditions of Nanjing. The results indicate that the optimal configuration places a 10 mm CPCM layer at the middle of the wall, with target PCTs of 32 °C for summer and 14.5 °C for winter. Based on these targets, a binary non-eutectic caprylic acid–tetradecanol CPCM with a mass ratio of 3.0:7.0 was prepared, exhibiting two PCTs of 14.67 °C and 36.67 °C and a total latent heat of 143.83 J/g. Compared with an ordinary wall, the CPCM wall reduced indoor surface temperature amplitude by 39.55% in summer and 18.09% in winter. Relative to a single PCM wall, the corresponding reductions were 25.88% and 5.71%. The maximum indoor surface heat flux reductions reached 16.23 W/m² in summer and 3.84 W/m² in winter. In addition, a transferable climate–wall–material design framework was developed for adapting the proposed method to different cities and wall structures. These findings demonstrate that single-layer dual-PCT CPCM walls can enhance seasonal thermal buffering and support energy-flexible building design in smart cities.

Keywords: composite phase change material, dual phase change temperatures, seasonal thermal energy storage, climate-adaptive building envelope, smart cities

1. Introduction

Global climate change induced by rising temperatures poses unprecedented challenges to human society, with the building sector accounting for 39% of global energy-related carbon emissions [1]. As a key contributor to energy consumption, improving building energy efficiency is critical for achieving carbon neutrality goals [2].

Phase change materials (PCMs) have gained significant attention as effective heat storage media in building applications, owing to their exceptional heat storage capacity and temperature-stabilizing phase change properties [3, 4]. When integrated into building envelopes, PCMs absorb excess thermal energy during their daytime endothermic phase transition. This occurs as solar

radiation and ambient heat generate heat fluxes that penetrate the wall structure, effectively delaying or mitigating the peak heat influx into the interior. As ambient temperatures decline at night, PCMs release the stored thermal energy to both indoor and outdoor environments, stabilizing indoor temperatures. This thermal regulation improves indoor comfort conditions while simultaneously decreasing Heat, Ventilation & Air-conditioning (HVAC) runtime and achieving energy savings [5, 6]. Numerical simulations and experimental validation claim that using PCMs in walls can reduce the total indoor thermal load by 54.12% relative to ordinary walls and increase the coefficient of performance of indoor air conditioning by 23%, with significant economic benefits [7].

Current research on PCM-enhanced walls has focused on three primary integration methods: direct mixing [8], immersion [7], and macro-encapsulation [9]. Recent advancements by Al-Absi et al. [10] revealed that microencapsulated PCMs in foam concrete could reduce peak inner surface temperature by 3.95 °C.

*Corresponding author: Chong Zhai, School of Energy Science and Engineering, Nanjing Normal University, China. Email: zhaichong@nnu.edu.cn

Similarly, Abbas et al. [11] reported a 23.84% reduction in temperature fluctuations through PCM-incorporated hollow bricks. Wijesuriya and Tabares-Velasco [12] found a 2–3 °C reduction in the inner surface peak temperature and 2.5 hours increment in time lag. These findings prove the efficacy of PCM incorporation approaches for optimizing building thermal performance [13].

The thermal regulation capacity of PCM walls depends critically on material characteristics and design parameters. Key factors include PCM layer thickness [14], phase change temperature (PCT) [15, 16], integration position [17], and quantity [18]. Sun et al. [19] established that optimal PCM thickness varies nonlinearly with thermal performance. Li et al. [20] identified distinct optimal PCT ranges for summer (26–30 °C) and winter (20–24 °C). Wu et al. [21] optimized the position of the multilayer PCM in the wall to obtain the best thermal flux and temperature fluctuations. The selection of PCM thickness, position, and melting point is closely related to the climatic conditions of the region [22]. However, ordinary single-PCT systems face limitations in regions with significant seasonal variations, as they cannot simultaneously address summer cooling and winter heating requirements [23, 24].

Researchers have discovered that the limitation of a single PCT can be overcome by combining multiple layers of PCMs with different transition temperatures. Wang et al. [25] applied a dual-layer material with low and high PCTs of 36.5 °C and 41 °C, respectively, to a battery thermal management system (BTMS). They proposed three fundamental design principles, providing theoretical guidance for optimizing BTMS with dual-layer PCMs. Gao et al. [26] demonstrated that double-layer PCM walls achieved the best overall annual performance compared to single-layer systems. Arfi et al. [27] further reported a 15% indoor temperature fluctuation reduction and a 3 °C surface temperature reduction in summer, a 13 °C indoor temperature heat flux reduction, and a 2.5% attenuation rate reduction in winter through optimized dual-PCM arrangements. Louanate et al. [28] also claimed that a double-layer system in the Mediterranean climate using two different PCMs achieved an annual energy savings of 55.41%. While promising, such multilayer designs introduce construction complexity and may compromise wall structural integrity [29]. Beyond wall-integrated systems, multilayer PCM designs have also been explored in roofs, ventilated facades, and passive ventilation ducts, where they improve thermal buffering and seasonal adaptability. While effective, these approaches typically increase structural thickness and construction complexity. In contrast, the present study introduces a single-layer composite phase change material (CPCM) wall with dual PCTs, achieving comparable adaptability in a simpler and more practical form. Compared with these multilayer PCM configurations, the proposed CPCM approach offers notable advantages. By integrating dual PCTs into a single composite material layer, it provides seasonal adaptability without the need for multiple PCM layers. This simplifies the structural design, avoids excessive wall thickness, and reduces construction complexity, while still maintaining effective thermal regulation in both summer and winter. Such compactness and feasibility make CPCM-based walls more practical for large-scale building applications, thereby enhancing their potential for real-world deployment. This motivates our investigation into CPCM with dual PCTs as an innovative single-layer solution, which is more compact and simpler than the two-layer PCM-based temperature-regulating walls.

In this study, we propose a novel seasonal composite PCM wall system using binary CPCM with distinct summer/winter PCTs. Focusing on the Nanjing climate, we establish a 3D heat

transfer model to systematically investigate the effects of PCM position, PCT selection, and layer thickness on wall thermal performance. Through numerical simulations validated by experimental data, we determine optimal design parameters for a period of 48 hours of operation under actual working conditions. This research advances the development of seasonally adaptive building envelopes for enhanced energy efficiency.

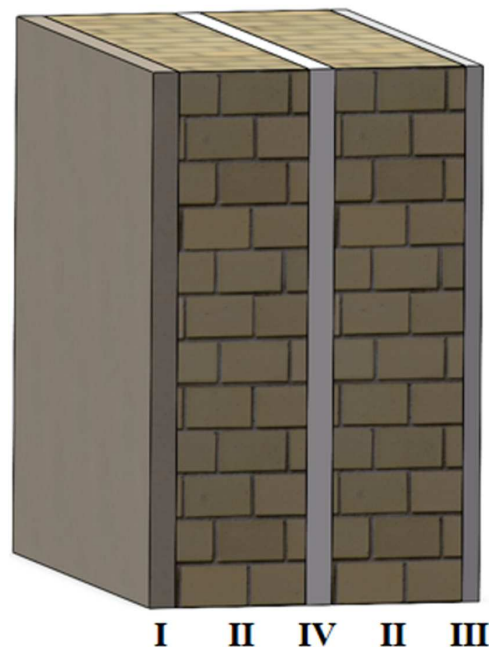
2. Climate-Adaptive Design and Methodology

2.1. Building wall model and validation

2.1.1. Physical model

The physical model structure of the wall is shown in Figure 1; from the outside to the inside, it consists of 15 mm of cement mortar (Layer I), 180 mm of clay brick masonry (Layer II), 15 mm of gypsum board (Layer III), and a PCM layer (Layer IV). The dimensional parameters are 300 mm × 300 mm × 220 mm. This study adopts a macro-encapsulation approach, in which the CPCM is physically confined within a sealed container to prevent leakage of the molten material into the surrounding wall layers. Besides, the solid–liquid phase transition of the CPCM layer was modeled using the Solidification/Melting model, which has been widely applied in PCM-based building envelope research. The physical properties of these materials are shown in Table 1.

Figure 1
The physical model structure
The PCM wall



To establish a computationally efficient heat transfer model for the PCM-integrated wall system, the following simplifications were implemented:

- 1) The internal part of the PCM wall only considers heat transfer by conduction;
- 2) Convection arising from liquid PCM motion is considered negligible;

Table 1
Thermal and physical property parameters of the wall structure

Material	Thickness / <i>e</i> [mm]	Thermal conductivity / λ [W/(m·K)]	Density/ ρ [kg/m ³]	Heat capacity/ C_p [J/(kg·K)]
Cement mortar (I)	15	0.93	1800	1050
Clay brick masonry (II)	180	0.81	1800	1050
Gypsum board (III)	15	0.57	1100	1000

- 3) Material properties remain temperature-invariant, except for the PCM's apparent heat capacity during phase transition;
- 4) Material properties are treated as homogeneous and isotropic.

2.1.2. Numerical model and boundary conditions

Mesh generation was performed using Gambit software, employing a type 4 model as an example. The mesh quality analysis revealed that the number of meshes with a quality value less than 0.1 accounted for 99%, meeting ANSYS Fluent quality standards.

A systematic independence study compared four mesh resolutions (3–5 mm minimum size). As shown in Table 2, the 4 mm mesh (1.28×10^3 elements) achieved <0.1% variation in inner surface temperature compared to finer 3 mm meshes, while reducing computational time by 41%. This resolution optimally balances accuracy and efficiency.

Table 2
Grid independence study

Minimum size/mm	Elements/ $\times 10^3$	Wall inner surface temperature/K
3.0	219	300.261
4.0	128	300.231
4.5	96	300.191
5.0	79	300.158

Establish the governing equations based on the enthalpy method model; when PCMs are present in the wall, select the Solidification/Melting model to simulate the phase change process. The indoor air temperature of the wall in summer is 299.15 K, and in winter, it is 291.15 K [30]; the other surfaces are set as adiabatic boundaries. The initial temperature of the PCT-regulating wall is set to 299.15 K in summer and 283.15 K in winter.

Considering the influence of solar radiation and environmental temperature, this paper adopts the comprehensive outdoor air temperature (COT) as the outdoor temperature of the wall [31]. Figures 2(a) and (b) show the outdoor ambient temperature, solar radiation intensity, and the COT of the outdoor wall surface for summer and winter in Nanjing, respectively.

$$T_{oq} = T_0 + \frac{\alpha \cdot I}{h_0} \quad (1)$$

where T_{oq} is the COT of the outer surface of the wall, K, and T_0 is the outdoor climate environmental temperature, K. The outdoor climate environmental temperature data for typical summer and winter days in Nanjing are measured by the China

Meteorological Administration [32]; α is the outer surface solar absorptivity of the wall; I is the outdoor climate environmental solar flux density, W/m²; the outdoor climate environmental solar flux density for typical summer and winter days in Nanjing is obtained from the Weather Network [32]; and h_0 is the convective heat transfer coefficient of the outer surface of the building wall. The convective heat transfer coefficient is 19 W/(m²·K) in summer and 23 W/(m²·K) in winter [33].

2.1.3. Model validation

The numerical model was validated against experimental data from Reference [34] for walls under the same simulation conditions. The thermophysical properties of the panels and materials used for constructing the reference chamber and the PCM chamber are presented in Table 3. As demonstrated in Figure 3, simulation results show excellent agreement with experimental measurements. The peak temperature difference is approximately 0.14 K with a time lag of 47.5 minutes, while the valley temperature difference is 0.96 K with a time advance of 5 seconds.

2.2. Thermal performance evaluation indicators

The thermal efficiency of PCM walls can be assessed by analyzing two key parameters: temperature delay time and attenuation factor. These metrics primarily reflect variations in the outer surface temperature of PCM wall systems [35, 36].

