



## Optimization of Thermal Performance in Green Building Materials Based on Thermodynamic Principles

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### ABSTRACT

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*green building materials, thermodynamic principles, thermal performance optimization, phase change thermal storage, heat transfer analysis*

With the intensifying global energy crisis and environmental issues, the energy consumption and environmental impact of the construction sector have garnered significant attention. The development and application of green building materials have become crucial research areas. Traditional building materials cause substantial resource waste and environmental pollution during production, usage, and disposal. In contrast, green building materials based on thermodynamic principles, owing to their superior thermal performance and energy storage capabilities, have gradually gained attention. This paper aims to systematically optimize the thermal performance of green building materials through a research approach grounded in thermodynamic principles. The study consists of two main parts: first, constructing the control equations for the phase change thermal storage process of green building materials, and analyzing the thermodynamic characteristics during the phase change process in detail; second, conducting an in-depth analysis of the heat transfer process in phase change thermal storage green building materials to explore their thermal performance in practical applications. Despite extensive research on the thermal performance of green building materials, there are still shortcomings in the systematic analysis and optimization of material thermal performance, and existing research methods often fail to comprehensively and accurately reflect the actual thermal behavior of materials. This paper aims to provide a scientific basis for the optimized design of green building materials, further promoting their application and development in the construction field.

## 1. INTRODUCTION

With the increasingly severe global energy crisis and environmental issues, the energy consumption and environmental impact of the construction sector have garnered significant attention [1-8]. Traditional building materials, during production, usage, and disposal, often cause substantial resource waste and environmental pollution [9-12]. Therefore, the development and application of green building materials have become important research directions in the construction sector [13-16]. Green building materials not only have good environmental performance but also can significantly reduce building energy consumption and improve building energy efficiency. Now, green building materials based on thermodynamic principles are gradually attracting researchers' attention due to their superior thermal performance and energy storage capabilities.

Research on the thermal performance optimization of green building materials based on thermodynamic principles has important practical significance [17-19]. Firstly, optimizing the thermal performance of green building materials can effectively improve the insulation and thermal insulation effects of buildings, reduce energy consumption, and lower building operating costs [20-23]. Secondly, in-depth research on the thermal performance of green building materials helps

promote technological innovation in building materials and enhance the overall technical level of the construction industry. In addition, this research can also provide a scientific basis for formulating relevant policies and standards, promote the development of green buildings, and contribute to the achievement of sustainable development goals.

Despite the extensive research on the thermal performance of green building materials, there are still some shortcomings. On the one hand, many studies mainly focus on the physical and chemical properties of the materials themselves, lacking systematic analysis and optimization of the thermal performance of the materials [24, 25]. On the other hand, most of the existing research methods use empirical models or experimental methods, which are difficult to comprehensively and accurately reflect the thermal behavior of materials in actual use [26-28]. Moreover, some studies ignore the nonlinearity and complexity of the phase change thermal storage process, resulting in limited accuracy and practicality of their results.

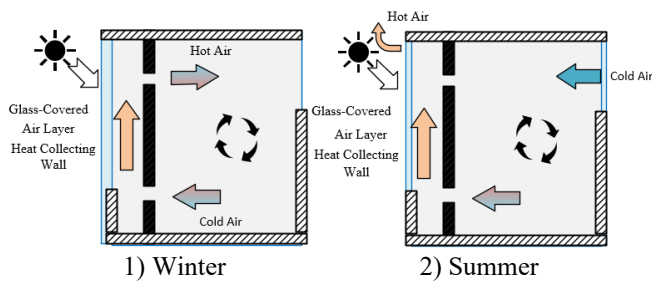
This paper aims to systematically optimize the thermal performance of green building materials through a research approach based on thermodynamic principles. The research content mainly includes two parts: firstly, constructing the control equations for the phase change thermal storage process of green building materials and analyzing the thermodynamic

characteristics during the phase change process in detail; secondly, conducting an in-depth analysis of the heat transfer process in phase change thermal storage green building materials to explore their thermal performance in practical applications. Through the above research, this paper will provide a scientific basis for the optimized design of green building materials, further promoting the application and development of green building materials in the construction sector, and has important research value and practical significance.