Temperature delay time is defined as:

$$\varphi_T = \tau_{T_{i,max}} - \tau_{T_{o,max}} \quad (2)$$

The temperature attenuation factor is defined as:

$$f_T = \frac{T_{i,max} - T_{i,min}}{T_{o,max} - T_{o,min}} \quad (3)$$

where $\tau_{T_{i,max}}$ and $\tau_{T_{o,max}}$ represent the times when the inner and outer surface temperatures of the PCM wall reach their maximum values, respectively; $T_{i,max}$ and $T_{o,max}$ represent the maximum values of the inner surface temperature and the outer surface temperature of the wall, respectively; and $T_{i,min}$ and $T_{o,min}$ represent the minimum values of the inner surface temperature and the outer surface temperature of the wall, respectively.

As illustrated in Figure 4, an extended temperature delay time and a lower attenuation factor signify enhanced thermal buffering performance, effectively mitigating outdoor temperature fluctuations on indoor environments.

3. Climate-Driven PCM Layer Optimization

In this study, “optimal” is defined based on the overall thermal regulation performance rather than a single indicator.

Figure 2
The outdoor climatic environment in Nanjing: (a) summer outdoor climatic environment and (b) winter outdoor climatic environment

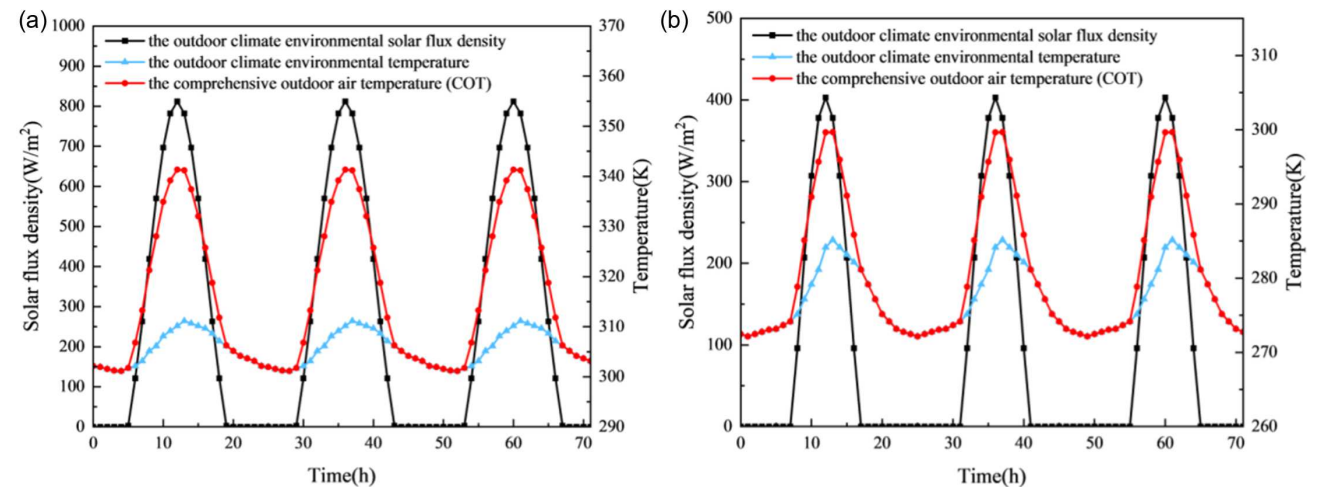
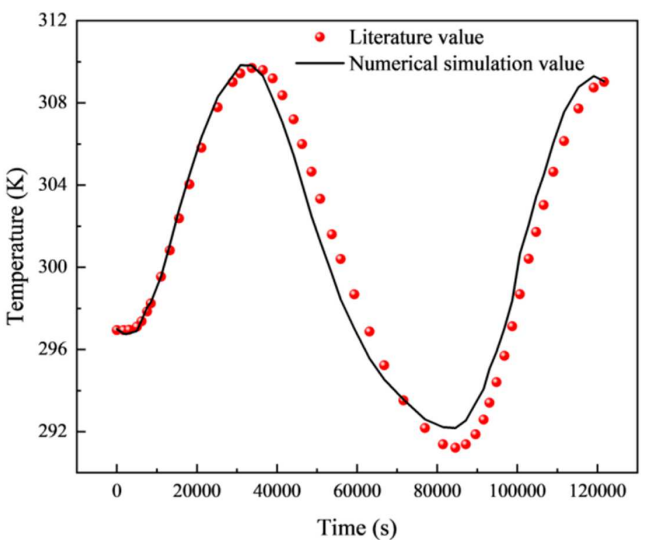


Table 3
Thermophysical properties of the panels and materials used to construct the reference room and the PCM room

Material	Density (kg/m ³)	Thermal conductivity (W/(m·K))	Specific heat capacity (J/(kg·K))
OSB	696.1	0.19	1869
EPS	10.3	0.045	1380
Plasterboard	803.1	0.33	1013
PVC	1367	0.20	1040
CaCl ₂ ·6H ₂ O /EG	875	3.2	2516
RT27/EG	875	2.5	2206

Figure 3
Comparative validation of inner surface temperatures between numerical and experimental results



A longer temperature delay time, a lower attenuation factor, and a lower inner surface heat flux were jointly considered for the selection of PCM position and PCT. For PCM thickness, material usage and cost were additionally considered, and the thickness at which further increases produced only marginal thermal improvement was selected.

3.1. Optimization of PCM layer position

Six distinct wall configurations were established by varying the PCM layer placement within the multilayered wall structure (Figure 5). The injection positions spanned from exterior-proximal (Type 2) to interior-proximal (Type 6) placements, enabling comparative analysis of thermal buffering effects relative to wall depth.

3.1.1. Summer performance

The thermal regulation performance of phase change walls was systematically evaluated through seasonal simulations comparing six distinct PCM injection positions (Figure 5). In summer conditions, Figure 6(a) demonstrates that ordinary walls (Type 1) exhibited the highest inner surface temperature fluctuation (305.80 K max vs 301.29 K min), while PCM-enhanced walls showed reduced thermal variability. Notably, Type 6 configuration (innermost PCM placement) achieved the lowest peak temperature of 304.87 K, attributable to its proximity to the interior surface, enabling later phase change initiation. The observed 4-hour temperature plateau in Type 6 corresponds to the latent-heat absorption period during PCM melting (Figure 6(a)), effectively buffering external thermal perturbations.

Thermal flux analysis (Figure 6(b)) revealed that all PCM-integrated walls reduced heat transfer by 8.14 W/m² compared to ordinary walls. Type 6 exhibits the best performance, featuring the longest temperature delay time (6.39 h) and the lowest attenuation factor (0.121), followed by Type 4 with a temperature delay time of 6.25 hours and an attenuation factor of 0.121. This phenomenon arises from balanced heat propagation dynamics, where centrally

Figure 4
Schematic illustration of temperature delay time and attenuation factor

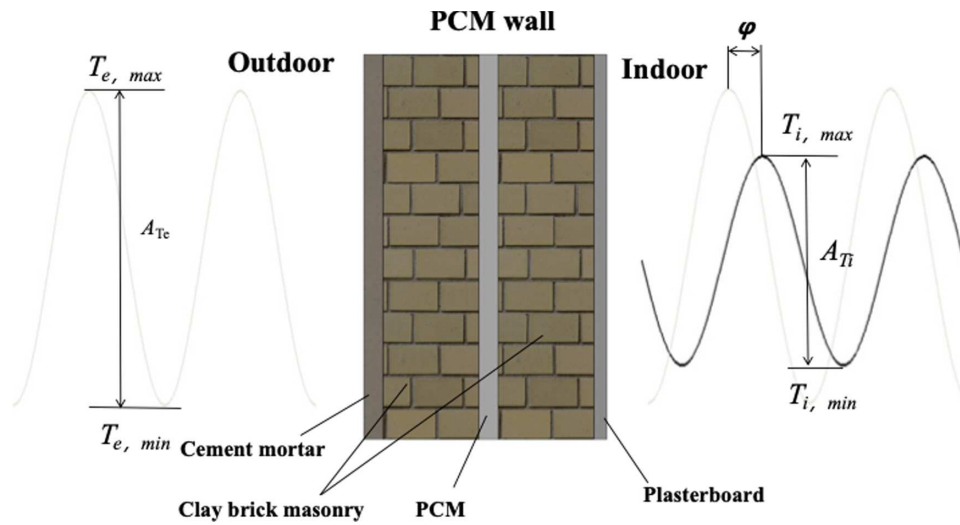
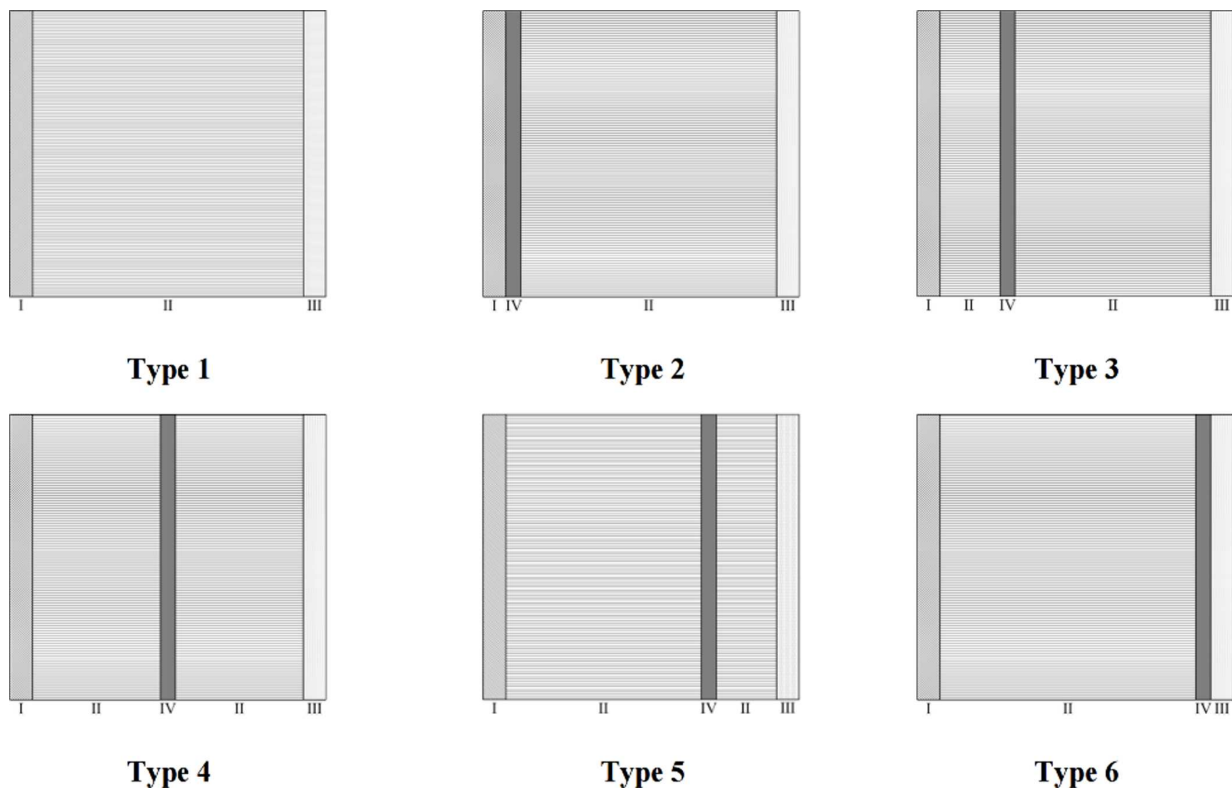


Figure 5
Schematic diagram of building wall models with PCM in different injection locations



located PCM layers effectively intercept thermal waves from both exterior and interior surfaces.