## 2. CONSTRUCTION OF CONTROL EQUATIONS FOR PHASE CHANGE THERMAL STORAGE PROCESS IN GREEN BUILDING MATERIALS

Green building materials play an important role in achieving building energy conservation and improving indoor comfort, especially those with phase change thermal storage characteristics. Phase change thermal storage materials can absorb or release a large amount of heat energy by changing their state when the temperature reaches their phase change point. This characteristic allows them to absorb excess environmental heat during the day and release it at night, thereby regulating the temperature inside the building and enhancing indoor environmental comfort.

The phase change thermal storage process of green building materials can be modeled and optimized through control equations. That is, by constructing accurate mathematical models to describe the thermophysical behavior of phase change materials (PCM) in building structures. Through these control equations, the dynamic behavior of PCM in building structures can be described in detail, including the temperature changes of the materials, the movement of the phase change position, and the process of heat storage and release. These equations usually include parameters such as thermal conductivity, specific heat capacity, density, and latent heat of phase change of the materials, and are combined with the external environmental temperature and internal thermal load of the building for comprehensive analysis. Through these analyses, the arrangement and amount of PCM can be optimized to ensure that they maximize their energy-saving and temperature-regulating roles in practical applications. Figure 1 shows a schematic diagram of the temperature regulation effect of green building material walls.



**Figure 1.** Schematic diagram of the temperature regulation effect of green building material walls

Green building materials with phase change thermal storage characteristics are usually composed of ph PCM, carrier materials, reinforcing materials, and additives. Lipophilic paraffin, as an excellent PCM, can ensure sufficient thermal storage capacity with an appropriate content, thereby

improving the energy-saving effect of buildings. Hydrophilic sodium nitrate has good phase change characteristics and thermal conductivity, and an appropriate content can enhance the thermal conductivity of the material, thus improving the thermal comfort of buildings. Taking lipophilic paraffin and hydrophilic sodium nitrate as examples, the main component proportions for designing such materials can be considered as follows: lipophilic paraffin accounts for about 25% to 35% of the overall material, while hydrophilic sodium nitrate usually has a lower content, accounting for 5% to 15% of the overall material. Additionally, an appropriate content of carrier materials can support and fix the PCM while maintaining the stability and durability of the materials, accounting for about 20-40%. Reinforcing materials and additives help to enhance the strength, stability, and processing performance of the materials, accounting for about 5-10%.

In the application scenarios of green building materials, structural parts such as walls, floors, and roofs need to have good energy storage and temperature control performance to achieve building energy conservation and improve indoor comfort. To optimize the thermal performance of these materials, this paper constructs control equations for the phase change thermal storage process to deeply analyze and simulate the thermal behavior of materials in actual use. Based on this background, COMSOL Multiphysics software is selected for modeling and simulation. COMSOL Multiphysics is a powerful multiphysics simulation software capable of handling the coupling effects of thermal conduction, phase change processes, and other related physical fields simultaneously. This multiphysics coupling capability is crucial for a comprehensive analysis of the thermal performance of phase change thermal storage materials because, in practical applications, the thermal behavior of materials is not merely a simple thermal conduction process but also involves complex phase change and energy storage and release mechanisms.

When constructing control equations for the phase change thermal storage process of green building materials, multiple factors need to be considered to ensure the accuracy and practicality of the model. First, the geometric shape of the material needs to be determined. Green building materials are usually applied to building structures such as walls, floors, and roofs. The geometric shapes in different application scenarios have a significant impact on the heat transfer process. The specific geometric shape needs to be reasonably selected in conjunction with architectural design and accurately modeled in numerical simulations. Furthermore, the physical parameters of the materials are the basis for constructing control equations. The thermophysical parameters of PCM such as phase change temperature, specific heat capacity, thermal conductivity, and density directly affect their energy storage and temperature control performance. Determining boundary conditions is one of the key factors in numerical simulation. In practical applications, the boundary conditions such as ambient temperature, heat flux density, and thermal radiation where green building materials are located are complex and variable. Reasonably setting these boundary conditions helps to simulate the real working environment and improve the reliability and prediction accuracy of the model. When constructing control equations for the phase change thermal storage process of green building materials, a series of assumptions are considered to ensure the accuracy of the model and the stability of the solution:

(1) It is assumed that the flow of green building materials is

unsteady, incompressible, and laminar. That is, the velocity and direction of the fluid change with time, but its density remains constant, and the flow is laminar without turbulence.