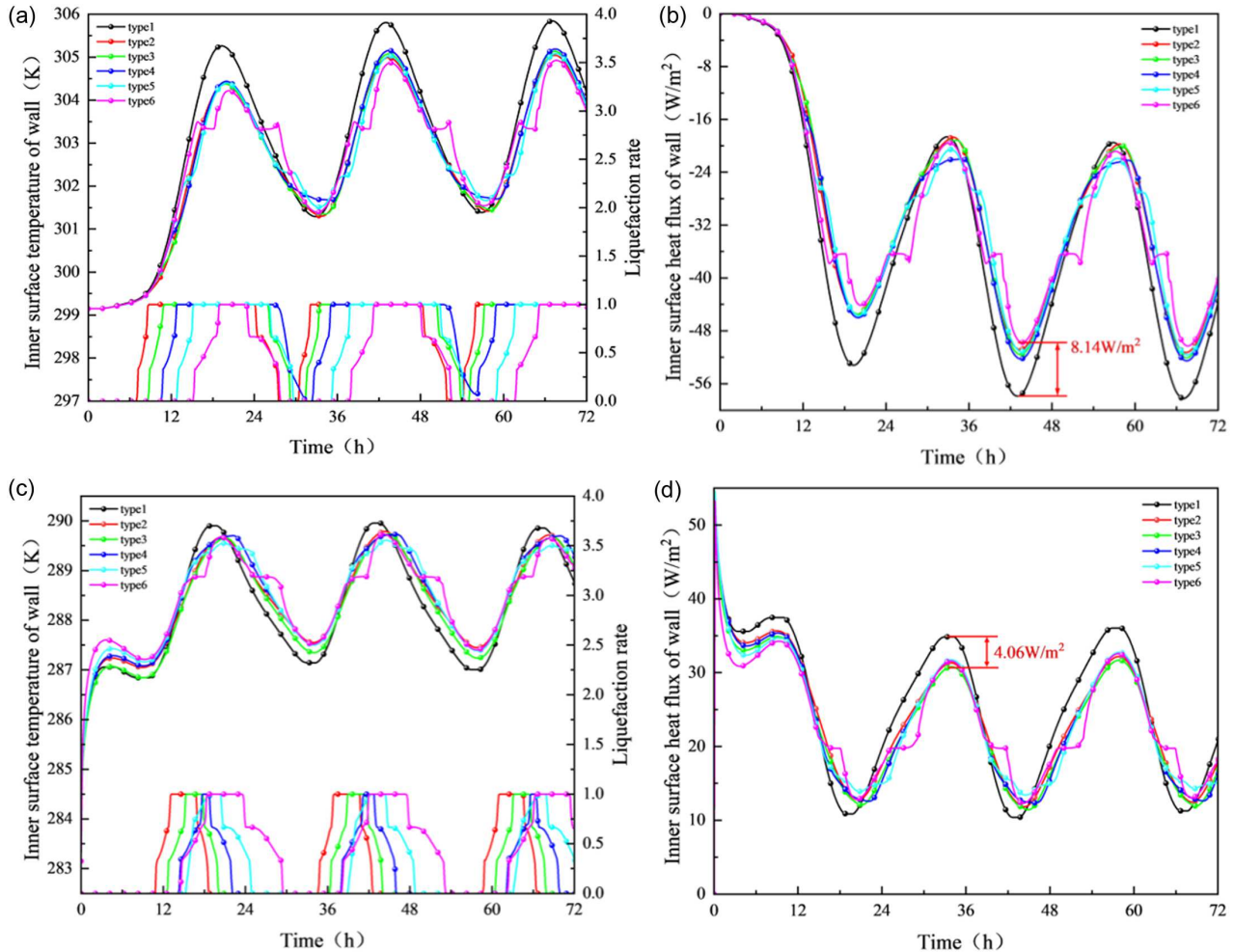
3.1.2. Winter performance

Figures 6(c) and 6(d) present the winter thermal performance of various PCM configurations. The ordinary wall (Type 1) showed maximum and minimum inner surface temperatures of 289.96 K and 287.14 K, respectively ($\Delta T = 2.82$ K). PCM integration reduced this amplitude by 15–22%, with Type 4 configuration maintaining the most stable thermal environment ($\Delta T = 2.22$ K).

The daily phase change cycle exhibited distinct winter characteristics—PCM melting initiated 3.2 hours later than summer conditions due to reduced thermal driving forces. As shown in Figure 6(c), all PCM configurations completed solidification within nocturnal periods, confirming effective diurnal energy cycling. Heat flux analysis (Figure 6(d)) revealed PCM walls reduced heat loss by 19–31%, with Type 4 configuration absorbing 4.06 W/m² less than ordinary construction during peak heating hours. The seasonal adaptation capability demonstrates that mid-wall PCM placement (Type 4) achieved an 8.61-hour temperature delay (55% improvement over baseline) and a 0.112 attenuation

Figure 6

Summer and winter performance of PCM wall at different injection positions: (a) summer inner surface temperature and liquefaction rate, (b) summer heat flux on the inner surface of the PCM wall, (c) winter inner surface temperature and liquefaction rate, and (d) winter heat flux on the inner surface of the PCM wall



factor (21% reduction). This configuration extended thermal lag by 2.05 hours compared to summer operation, highlighting its responsiveness to seasonal thermal load variations.

Based on the comparison of temperature delay time and attenuation factor, Type 4 performs best in winter and ranks second in summer. Considering both seasons, when replacing two single PCMs with one CPCM, the middle position should be selected for the PCM layer placement. The balanced thermal resistance distribution in central positioning minimizes thermal bridging effects while maximizing PCM utilization efficiency during phase transitions, making it the optimal configuration for Nanjing's continental monsoon climate characterized by significant seasonal temperature variations.

3.2. Optimization of PCM layer thickness

As shown in Figure 7, PCM layer thickness was varied from 0 to 15 mm across five configurations (within the thickness range that exerts negligible influence on the wall structure [37, 38]), balancing thermal mass enhancement against material cost considerations.

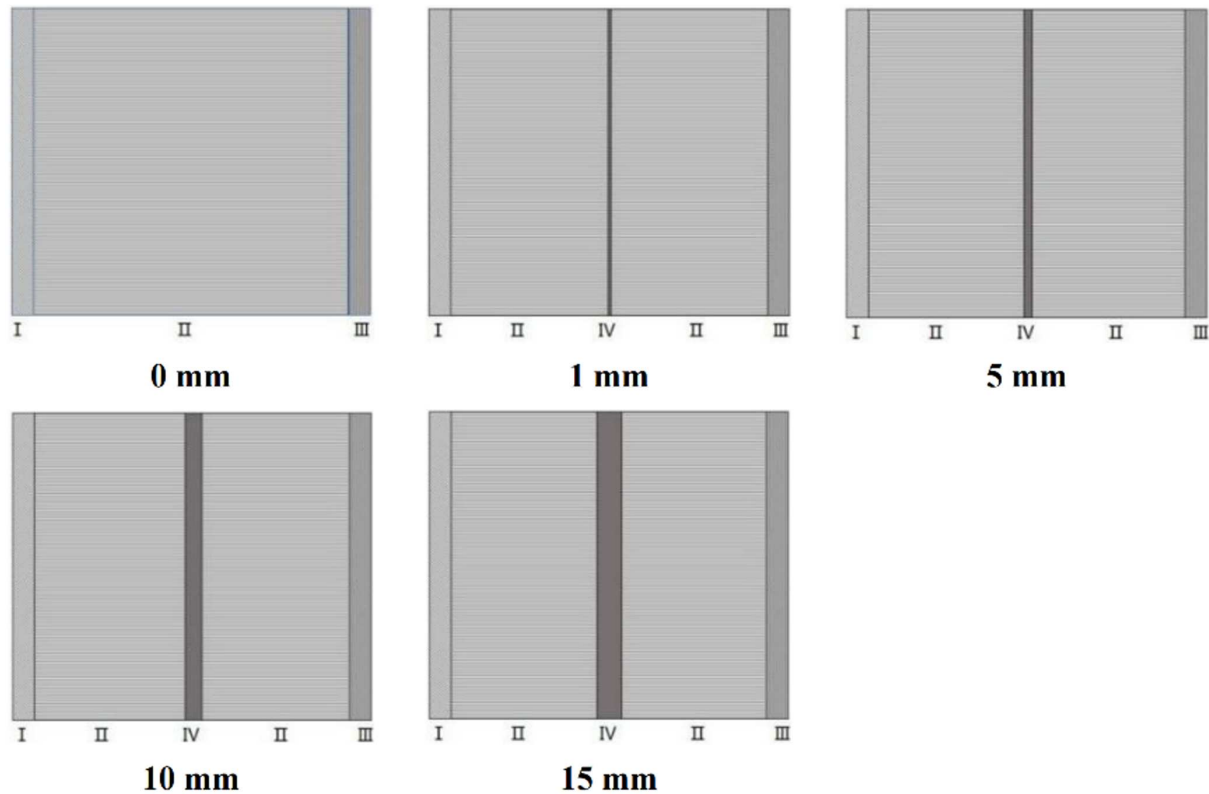
3.2.1. Summer response

To explore the influence of PCM thickness on the thermal performance of the wall in summer, five distinct thicknesses, as depicted in Figure 7, were selected for investigation. The temporal variations of the inner surface temperature of the wall and the liquefaction rate of the PCM within the wall are presented in Figure 8(a), while Figure 8(b) shows the changes in the heat flux density on the inner surface of the wall over time.

As evident from Figure 8(a), all five PCM thickness configurations underwent melting and solidification processes. The highest inner surface temperature of the 15-mm-thick PCM wall was 1.46 K lower than that of the 0-mm-thick wall, and it was comparable to that of the 10-mm-thick wall. This indicates that PCM layers with thicknesses of 10 mm and 15 mm are more effective in reducing the inner surface temperature of the PCM wall. By lowering the inner surface temperature, less heat is transferred into the indoor space, thereby reducing the energy consumption required for indoor cooling.

Figure 8(b) reveals that the inner surface of the building wall is constantly in a state of releasing heat to the indoor environment. At any given moment, as the thickness of the PCM increases, the absolute value of the inner surface heat flux density gradually

Figure 7
Schematic diagram of building walls with PCMs in different injection thicknesses



decreases. Notably, there is no significant difference in heat flux density between the 10 mm and 15 mm thicknesses.

It can also be observed that as the PCM thickness increases, the inner surface temperature delay time of the PCM wall becomes longer, and the attenuation factor becomes smaller. However, an increase in the PCM layer thickness also leads to a corresponding increase in cost. By comparing the effects of 10 mm and 15 mm PCM thicknesses on the inner surface temperature of the wall in both summer and winter, it was found that the changes in temperature delay time and attenuation factor are minimal. Considering both performance and cost, a PCM thickness of 10 mm is deemed optimal for summer applications.

3.2.2. Winter response

Figure 8(c) illustrates the temporal variations of the inner surface temperature of the wall and the liquefaction rate of the PCM within the wall, and Figure 8(d) shows the changes in the heat flux density on the inner surface of the wall over time.

Figure 8(c) indicates that melting and solidification processes occurred for all five material thicknesses. During the night, the minimum temperature on the inner surface of the 15-mm-thick wall was higher than that of the 0-, 1-, and 5-mm-thick walls. The 10- and 15-mm-thick PCM layers absorbed the least amount of heat from the interior, meaning they required less heat to be supplied by the heating system, and their performance in this regard was similar. Figure 8(d) shows that an increase in PCM thickness reduces the amount of heat absorbed by the inner surface of the wall from the indoor environment. This effectively acts as better insulation, preventing indoor heat from being transferred to the outdoor environment.

In the ordinary wall without PCM, the inner surface temperature delay time was 5.56 hours, and the temperature attenuation factor was 0.142. When the PCM thickness was 10 mm, the PCM wall exhibited the longest inner surface temperature delay time of 7.22 hours and the smallest temperature attenuation factor of 0.119. Therefore, a 10-mm PCM thickness is recommended for winter, as it is more conducive to maintaining a stable indoor temperature and reducing heat loss.