(2) It is assumed that the liquid and solid phases of the materials are isotropic and homogeneous, meaning that the physical properties are the same in different directions, and these properties remain constant throughout the phase change process.

To simulate the phase change process, it is assumed that there is a mushy region on the solid-liquid interface. In this region, the phase change is assumed to occur within a very small temperature range  $[S_t, S_m]$ , where  $S_t$  and  $S_m$  represent the temperature boundaries of the solid and liquid phases, respectively.  $S_t$  is usually set to the phase change temperature minus half of a small temperature interval  $\Delta S$ , while  $S_m$  is set to the phase change temperature plus half of  $\Delta S$ .  $\Delta S$  is a small temperature interval, typically taken as 1K. This assumption simplifies the phase change process, making the phase change more stable to solve in numerical models. Based on the above assumptions, the control equations for the phase change thermal storage process of green building materials can be constructed as follows.

The continuity equation describes the conservation of mass in the fluid flow process. For the phase change thermal storage system of green building materials, it is assumed that the fluid is incompressible, which means that the density of the fluid remains constant during the flow process. The continuity equation ensures that the inflow and outflow of the fluid are balanced, i.e., at any point in time, the mass of fluid entering the system is equal to the mass of fluid exiting the system. Assuming the density of the PCM is represented by  $\rho$ , the phase change latent heat by  $M$ , the specific heat capacity by  $Z_o$ , the dynamic viscosity by  $\omega_o$ , and the volume force vector by  $i$ , the expression is:

$$\frac{\partial \rho}{\partial s} + \rho \nabla \cdot i = 0 \quad (1)$$

In the phase change thermal storage process of green building materials, the momentum equation considers the flow characteristics of the fluid at different temperatures and pressures. Assuming the fluid is laminar and incompressible, the momentum equation takes into account factors such as fluid viscosity, pressure gradient, and external forces. These factors determine the velocity distribution and flow path of the fluid, thereby affecting the heat transfer effect between the heat source and the cold source in the PCM. The expression is:

$$\rho \frac{\partial i}{\partial s} + \rho (\nabla \cdot i) i = -\nabla o + \omega_o \nabla^2 i + D \quad (2)$$

In the phase change thermal storage process, the energy equation is particularly important because it involves not only the transfer of sensible heat but also the release or absorption of latent heat during the phase change process. The energy equation considers the heat conduction and convection between the solid and liquid phases of the materials and describes the heat changes at the solid-liquid interface. Through the energy equation, the temperature distribution and phase change process of the materials under different temperature conditions can be simulated, thereby evaluating and optimizing the thermal storage performance of the materials. The expression is:

$$\rho Z_o \left( \frac{\partial S}{\partial t} + i \cdot \nabla S \right) = j \nabla^2 S - \frac{\partial (\rho M_t d)}{\partial s} \quad (3)$$

In the application of green building materials, considering buoyancy is very important for optimizing the design and performance of PCM. Buoyancy can significantly influence liquid phase flow, thereby affecting heat transfer efficiency and the dynamic behavior of the phase change process. In the momentum equation of the phase change thermal storage process, buoyancy can be calculated through the temperature gradient. Specifically, when the temperature rises, the fluid density decreases, and the fluid rises; conversely, when the temperature decreases, the fluid density increases, and the fluid sinks. This density difference generates buoyancy in the gravitational field, driving the natural convection of the fluid. This phenomenon can be described by the Boussinesq approximation. Assuming the reference temperature is represented by  $S_{RE}$ , which is usually set to the melting point temperature, the thermal expansion coefficient is represented by  $\beta$ , and the gravitational acceleration is represented by  $h$ , the calculation formula is:

$$D = -\rho [1 - \beta(S - S_{RE})] h \quad (4)$$

In the constructed control equations for the phase change thermal storage process of green building materials, effective thermal conductivity, effective density, specific heat capacity, mass fraction, melting fraction, and dynamic viscosity are key parameters that define the thermophysical properties and flow behavior of materials during the phase change process. Among them, the effective thermal conductivity refers to the thermal conductivity of the material during the phase change process. In green building materials, the effective thermal conductivity determines the efficiency of the material in the heat storage and release process, which is crucial for optimizing building energy efficiency. Effective density is the comprehensive density of the PCM in the solid-liquid coexistence state. It considers the density differences in different phases of the material and is usually calculated by the weighted average of the liquid phase fraction and the solid phase fraction. Specific heat capacity refers to the amount of heat required to raise the temperature of the material by one degree per unit mass. In the phase change process, specific heat capacity may differ between the solid phase and the liquid phase. Assuming the solid phase is represented by the subscript  $t$  and the liquid phase by the subscript  $m$ , the calculation formulas for effective thermal conductivity  $j$ , effective density  $\rho$ , and specific heat capacity  $Z_o$  are given as follows:

$$j = (1-d)j_t + dj_m \quad (5)$$

$$\rho = (1-d)\rho_t + d\rho_m \quad (6)$$

$$Z_o = \frac{1}{\rho} [(1-d)\rho_t Z_{o,t} + d\rho_m Z_{o,m}] + M_l \frac{d\zeta}{dS} \quad (7)$$

The mass fraction refers to the ratio of the mass of a certain component in the green building material to the total mass, used to describe the proportion of the solid phase and the liquid phase in the entire green building material. The definition formula for the mass fraction  $\zeta$  is as follows:

$$\zeta = \frac{1}{2} \frac{d\mathcal{G}_m - (1-d)\mathcal{G}_l}{\mathcal{G}} \quad (8)$$

The melting fraction describes the proportion of green building materials reaching the melting point during the phase change process, it defines the extent to which the green building material transitions from the solid phase to the liquid phase. The change in the melting fraction is crucial for accurately describing the temperature distribution and heat transfer during the phase change process of green building materials, ensuring that the model can effectively simulate the heat storage and release behavior of PCM in green buildings. The definition formula is as follows:

$$d = \begin{cases} 0, S \leq S_t \\ \frac{S - S_t}{S_m - S_t}, S_t < S < S_m \\ 1, S \geq S_m \end{cases} \quad (9)$$

In the phase change process of green building materials, the viscosity of the liquid phase material will significantly affect its flow characteristics. Effective dynamic viscosity describes the flow resistance of the material in different phases by comprehensively considering the viscosity characteristics of the solid phase and the liquid phase. The approximate value of the dynamic viscosity of green building materials is represented by  $\omega_o$ , and the calculation formula is:

$$\omega_o = \omega_{o,m} \left[ 1 + \frac{Z(1-d)^2}{\sigma + d^3} \right] \quad (10)$$

### 3. HEAT TRANSFER ANALYSIS OF PHASE CHANGE THERMAL STORAGE GREEN BUILDING MATERIALS

Phase change thermal storage green building materials can absorb or release a large amount of heat during the phase change process, thereby regulating the temperature inside the building. How to effectively integrate PCM into building components is key to realizing their function. Currently, there are three main successful methods to combine PCM with building materials. The direct mixing method mixes PCM directly into the building materials, but this may affect the mechanical properties and durability of the building materials. The impregnation method soaks these materials in a melted PCM solution, which is only suitable for building materials with high porosity and is prone to leakage or material performance degradation over long-term use. Microencapsulation technology encapsulates the PCM in small spheres made of polyethylene or other polymer materials, and then mixes these spheres into the building materials. The microencapsulation method effectively prevents direct contact between the PCM and the building materials, thus avoiding any adverse effects of the PCM on the mechanical properties of the building materials. The encapsulated microcapsules provide a layer of protection, keeping the PCM stable during the phase change process and preventing leakage. The advantage of this method is the flexible adjustment of the amount and distribution of PCM, and the simplicity of the construction process.