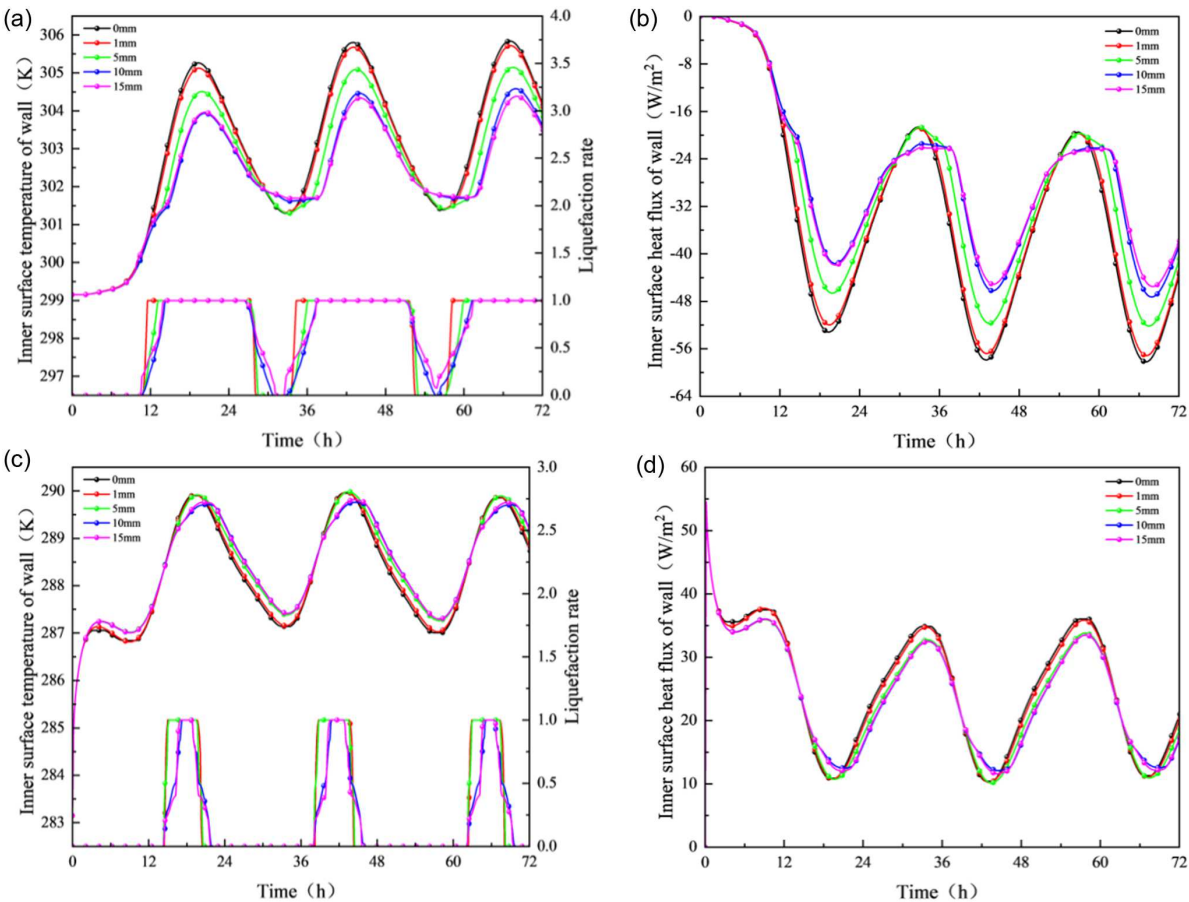
It can be concluded that a PCM thickness of 10 mm is the most suitable choice for the PCM wall after a comprehensive evaluation. This thickness strikes a balance between enhancing thermal performance and controlling costs, making it an ideal option for practical applications in the Nanjing region. It should be emphasized that the recommended 10 mm CPCM thickness is derived from simulations based on the specific wall configuration used in this study, consisting of cement mortar, clay brick, and gypsum board. The optimal thickness is sensitive to the thermal conductivity, density, and heat capacity of the surrounding wall layers, as well as construction practices that determine overall thermal resistance. Therefore, while 10 mm was found to be optimal under the present conditions, the same value may not apply to other wall assemblies or construction types.

3.3. Identification of target PCTs

We referred to the literature by Meng et al. [39] and selected a PCT of 18 °C for winter and 29 °C for summer in the simulations. The results showed that the PCM in the wall was unable to achieve a complete melting and solidification process.

Therefore, based on the reference literature [40, 41] and combined with the climatic conditions of the Nanjing area, we selected

Figure 8
Summer and winter performance of PCM wall with different PCM thicknesses: (a) summer inner surface temperature and liquefaction rate, (b) summer heat flux on the inner surface of the PCM wall, (c) winter inner surface temperature and PCM liquefaction rate, and (d) winter heat flux on the inner surface of the PCM wall



an optimized temperature range of 23–35 °C for summer and 12.5–20.5 °C for winter to determine the optimal PCT under the climatic conditions of Nanjing (Table 4).

Table 4
Different PCTs of PCM

No.	PCI/°C	
	Summer	Winter
I	23.0	12.5
II	26.0	14.5
III	29.0	16.5
IV	32.0	18.5
V	35.0	20.5

3.3.1. Summer target PCT

To evaluate the effect of PCT on thermal performance, five distinct PCT configurations listed in Table 4 were simulated.

Figure 9(a) illustrates the temporal evolution of the inner surface temperature and PCM liquefaction rate. PCM layers with PCTs of 23 °C, 26 °C, and 29 °C undergo daytime melting but fail to solidify at night, resulting in incomplete phase change cycles. This phenomenon arises because the low-set PCTs cause the wall

temperature to remain above the solidification point throughout the night, preventing latent-heat release. In contrast, PCTs of 32 °C and 35 °C enable full daily phase change cycles: daytime melting stores excess heat from solar radiation, and nighttime solidification releases stored latent heat, stabilizing the indoor environment. Consequently, these higher PCTs reduce inner surface temperature fluctuations, enhancing thermal comfort.

Figure 9(b) reveals that all PCM walls exhibit heat-releasing behavior on their inner surfaces. During peak solar radiation and ambient temperature (12:00–15:00), the 32 °C and 35 °C PCT walls demonstrate the lowest heat flux densities, indicating minimal heat transfer to the indoor space. This outcome aligns with their ability to sustain latent-heat storage during the hottest periods, effectively mitigating thermal intrusion.

The 32 °C PCT wall achieves the longest temperature delay time (6.51 hours) and smallest attenuation factor (0.117), outperforming other configurations. These results highlight that an optimal PCT ensures complete phase change cycles, delaying heat transfer and reducing cooling loads by leveraging latent-heat storage during summer.

3.3.2. Winter target PCT

For winter conditions, the five PCTs were analyzed, with results presented in Figure 9(c) (inner surface temperature and liquefaction rate) and Figure 9(d) (inner surface heat flux density).

Figure 9

Summer and winter performance of PCM wall with different PCM thicknesses: (a) summer inner surface temperature and the liquefaction rate, (b) summer heat flux on the inner surface of the PCM wall, (c) winter inner surface temperature and the liquefaction rate, and (d) winter heat flux on the inner surface of the PCM wall

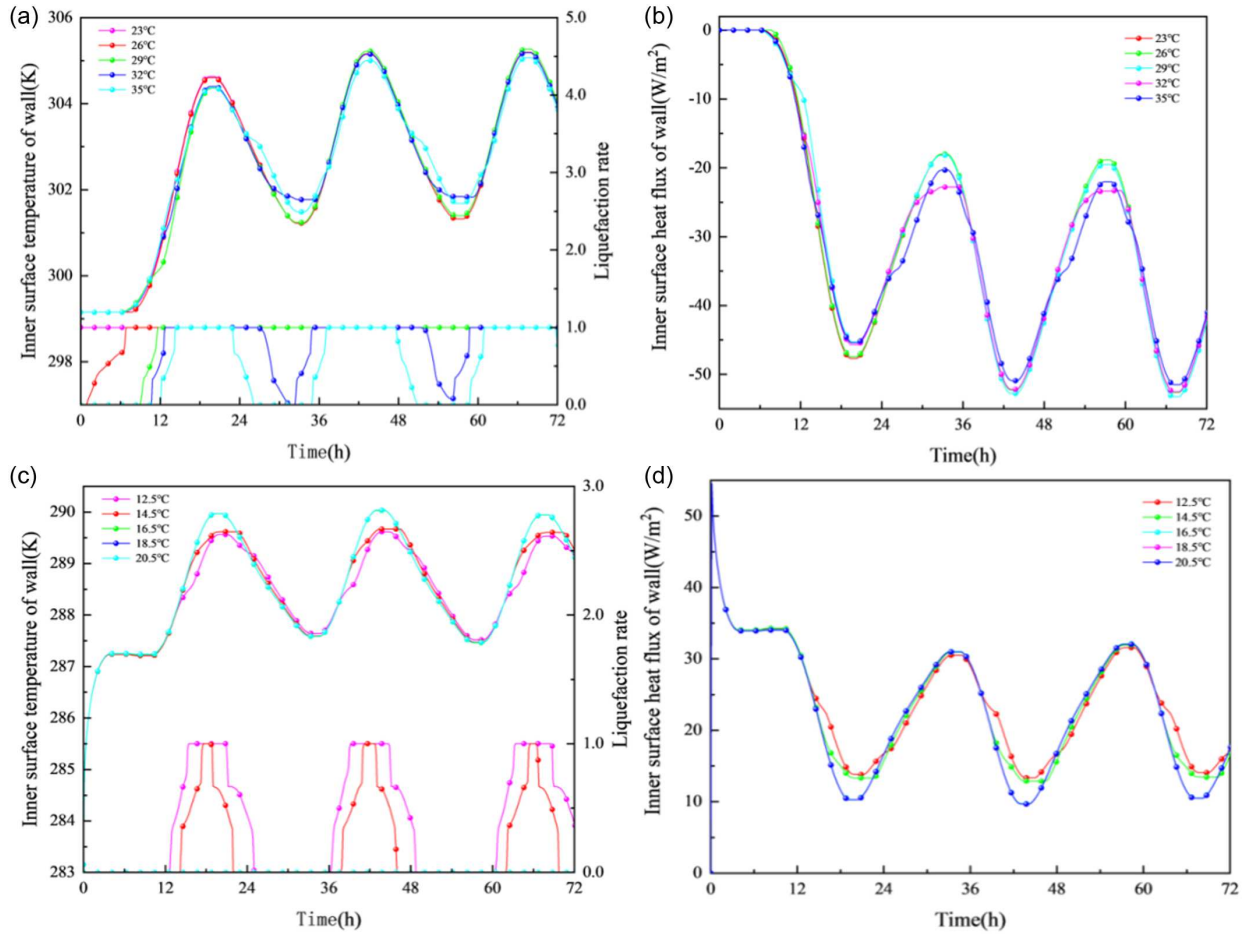


Figure 9(c) shows that PCTs of 12.5 °C and 14.5 °C facilitate daily melting-solidification cycles, allowing the PCM to absorb indoor heat during the day and release it at night. Conversely, higher PCTs (16.5 °C, 18.5 °C, 20.5 °C) remain in a solid state, as winter heat flux densities are insufficient to trigger melting. This indicates that excessively high PCTs render the PCM ineffective for winter thermal regulation.

Figure 9(d) demonstrates that all PCM walls absorb heat from the indoor environment, with the 12.5 °C and 14.5 °C PCT walls exhibiting the highest heat flux densities. This paradox arises because lower PCTs enable more frequent phase changes, enhancing heat absorption during the day and releasing stored heat at night, thereby reducing net heat loss.