In the microencapsulation method, it is assumed that the building envelope structure is composed of three layers: the inner and outer layers are ordinary building material layers, and the middle layer is the PCM layer. Specifically, the thickness of the inner building material layer is  $(L_3-L_2)$ , the thickness of the outer building material layer is  $L_1$ , and the thickness of the middle PCM layer is  $(L_2-L_1)$ . This structure's mathematical model can be described by establishing a simplified coordinate system. In the simplified model, we ignore the impact of the capsule walls between the microcapsules on heat transfer, assuming that the PCM is arranged neatly in the middle layer, and that heat conduction mainly occurs between the inner and outer building material layers and the middle PCM layer. The heat transfer process in the model can be described as follows:

(1) Inner ordinary building material layer: The heat transfer process in this layer is mainly influenced by the thermal conductivity and heat capacity of the building materials. Heat flows from the indoor environment to the inner material layer, gradually passing through this layer to reach the PCM layer.

(2) Middle PCM layer: The PCM in this layer plays the role of heat storage and release. When the environmental temperature rises, the PCM absorbs heat and undergoes phase change, transforming from solid to liquid; when the environmental temperature drops, the PCM releases heat and re-solidifies. This process significantly improves the thermal stability and heat storage capacity of the materials.

(3) Outer ordinary building material layer: The heat transfer process in this layer mainly involves transferring heat from the PCM layer to the external environment. The thermal conductivity and heat capacity of the outer building materials also affect the overall heat transfer effect.

By establishing the above-mentioned heat transfer mathematical model of the three-layer structure, the impact of different thicknesses, material properties, and PCM performance on the overall heat transfer effect can be analyzed in detail. Figure 2 shows a simplified mathematical model of the green building material wall. Assuming that the temperatures of the outer and inner layers of the wall are represented by  $s_1$  and  $s_2$ , and the thermal diffusivities of the outer and inner layers of the wall are represented by  $\beta_1$  and  $\beta_2$ , and the time is represented by  $\pi$ . The following gives the mathematical expression for the encapsulated phase change thermal storage green building materials:

$$\begin{aligned} \frac{\partial s_1}{\partial \pi} &= \beta_1 \frac{\partial^2 s_1}{\partial a^2} & 0 < a < M_1 \\ \frac{\partial s_2}{\partial \pi} &= \beta_2 \frac{\partial^2 s_2}{\partial a^2} & M_2 < a < M_3 \end{aligned} \quad (11)$$

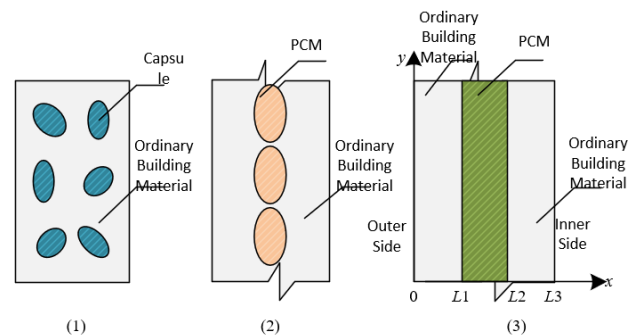


Figure 2. Simplified mathematical model of green building material wall

When studying the heat transfer analysis of phase change thermal storage in green building materials, understanding the principles of constructing the phase interface equation is crucial. The purpose of using PCM is to utilize their significant absorption or release of latent heat during the solid-liquid phase change process, thereby achieving temperature regulation, energy conservation, and emission reduction. In the specific heat transfer model, the central region of the wall  $M_1 < a < M_2$  is composed of PCM, where a phenomenon of solid-liquid coexistence occurs during the phase change process. To describe this process, we need to construct a phase interface equation. During heating or cooling, PCM undergoes phase change, forming solid and liquid regions. The interface between these two regions is called the phase interface. Assuming that at a certain time  $\pi$ , the position of the phase interface is represented by the function  $t(\pi)$ , which indicates the distance of the solid-liquid phase interface from the coordinate origin. This function is key to describing the movement of the solid-liquid interface during the phase change process. In the application scenario of green building materials, such as the heat transfer model of a wall, it is assumed that the wall is composed of a three-layer structure: the inner side is ordinary building material, the middle is PCM, and the outer side is also ordinary building material. The thicknesses of the inner and outer sides are  $M_3 - M_2$  and  $M_1$ , respectively, and the thickness of the middle PCM is  $M_2 - M_1$ . In this structure, the heat transfer model of the PCM layer needs to consider both sensible heat and latent heat during the phase change process. Assuming that the temperatures of the solid phase region, liquid phase region, and phase change of the PCM are represented by  $s_t$ ,  $s_m$ , and  $s_o$ , the thermal conductivities of the liquid phase and solid phase of the PCM are represented by  $\eta_t$  and  $\eta_m$ , the density of the PCM is represented by  $\varrho$ , and the latent heat of the PCM is represented by  $w_o$ , the expression is:

$$s_t = s_m = s_o$$

$$\eta_t \frac{\partial s_t}{\partial a} - \eta_m \frac{\partial s_m}{\partial a} = \varrho w_o \frac{dt(\pi)}{d\pi} \quad (12)$$

The liquid phase region in phase change thermal storage green building materials refers to the area where the building materials have completely melted during the phase change process. The temperature in this region is higher than the melting point of the material. In the liquid phase region, heat conduction mainly occurs through the thermal conductivity of the liquid. Assuming that the thermal diffusivities of the solid phase and liquid phase of the PCM are represented by  $\beta_t$  and  $\beta_m$ , the equation for constructing the liquid phase region is as follows:

$$\frac{\partial s_m}{\partial \pi} = \beta_m \frac{\partial^2 s_m}{\partial a^2} \quad M_m < a < t(\pi) \quad (13)$$

The solid phase region refers to the area in the phase change thermal storage green building materials that has not yet melted during the phase change process. The temperature in this region is lower than the melting point of the material. In the solid phase region, heat conduction mainly occurs through the thermal conductivity of the solid. The equation for constructing the solid phase region is as follows:

$$\frac{\partial s_t}{\partial \pi} = \beta_s \frac{\partial^2 s_t}{\partial a^2} \quad t(\pi) < a < M_2 \quad (14)$$

These equations for the liquid and solid phases are used to simulate the heat transfer behavior of walls or other building components under different temperature conditions. For example, when the PCM layer in the middle of the wall begins to absorb heat and melt, the liquid phase region equation describes the heat conduction in the liquid material, while the solid phase region equation describes the heat conduction in the solid material that has not yet melted. By combining the equations for these two regions, a comprehensive understanding of how the material regulates temperature during the phase change process can be obtained, thus optimizing the energy efficiency of buildings.

Regarding boundary conditions, for air-conditioned buildings, it is usually assumed that the indoor temperature  $s_0$  is a constant value, as the air conditioning system can maintain a stable indoor temperature. Under such conditions, the heat exchange between the wall's inner surface temperature  $s_v$  and the indoor air can be described by convective heat transfer. The external part is mainly affected by solar radiation and outdoor air temperature. To simplify the model, the comprehensive outdoor temperature  $S_{out}$  can be used, equivalently incorporating solar radiation into the outdoor air temperature. The heat exchange between the wall's outer surface temperature  $s_q$  and the outdoor air can also be described by convective heat transfer, usually set as the third type of boundary condition:

$$w = g(s_c - s_q) \quad a = 0$$

$$w = g_v(s_v - s_0) \quad a = M_3 \quad (15)$$

Other supplementary boundary conditions are:

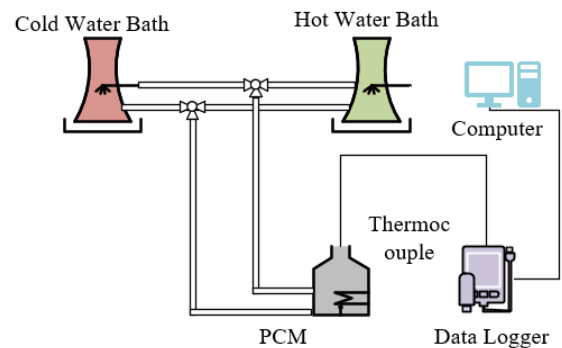
$$w = -\eta_m \frac{\partial s_m}{\partial a} \quad a = 0$$

$$s_1 = s_l \quad a = M_1$$

$$\mu_1 \frac{\partial s_1}{\partial a} = \eta_m \frac{\partial s_m}{\partial a}$$

$$s_t = s_2 \quad a = M_2$$

$$\eta_t \frac{\partial s_t}{\partial a} = \eta_2 \frac{\partial s_2}{\partial a} \quad (16)$$



**Figure 3.** Test device for heat transfer performance of green building materials

The supplementary initial conditions are  $s_1=s_2=s_r=s_m=s_0<s_o$ ,  $\pi = 0$ . Figure 3 shows the test device for the heat transfer performance of green building materials.