The 14.5 °C PCT wall is the optimal performer, featuring the longest delay time (7.92 hours) and a low attenuation factor (0.105). These metrics indicate improved thermal inertia, effectively minimizing indoor heat loss and reducing heating energy demand.

Through comparative analysis of delay times and attenuation factors, the optimal PCTs are determined as 32 °C for summer and 14.5 °C for winter. These values strike a balance between latent-heat utilization and climatic requirements: the higher summer PCT prevents incomplete melting, while the lower winter PCT ensures effective heat storage and release under lower ambient temperatures. This seasonal optimization strategy enhances

the adaptive thermal performance of PCM walls, aligning with the climatic characteristics of the Nanjing region.

4. Thermodynamic Design of Dual-PCT CPCMs

4.1. Candidate PCM library and binary PCM system

The numerical simulation results indicated that the optimal PCTs for the PCMs in the PCM wall are 32 °C in summer and 14.5 °C in winter. Based on the simulated temperature, nine single PCMs were selected for theoretical calculations: octanoic acid (OA), caprylic acid (CA), tetradecanol (TD), lauric acid (LA), paraffin wax (62#), myristic acid (MA), octadecanol (C18), palmitic acid (PA), and stearic acid (SA). The detailed information about the candidate PCM is listed in Table 5.

The eutectic points of binary PCMs were determined using the Schrader equation and phase diagrams among these 9 PCMs. The eutectic PCT and latent heat of binary PCM combinations are presented in Figures 10(a) and (b).

4.2. Non-eutectic design of CPCMs

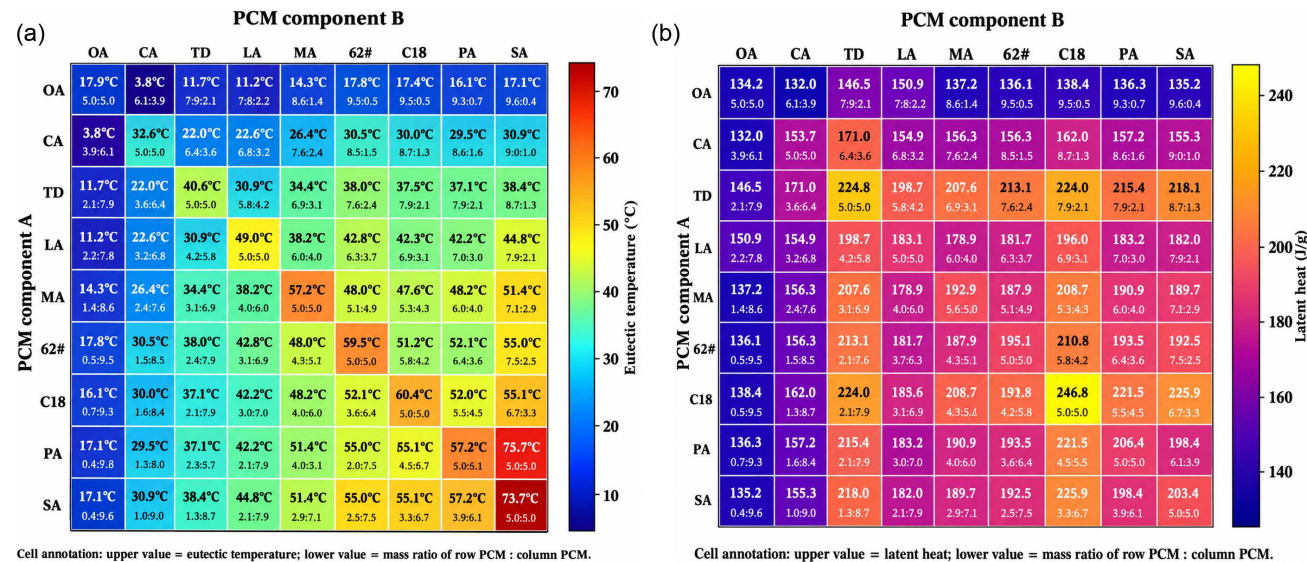
To meet the energy storage requirements of building walls in both winter and summer and to reduce the energy consumption of indoor air conditioning equipment in the walls, it is necessary to

Table 5
Candidate PCM library

Name	Molecular formula	Molecular weight	PCT (°C)	Price (yuan/100g)
OA	C ₈ H ₁₆ O ₂	144.21	16.0~16.5	12.09
CA	C ₁₀ H ₂₀ O ₂	172.26	≥29.0	11.89
TD	C ₁₄ H ₃₀ O	214.39	36.5~39.5	9.00
LA	C ₁₂ H ₂₄ O ₂	200.32	41.0~45.0	11.64
62#	C _n H _{2n+2}	394.00	60.0~62.0	4.38
MA	C ₁₄ H ₂₈ O ₂	228.37	54.0~55.0	14.40
C18	C ₁₈ H ₃₈ O	270.49	56.0~68.0	10.36
PA	C ₁₆ H ₃₂ O ₂	256.42	62.5~64.5	12.40
SA	C ₁₈ H ₃₆ O ₂	284.48	67.0~70.0	8.00

Figure 10

Eutectic PCTs and enthalpy with mass ratio of binary PCM combinations: (a) eutectic phase change temperature and (b) eutectic enthalpy



select CPCMs with two PCTs. The PCT should be around 32 °C in summer and around 14.5 °C in winter. Through experimental studies and theoretical calculations on single PCMs and binary eutectic PCMs, the suitable PCMs OA, CA, TD, and PA were selected.

Avoiding the eutectic mass ratios obtained from theoretical calculations using the Schroder formula, a series of binary non-eutectic CPCMs were prepared, and their thermophysical properties are shown in Table 6. As indicated in the table, when the CA–TD is developed in ratio 2 (3.0:7.0), the low and high PCTs are 14.67 °C and 36.67 °C, respectively, which meet the temperature requirements for PCMs in PCM walls in the Nanjing area.

4.3. Experimental test of developed CPCMs

The differential scanning calorimetry (DSC) curves of binary non-eutectic PCMs CA–TD with different ratios are shown in Figure 11(a). It can be observed that all CA–TD binary non-eutectic PCMs exhibit two well-defined phase change peaks. For the ratio 2 (3.0:7.0), the lower PCT is 14.67 °C, and the higher PCT is 36.67 °C. The lower PCT of 14.67 °C closely

matches the numerical winter target of 14.5 °C, whereas the higher PCT of 36.67 °C is 4.67 °C above the numerical summer target of 32 °C. This deviation reflects the practical constraint of simultaneously tailoring two PCTs within a single non-eutectic CPCM and is further evaluated at the wall level in Section 5.1. Notably, the enthalpy values of the high and low components are approximately equal. This binary non-eutectic PCM thus meets the temperature requirements for CPCMs in PCM walls in the Nanjing area.

Figure 11(b) depicts the cooling curves of binary non-eutectic PCMs CA–TD at different ratios. It is evident that all binary PCMs CA–TD display two PCTs. For ratios 3 and 4, the higher PCT shows significant undercooling, with undercooling degrees of 2.56 °C and 1.24 °C, respectively. In contrast, when the CA component is at ratios 1 and 2, no undercooling phenomenon occurs.

A total of 300 thermal cycling tests were conducted on CA–TD (3.0:7.0). The DSC curves before and after 300 thermal cycles are shown in Figure 12. After 300 thermal cycles, the low and high PCTs changed from 14.67 °C and 36.67 °C to 14.64 °C and 36.62 °C, respectively, corresponding to decreases of only 0.03 °C and 0.05 °C. The corresponding latent heats decreased

Table 6
Thermophysical properties of binary non-eutectic PCMs

Binary non-eutectic PCMs	Ratio	DSC test				Total enthalpy H (J/g)
		Peak T_1 (°C)	Enthalpy H_1 (J/g)	Peak T_2 (°C)	Enthalpy H_2 (J/g)	
OA-CA	1	6.02	4.08	29.91	129.86	133.94
	2	7.17	36.86	24.61	96.71	132.57
	3	8.51	48.93	20.56	40.33	89.26
	4	8.15	115.77	—	—	115.77
OA-TD	1	2.10	8.39	12.88	113.29	121.68
	2	10.95	105.26	—	—	105.26
	3	4.41	4.86	16.69	101.11	105.97
	4	1.98	10.00	15.53	118.26	128.26
CA-TD	1	25.07	38.61	37.00	140.93	179.54
	2	14.67	68.29	36.67	73.54	143.83
	3	17.03	23.75	24.21	168.53	192.28
	4	23.41	62.53	31.53	103.08	165.61
TD-PA	1	34.30	42.95	59.67	119.61	162.56
	2	35.73	109.87	54.44	33.79	143.66
	3	37.24	33.82	45.47	85.43	119.25
	4	38.03	181.49	—	—	181.49

Figure 11
Thermal performance test curve of CA-TD with different mass ratios: (a) DSC test and (b) step cooling test

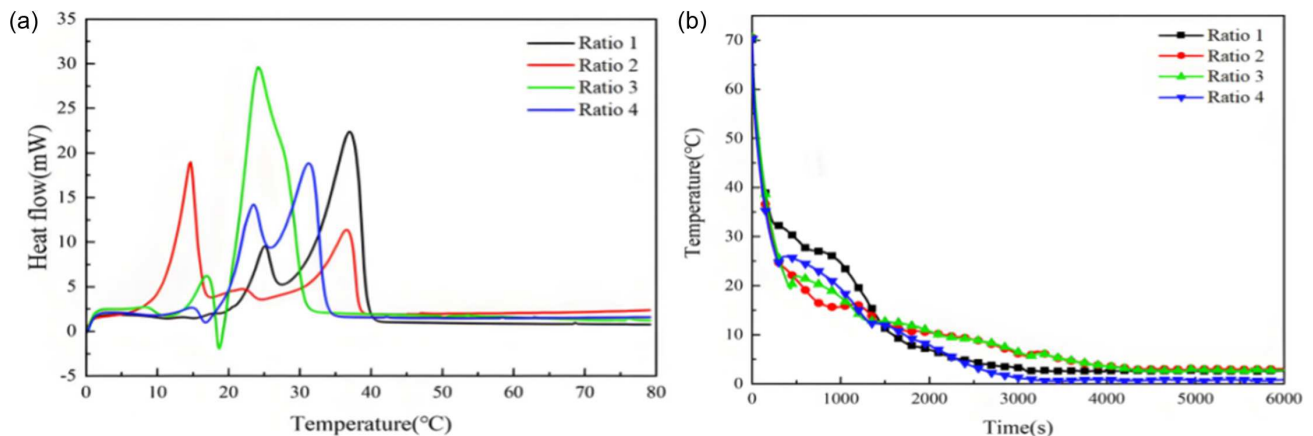
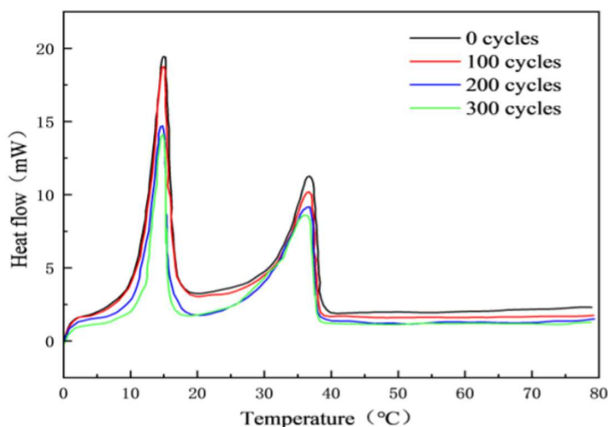


Figure 12
Thermal cycling test curve of CA-TD (3.0:7.0)



from 68.29 and 73.54 J/g to 65.72 and 70.63 J/g, representing reductions of 3.76% and 3.96%, respectively. These relatively small variations indicate that CA-TD (3.0:7.0) maintains good thermal stability after 300 thermal cycles. Finally, the CA-TD with a ratio of 2 (3.0:7.0) was selected as the CPCM to be applied in the wall, and the detailed thermophysical properties of the CA-TD (3.0:7.0) are presented in Table 7. The relatively low thermal conductivity of CA-TD (0.21 W/(m·K)) may constrain its heat charging/discharging rate. Although the 10-mm CPCM layer can complete the required phase change process under the present conditions, future work should investigate thermal-conductivity enhancement using conductive additives or supporting matrices. Although CA-TD (3.0:7.0) showed stable PCTs and latent heat after 300 thermal cycles, this test duration is much shorter than the expected 20–30-year service life of building envelopes. Extended cycling may induce component segregation or gradual degradation in non-eutectic CPCM, thereby altering their

thermal properties. Therefore, long-term tests involving thousands of thermal cycles are required to further assess the durability of the proposed CPCM.

5. Seasonal Thermal Performance of the CPCM Building Walls

5.1. Summer thermal performance

Figure 13 depicts the temporal variations of the indoor surface temperature and liquefaction rate under summer conditions. By comparing the indoor surface temperature profiles of the ordinary wall, single PCM wall, and CPCM wall, it was determined that the maximum and minimum indoor surface temperatures of the ordinary wall were 306.23 K and 301.35 K, respectively, resulting in a temperature amplitude of 4.88 K. For the single PCM wall, these values were 305.22 K and 301.24 K, with a temperature amplitude of 3.98 K. The CPCM wall, however, exhibited the lowest temperature amplitude, with maximum and minimum indoor surface temperatures of 304.45 K and 301.5 K, respectively, and an amplitude of only 2.95 K. This represents a reduction of 39.55% and 25.88% in temperature amplitude compared to the ordinary wall and single PCM wall, respectively, indicating that the CPCM wall experiences the smallest temperature fluctuations.

When analyzing the liquefaction rate shown in Figure 13, it was observed that the CPCM started to partially liquefy from the beginning. This is due to its lower PCT of 287.82 K, which the temperature of the wall rapidly reached and surpassed. The low-temperature PCM fully liquefied, absorbing latent heat during the phase change and continuing to absorb sensible heat in the liquid state. At 13.06 hours, the high-temperature PCM in the CPCM began its solid-liquid phase change, which lasted for 5.5 hours. As the wall temperature decreased, the high-temperature PCM in the CPCM first released latent heat in the liquid state. At 19.72 hours, when the material temperature dropped to the high PCT, a liquid-solid phase change was triggered, releasing latent heat until 24.86 hours. Subsequently, the high-temperature PCM released sensible heat in the solid state, while the low-temperature PCM released sensible heat in the liquid state. At 35.97 hours, as the COT increased, a new heat storage cycle commenced, maintaining the stability of the inner surface temperature of the wall. In contrast, the single PCM started to liquefy at 9 hours, with the phase change process lasting for 2.64 hours. It then remained in the liquid phase, storing heat sensibly during the day and releasing it at night to maintain the temperature stability within the thermally regulated wall.

Figure 14 shows the variation of the indoor surface heat flux density of the wall over time in summer. From the curve, it can be seen that at 22.50 hours, compared with the ordinary wall and the single PCM wall, the CPCM regulated wall had the smallest absolute value of indoor surface heat flux density. This implies that it transferred the least amount of heat to the indoor space, with a

Figure 13 The variation of inner surface temperature and liquefaction rate under summer conditions

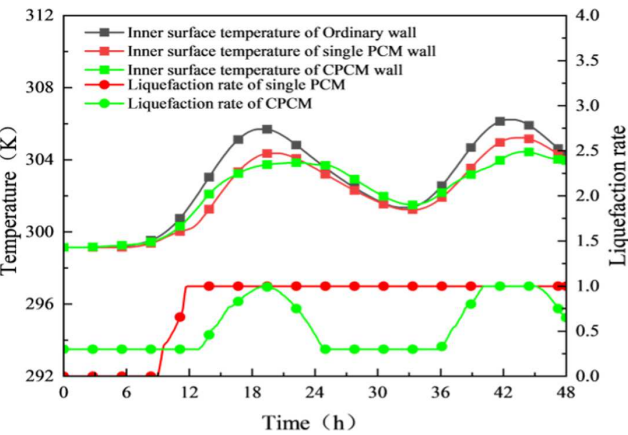
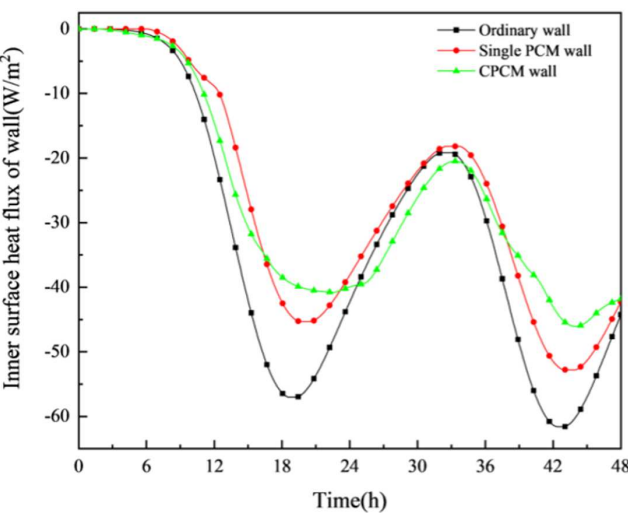


Figure 14 The variation of heat flux of wall inner surface under summer conditions



maximum difference in heat flux density of 16.23 W/m². Moreover, the CPCM thermally regulated wall exhibited the smallest fluctuations in indoor surface heat flux density compared to the other two types of walls.

It can be observed that the CPCM thermally regulated wall had the longest delay time of 6.67 hours in indoor surface temperature compared to the ordinary wall and the single PCM wall. Additionally, it had the smallest temperature attenuation factor of 0.102. The longer the delay time is, the more effectively it can avoid the high-temperature period and reduce the peak load of air conditioners. The smaller the temperature delay factor, the more

Table 7 Thermophysical properties of the CA-TD (3.0:7.0)

Material	Density (kg/m³)	Thermal conductivity (W/(m·K))	Specific heat capacity (J/(kg·K))	PCT (°C)	Enthalpy (J/g)
Low phase	890	0.21	2100	14.67	68.29
High phase	834	0.21	2500	36.67	73.54

effectively it can reduce the impact of outdoor environmental thermal disturbances on the indoor surface temperature of the wall, decrease the energy consumption of indoor cooling equipment, and ultimately achieve energy savings.

It should be noted that the experimentally obtained high PCT of 36.67 °C is 4.67 °C higher than the numerically identified target of 32 °C. This temperature offset delays the activation of latent-heat storage because a greater thermal driving force is required before the high-temperature component begins to melt. Nevertheless, the high-temperature phase change starts at 13.06 hours and lasts for approximately 5.5 hours, substantially overlapping with the period of strong daytime thermal loading. Therefore, latent-heat absorption is still effectively utilized to suppress and shift the heat transferred toward the indoor environment. At the wall level, the CPCM wall exhibits an inner surface temperature delay time of 6.67 hours, compared with 6.34 hours for the single PCM wall and 5.42 hours for the ordinary wall. Moreover, its temperature amplitude is reduced to 2.95 K, corresponding to reductions of 39.55% and 25.88%, respectively. These results demonstrate that the 4.67 °C upward shift does not eliminate the summer peak-shifting function, although it causes the latent-heat storage process to be activated later than would be expected for the ideal 32 °C target. This result also highlights that the numerically optimized PCT should be regarded as a target for material design rather than a strict threshold for satisfactory thermal performance.

5.2. Winter thermal performance

Figure 15 shows the variation of the indoor surface temperature and liquefaction rate over time under winter conditions. Comparing the indoor surface temperature profiles of the ordinary wall, single PCM wall, and CPCM wall, it was found that the maximum and minimum indoor surface temperatures of the ordinary wall were 289.96 K and 287.14 K, respectively, with a temperature amplitude of 2.82 K. For the single PCM wall, these values were 290.03 K and 287.58 K, with a temperature amplitude of 2.45 K. The CPCM wall showed the smallest temperature amplitude, with maximum and minimum indoor surface

temperatures of 289.68 K and 287.37 K, respectively, and a temperature amplitude of only 2.31 K. This represents a reduction of 18.09% and 5.71% in temperature amplitude compared to the ordinary wall and single PCM wall, respectively. The CPCM wall's minimal temperature fluctuations throughout the day can be attributed to its higher thermal inertia.

When comparing the liquefaction rate curves of the single PCM and CPCM, it was discovered that the single PCM did not undergo any phase change process. In contrast, the CPCM began its solid–liquid phase change in the low-temperature PCM at 14.72 hours, with the phase change process lasting for 2.92 hours and a maximum liquefaction rate of 0.22 during this process. As the wall temperature decreased, the high-temperature PCM in the CPCM released latent heat in the solid state, while the low-temperature PCM released latent heat during its phase change, which ended at 21.53 hours. Subsequently, the CPCM released latent heat in the solid state. At 38.33 hours, with rising COT, the PCM enters the heat storage state, and the indoor temperature can be maintained stably. Under winter conditions, only the low-temperature component of the CPCM underwent phase change, while the high-temperature component did not reach its PCT. The single PCM did not reach its PCT at all.

Figure 16 shows the variation of the indoor surface heat flux density of the wall over time under winter conditions. From the curve, it can be seen that at 33.75 hours, compared with the ordinary wall and the single PCM wall, the CPCM thermally regulated wall absorbed less heat from the indoor space. The surface heat flux density was reduced by 3.84 W/m² and 1.95 W/m², respectively. Moreover, the CPCM thermally regulated wall exhibited the smallest fluctuations in indoor surface heat flux density.

Comparisons indicate that the CPCM thermally regulated wall had a longer delay time in indoor surface temperature compared to the ordinary wall and the single PCM wall, with a delay of 8.47 hours. Additionally, it had a smaller temperature attenuation factor of 0.118. These features clearly demonstrate the excellent temperature buffering effect of this material, which can effectively mitigate the impact of outdoor temperature fluctuations on the indoor surface temperature, thereby reducing building energy consumption.

Figure 15
The variation of wall inner surface temperature and liquefaction rate under winter conditions

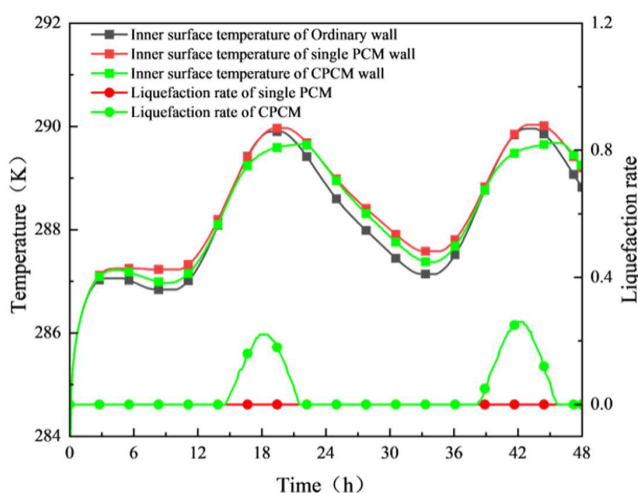
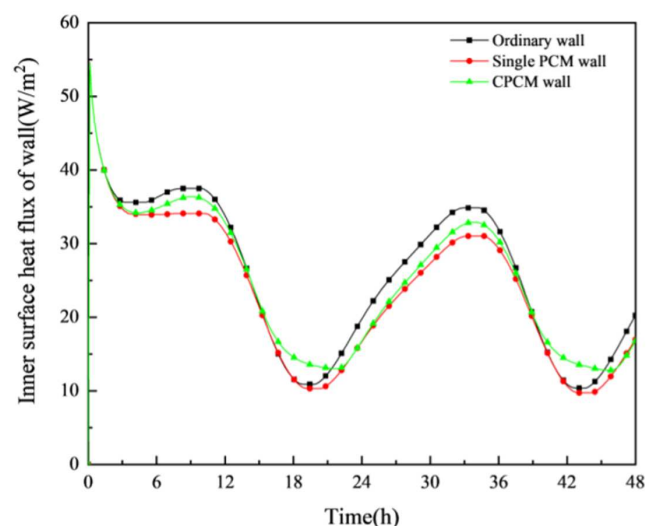


Figure 16
The variation of heat flux of wall interior surface under winter conditions



It should be noted that the present study focused on Nanjing as a representative hot summer and cold winter climate. While the numerical results are region-specific, the proposed methodology and design principle of using a single-layer CPCM with dual transition temperatures can be extended to other climatic zones, with necessary adjustments to the PCT ranges and wall parameters.

5.3. Building-level energy-saving potential

Under summer conditions, the maximum difference in heat flux density between the seasonal phase change temperature-regulating wall and ordinary walls is 16.23 W/m², while in winter, the maximum difference is 3.84 W/m². These maximum heat flux reductions were used as representative load reductions in the following simplified building-level calculation. Therefore, the estimated seasonal energy savings represent the potential savings under a peak-load reduction assumption rather than those derived from time-integrated or time-averaged heat loads. The operational energy consumption of the building's air conditioning system can be calculated using the following formula:

$$E = \frac{Q}{COP_s} \times t \tag{4}$$

Among these, the comprehensive energy efficiency ratio of the air conditioning system is 3.5 for cooling conditions and 4.5 for heating conditions. The load on the air conditioning system refers to the reduction in external wall load after adopting the seasonal phase change temperature-regulating wall.

Taking a public building in Nanjing with a floor area of 70 m² and an external wall area of 112 m² as an example, after applying the seasonal phase change temperature-regulating wall, assuming the air conditioning system operates for 120 days during the cooling season and 90 days during the heating season, the calculated energy consumption reduction during the cooling season is 1,495.8 kWh, and during the heating season, it is 206.4 kWh.

Combining the annual data, after adopting the CPCM wall, the potential annual electricity saving is estimated to be approximately 1,702.2 kWh under the above peak-load reduction assumption.

Taking the heat loss through a 1 m² wall as an example, the material costs and payback periods were calculated and are summarized in Tables 8 and 9. Based on the current prices of

CA and TD, the cost of the prepared CPCM layer (10 mm thickness) is approximately 158.9 RMB per square meter. Considering the local electricity tariff of 0.5583 RMB/kWh in Nanjing, the payback period of the CPCM wall is estimated at 10.45 years.

Although this payback time is relatively long, it should be emphasized that PCMs are now a rapidly developing research focus, and material prices are expected to decrease significantly in the coming years. With technological progress and large-scale application, the investment payback period of CPCM walls is projected to be shortened to within 3 years over the next 5–10 years. This highlights the promising economic feasibility of the proposed design.

5.4. Discussion

The results obtained for Nanjing can be further generalized into the overall design framework shown in Figure 17. The framework does not prescribe a fixed CPCM composition or wall configuration; instead, it provides a climate-adaptive procedure for designing dual-PCT CPCM walls in different cities and regions.

First, local meteorological conditions, including outdoor temperature, solar radiation, seasonal temperature variation, and indoor thermal requirements, are used to define the summer and winter thermal regulation targets. A numerical wall model is then established to optimize the PCM layer position and thickness according to indicators such as inner surface temperature, heat flux, temperature delay time, and attenuation factor. Based on the resulting temperature field and phase change behavior, suitable high and low target PCTs are identified for summer heat absorption and winter heat retention, respectively.

Candidate PCMs are subsequently screened according to their PCTs, latent heat, stability, safety, and cost. Thermodynamic calculations and phase diagrams can be used for preliminary composition screening, while non-eutectic ratios are selected to obtain two distinct PCTs. The prepared CPCMs should then be experimentally characterized using DSC, step cooling, thermal cycling, and compatibility tests. If the measured properties deviate from the target values, the CPCM composition and wall parameters can be iteratively adjusted. Therefore, the framework forms a closed design loop linking local climate, wall configuration, target PCTs, material formulation, and performance validation.

This framework can be applied to different climatic zones by replacing the Nanjing weather data, indoor setpoints, wall construction, and material database with local inputs. It also provides a potential basis for integrating weather databases, building information models, and material libraries into smart-city building design platforms. However, the current study is based on typical seasonal days, one wall structure, and simplified heat transfer assumptions. Annual simulations, full-scale experiments, and long-term durability and economic assessments are still required before large-scale application.

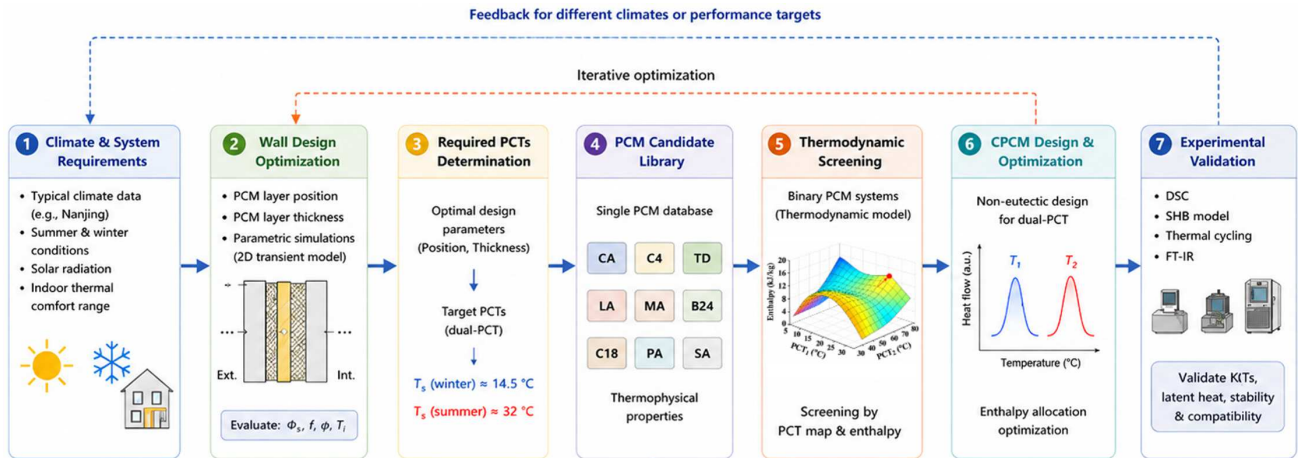
Table 8
Material cost of CA–TD (3.0:7.0)

Material	PCT (°C)	Price (RMB/100 g)
CA	≥29.0	1.80
TD	36.5~39.5	1.95
CA–TD (3.0:7.0)	14.67 and 36.67	1.905

Table 9
Payback period of CPCM walls

Material cost (RMB)	Electricity price in Nanjing (RMB/kWh)	Total heat loss (kWh/m ² /3 months)	Payback time (Years)
158.877	0.5583	27.23	10.45

Figure 17
Dual-PCT CPCM design framework for different climates/cities



6. Conclusions

This study developed a climate-adaptive building wall incorporating a single CPCM layer with two PCTs to meet different thermal regulation requirements in summer and winter. A combined numerical-experimental approach was employed to optimize the wall configuration and target PCTs, prepare a suitable binary non-eutectic CPCM, and evaluate its seasonal thermal performance under the climatic conditions of Nanjing.

- 1) The optimized wall configuration was identified for year-round operation. The CPCM layer should be placed in the middle of the investigated wall, with an optimal thickness of 10 mm. The target PCTs were determined as 32 °C for summer and 14.5 °C for winter, providing the best overall combination of temperature delay, attenuation, and material utilization.
- 2) A binary non-eutectic CPCM suitable for seasonal thermal regulation was successfully developed. The selected CA-TD mixture at a mass ratio of 3.0:7.0 exhibited two PCTs of 14.67 °C and 36.67 °C, with corresponding latent heats of 68.29 and 73.54 J/g and a total latent heat of 143.83 J/g. Its PCTs and enthalpy remained essentially stable after 300 thermal cycles, indicating good thermal reliability.
- 3) The CPCM wall significantly improved summer thermal performance. Its indoor surface temperature amplitude was reduced from 4.88 K for the ordinary wall and 3.98 K for the single PCM wall to 2.95 K, corresponding to reductions of 39.55% and 25.88%, respectively. The maximum indoor surface heat flux reduction reached 16.23 W/m² compared with the ordinary wall.
- 4) The CPCM wall also provided effective winter thermal buffering. Its indoor surface temperature amplitude was 2.31 K, which was 18.09% lower than that of the ordinary wall and 5.71% lower than that of the single PCM wall. The maximum heat flux reduction reached 3.84 W/m² and 1.95 W/m² relative to the ordinary and single PCM walls, respectively, while the temperature delay time increased to 8.47 hours and the attenuation factor decreased to 0.118.
- 5) The proposed design showed measurable building-level energy-saving potential. For the investigated public building with an external wall area of 112 m², the estimated cooling- and

heating-season electricity savings were 1495.8 and 206.4 kWh, respectively, resulting in a total annual saving of approximately 1702.2 kWh. The current estimated CPCM cost was about RMB 158.9/m², corresponding to a payback period of approximately 10.45 years.

Overall, the main contribution of this study is the establishment of a transferable climate-wall-material integrated design framework for developing compact, single-layer, dual-PCT CPCM envelopes with seasonal adaptability for energy-flexible buildings in smart cities.

Recommendations

Based on the findings, climate-adaptive CPCM walls should be designed according to local meteorological conditions, wall structures, and indoor thermal requirements rather than adopting fixed material parameters across different regions. For practical applications, the proposed framework is recommended to re-optimize the CPCM layer position, thickness, and dual PCTs using local weather data, followed by experimental verification of thermal properties, cycling stability, safety, and compatibility with encapsulation materials. Future studies should further evaluate annual HVAC energy savings, peak-load shifting, economic performance, and long-term durability through whole-building simulations and full-scale demonstration projects, thereby supporting the wider application of dual-PCT CPCM envelopes in energy-flexible buildings and smart cities.

Acknowledgements

The authors gratefully acknowledge the support from the Natural Science Foundation of Jiangsu Province (BK20240590) and the National Natural Science Foundation of China (52106094).

Funding Support

This work is sponsored by the Natural Science Foundation of Jiangsu Province (BK20240590) and the National Natural Science Foundation of China (52106094).

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contribution Statement

Wei Wu: Conceptualization, Methodology, Resources, Data curation, Writing – review & editing, Supervision, Project administration. **Haibin Han:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Wenzheng Li:** Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Zhengyu Chen:** Validation, Formal analysis. **Haoyu Li:** Investigation, Visualization. **Minfen Gu:** Resources. **Yahui Sun:** Funding acquisition. **Yunjun Wang:** Data curation. **Xing Jin:** Supervision. **Chong Zhai:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition.

References

- [1] Barber, E., Vansal, N., Fang, Z., Hung, Y.-W., Peoples, J., Ciez, R., . . . , & Ruan, X. (2025). Impacts of radiative cooling paints for CO₂ reduction and global warming mitigation. *Energy and Buildings*, 332, 115458. <https://doi.org/10.1016/j.enbuild.2025.115458>
- [2] International Energy Agency. (2025). *Buildings*. Retrieved from: <https://www.iea.org/energy-system/buildings>
- [3] Ju, J., & Wei, G. (2024). Xiāngbiàn xùnéng cáiliào zài jiànzhù zhōng de yīngyòng xiànzhuàng yǔ fāzhǎn qūshì yánjiū [Research on application status and development trend of phase change energy storage materials in construction]. *Block-Brick-Tile*, 10, 33–35. <https://doi.org/10.3969/j.issn.1001-6945.2024.10.007>
- [4] Hou, L., Tai, H., Liu, Y., Zhu, Y., Zhao, X., & Yang, L. (2024). Thermal design of insulation on the outside of the cavity for a Trombe wall with phase change materials. *Energy and Buildings*, 311, 114168. <https://doi.org/10.1016/j.enbuild.2024.114168>
- [5] Suresh, C., Hotta, T. K., & Saha, S. K. (2022). Phase change material incorporation techniques in building envelopes for enhancing the building thermal Comfort-A review. *Energy and Buildings*, 268, 112225. <https://doi.org/10.1016/j.enbuild.2022.112225>
- [6] Omle, I., Kovács, E., & Bolló, B. (2023). Applying recent efficient numerical methods for long-term simulations of heat transfer in walls to optimize thermal insulation. *Results in Engineering*, 20, 101476. <https://doi.org/10.1016/j.rineng.2023.101476>
- [7] Su, H., Zhang, Z., Dai, G., Guo, H., Li, X., & Xu, C. (2024). Investigating the thermal performance of a pipe-encapsulated movable PCM wall and its impact on reducing indoor heat gain during summer. *Renewable Energy*, 237, 121897. <https://doi.org/10.1016/j.renene.2024.121897>
- [8] Hamidi, Y., Aketouane, Z., Malha, M., Bruneau, D., Bah, A., & Goiffon, R. (2021). Integrating PCM into hollow brick walls: Toward energy conservation in Mediterranean regions. *Energy and Buildings*, 248, 112124. <https://doi.org/10.1016/j.enbuild.2021.112124>
- [9] Izadi, M., Taghavi, S. F., Safavi, S. H. N., Afsharpanah, F., & Yaici, W. (2023). Thermal management of shelter building walls by PCM macro-encapsulation in commercial hollow bricks. *Case Studies in Thermal Engineering*, 47, 103081. <https://doi.org/10.1016/j.csite.2023.103081>
- [10] Al-Absi, Z. A., Hafizal, M. I. M., & Ismail, M. (2022). Experimental study on the thermal performance of PCM-based panels developed for exterior finishes of building walls. *Journal of Building Engineering*, 52, 104379. <https://doi.org/10.1016/j.job.2022.104379>
- [11] Abbas, H. M., Jalil, J. M., & Ahmed, S. T. (2021). Experimental and numerical investigation of PCM capsules as insulation materials inserted into a hollow brick wall. *Energy and Buildings*, 246, 111127. <https://doi.org/10.1016/j.enbuild.2021.111127>
- [12] Wijesuriya, S., & Tabares-Velasco, P. C. (2020). Experimental apparatus and methodology to test and quantify thermal performance of micro and macro-encapsulated phase change materials in building envelope applications. *Journal of Energy Storage*, 32, 101770. <https://doi.org/10.1016/j.est.2020.101770>
- [13] Farouq, M. M., Mirzaei, P. A., Jimenez-Bescos, C., & Riffat, S. (2024). Experimental and numerical study on the thermal performance of earthbag-wall units incorporated with phase change materials. *Journal of Building Engineering*, 90, 109306. <https://doi.org/10.1016/j.job.2024.109306>
- [14] Li, W., & Chen, W. (2019). Numerical analysis on the thermal performance of a novel PCM-encapsulated porous heat storage Trombe-wall system. *Solar Energy*, 188, 706–719. <https://doi.org/10.1016/j.solener.2019.06.052>
- [15] Zhu, N., Deng, R., Hu, P., Lei, F., Xu, L., & Jiang, Z. (2021). Coupling optimization study of key influencing factors on PCM Trombe wall for year thermal management. *Energy*, 236, 121470. <https://doi.org/10.1016/j.energy.2021.121470>
- [16] Duan, S., Li, H., Zhao, Z., & Wang, L. (2021). Investigation on heating performance of an integrated phase change material Trombe wall based on state space method. *Journal of Energy Storage*, 38, 102460. <https://doi.org/10.1016/j.est.2021.102460>
- [17] Sheikholeslami, M., & Al-Hussein, H. R. A. (2023). Modification of heat storage system involving Trombe wall in existence of paraffin enhanced with nanoparticles. *Journal of Energy Storage*, 58, 106419. <https://doi.org/10.1016/j.est.2022.106419>
- [18] Cai, Y., Huang, Y., Shu, Z., Liu, Z., Zhong, H., & Zhao, F. (2024). Investigation of double-PCM based PV composite wall for power-generation and building insulation: Thermal characteristics and energy consumption prediction. *Energy and Built Environment*, 7(1), 14–27. <https://doi.org/10.1016/j.enbenv.2024.08.002>
- [19] Sun, X., Zhang, Y., Xie, K., & Medina, M. A. (2022). A parametric study on the thermal response of a building wall with a phase change material (PCM) layer for passive space cooling. *Journal of Energy Storage*, 47, 103548. <https://doi.org/10.1016/j.est.2021.103548>
- [20] Li, M., Cao, Q., Pan, H., Wang, X., & Lin, Z. (2021). Effect of melting point on thermodynamics of thin PCM reinforced residential frame walls in different climate zones. *Applied*

- Thermal Engineering*, 188, 116615. <https://doi.org/10.1016/j.applthermaleng.2021.116615>
- [21] Wu, D., Rahim, M., El Ganaoui, M., Bennacer, R., & Liu, B. (2022). Multilayer assembly of phase change material and bio-based concrete: A passive envelope to improve the energy and hygrothermal performance of buildings. *Energy Conversion and Management*, 257, 115454. <https://doi.org/10.1016/j.enconman.2022.115454>
- [22] Babaharra, O., Choukairy, K., Faraji, H., Khallaki, K., Hamdaoui, S., & Bahammou, Y. (2024). Thermal performance analysis of hollow bricks integrated phase change materials for various climate zones. *Heat Transfer*, 53(4), 2148–2172. <https://doi.org/10.1002/hjt.23031>
- [23] Dehkordi, B. S., & Afrand, M. (2022). Energy-saving owing to using PCM in buildings: Considering of hot and cold climate region. *Sustainable Energy Technologies and Assessments*, 52, 102112. <https://doi.org/10.1016/j.seta.2022.102112>
- [24] Askari, M., & Jahangir, M. H. (2023). Evaluation of thermal performance and energy efficiency of a Trombe wall improved with dual phase change materials. *Energy*, 284, 128587. <https://doi.org/10.1016/j.energy.2023.128587>
- [25] Wang, J., Zhang, Q., Zhang, Y., Shi, J., & Zhou, D. (2025). Research on arrangement principles and optimization of a battery thermal management system with double-layer PCMs under summer conditions. *Thermochimica Acta*, 751, 180085. <https://doi.org/10.1016/j.tca.2025.180085>
- [26] Gao, Y., Liu, Z., Gao, Y., Mao, W., Zuo, Y., & Li, G. (2023). Employing the double-PCM (phase-change material) layer to improve the seasonal adaption of building walls: A comparative studies. *Journal of Energy Storage*, 66, 107404. <https://doi.org/10.1016/j.est.2023.107404>
- [27] Arfi, O., Mezaache, E. H., Teggat, M., & Laouer, A. (2023). Thermal analysis of a dynamic double-layer phase change material building envelope. *Energy, Ecology and Environment*, 8(5), 485–502. <https://doi.org/10.1007/s40974-023-00289-2>
- [28] Louanate, A., Otmami, R. E., Kandoussi, K., & Boutaous, M. H. (2021). Dynamic modeling and performance assessment of single and double phase change material layer-integrated buildings in Mediterranean climate zone. *Journal of Building Physics*, 44(5), 461–478. <https://doi.org/10.1177/1744259120945361>
- [29] Wang, X., Li, W., Luo, Z., Wang, K., & Shah, S. P. (2022). A critical review on phase change materials (PCM) for sustainable and energy efficient building: Design, characteristic, performance and application. *Energy and Buildings*, 260, 111923. <https://doi.org/10.1016/j.enbuild.2022.111923>
- [30] Ye, R., Lin, W., Fang, X., & Zhang, Z. (2017). A numerical study of building integrated with $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ /expanded graphite composite phase change material. *Applied Thermal Engineering*, 126, 480–488. <https://doi.org/10.1016/j.applthermaleng.2017.07.191>
- [31] Vicente, R., & Silva, T. (2014). Brick masonry walls with PCM macrocapsules: An experimental approach. *Applied Thermal Engineering*, 67(1-2), 24–34. <https://doi.org/10.1016/j.applthermaleng.2014.02.069>
- [32] China Meteorological Administration. (2024). *Official website of the Government of China Meteorological Administration*. Retrieved from: <https://data.cma.cn/data-service/category/1/6/search/A.0012.0001>
- [33] Ministry of Housing and Urban-Rural Development of the People's Republic of China. (2016). *Thermal design code for civil buildings*. (Standard No. GB 50176-2016). China: China Architecture & Building Press
- [34] Yao, X., Ma, J., Wang, F., & Yang, X. (2024). Zhēndui xiàrè dōnglěng dìqū de xīnxíng chéngzài xùrè chāojiégòu qiángtǐ liúxué xìngnéng yǔ wēnkòng xiàonéng yánjiū [Investigation on mechanical properties and temperature control efficiency of novel load-bearing and heat-storing metastructure walls in hot summer-cold winter regions]. *Applied Mathematics and Mechanics*, 45(8), 1047–1057. <https://doi.org/10.21656/1000-0887.450172>
- [35] Zhang, Y., Sun, X., & Medina, M. A. (2024). Experimental assessment of concrete masonry units integrated with insulation and phase change material: A wall-pattern study. *Energy*, 289, 130038. <https://doi.org/10.1016/j.energy.2023.130038>
- [36] Wu, W., Li, W., Han, H., Xu, M., Lu, E., Wang, Z., & Zhai, C. (2024). Advanced thermal energy storage made of a ternary CPCM with two phase change temperatures in building walls. *Energy and Buildings*, 318, 114445. <https://doi.org/10.1016/j.enbuild.2024.114445>
- [37] Zhang, Y., Zhu, Z., Peng, Z., Luo, J., Sun, X., Li, J., & Peng, F. (2023). The Trombe wall equipped with PCMs for the enhancement of the indoor thermal quality. *Energy and Buildings*, 297, 113407. <https://doi.org/10.1016/j.enbuild.2023.113407>
- [38] Zhou, S., Song, M., Shan, K., Razaqpur, A. G., & Huang, J. J. (2024). Effects of the position and melting point of the PCM layer on the comprehensive thermal performance of a Trombe wall under mixed dry climate. *Energy and Buildings*, 307, 113932. <https://doi.org/10.1016/j.enbuild.2024.113932>
- [39] Meng, E., Yu, H., Zhan, G., & He, Y. (2013). Experimental and numerical study of the thermal performance of a new type of phase change material room. *Energy Conversion and Management*, 74, 386–394. <https://doi.org/10.1016/j.enconman.2013.06.004>
- [40] Meng, E., Yu, H., & Zhou, B. (2017). Study of the thermal behavior of the composite phase change material (PCM) room in summer and winter. *Applied Thermal Engineering*, 126, 212–225. <https://doi.org/10.1016/j.applthermaleng.2017.07.110>
- [41] El-Raheim, Abd., Mohamed, D., A., Abou-Ziyan., H., & Fatouh, M. (2023). The essential properties governing the appropriate selection of phase change materials integrated into heavy structure buildings. *Energy*, 266, 126515. <https://doi.org/10.1016/j.energy.2022.126515>

How to Cite: Wu, W., Han, H., Li, W., Chen, Z., Li, H., Gu, M., ..., & Zhai, C. (2026). Climate-Adaptive Dual-Temperature Composite Phase Change Wall Design for Energy-Flexible Buildings in Smart Cities. *Sustainability in Smart Cities*. <https://doi.org/10.47852/bonviewSSC620211542>