#### 4. EXPERIMENTAL RESULTS AND ANALYSIS

By analyzing the temperature and heat flux changes of green building materials with different thicknesses of phase change layers shown in Figure 4, we can observe the trends in temperature and heat flux changes over time at four different thicknesses: 0mm, 5mm, 10mm, and 15mm. At 0mm, the temperature reaches a peak of 31.6°C during the day and drops to a minimum of 22.8°C at night. As the thickness increases, the amplitude of temperature fluctuations decreases, with a temperature range of about 22.8°C to 29.4°C at 5mm, 22.6°C to 28.9°C at 10mm, and further reducing to 22.4°C to 28.6°C

at 15mm. The heat flux data indicate that the heat flux reaches a peak of 112 W/m<sup>2</sup> at noon at 0mm, while at 15mm, the peak decreases to 68 W/m<sup>2</sup>, showing that the buffer effect of PCM on heat flux becomes more significant with increasing thickness. The data in the figure demonstrate that the thickness of the PCM layer has a significant impact on the temperature regulation and heat flux buffering effects of green building materials. As the thickness of the phase change layer increases, the amplitude of temperature fluctuations decreases, and the heat flux peak significantly reduces, indicating that PCM plays an important buffering role in the storage and release of heat. This validates the effectiveness of PCM in improving the thermal performance of buildings, and by optimizing the thickness of the phase change layer, better temperature regulation effects can be achieved, reducing indoor temperature fluctuations and enhancing building energy efficiency.

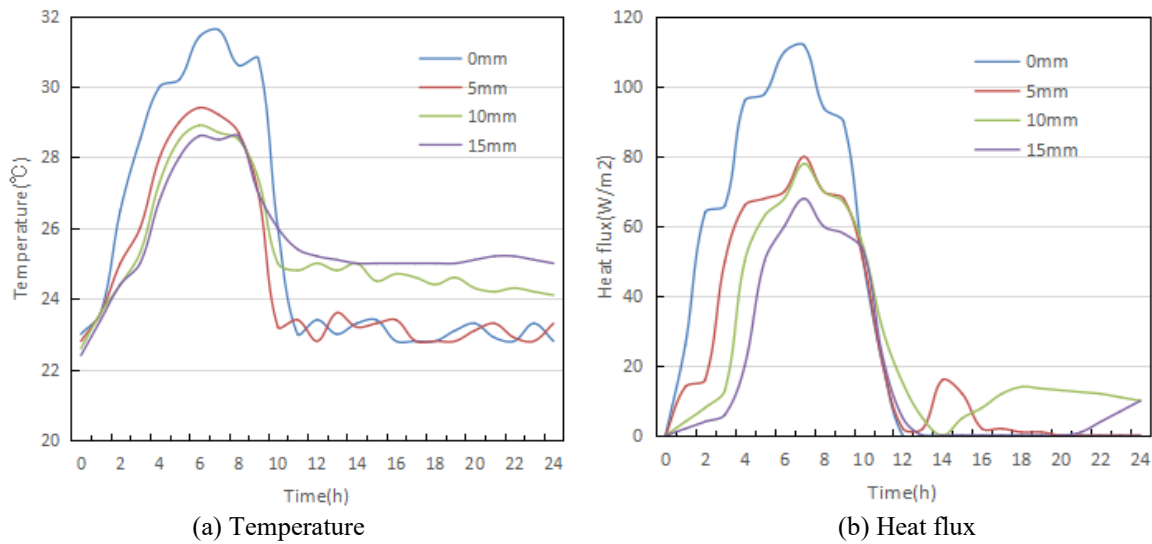


Figure 4. Temperature and heat flux changes of green building materials with different thicknesses of phase change layers

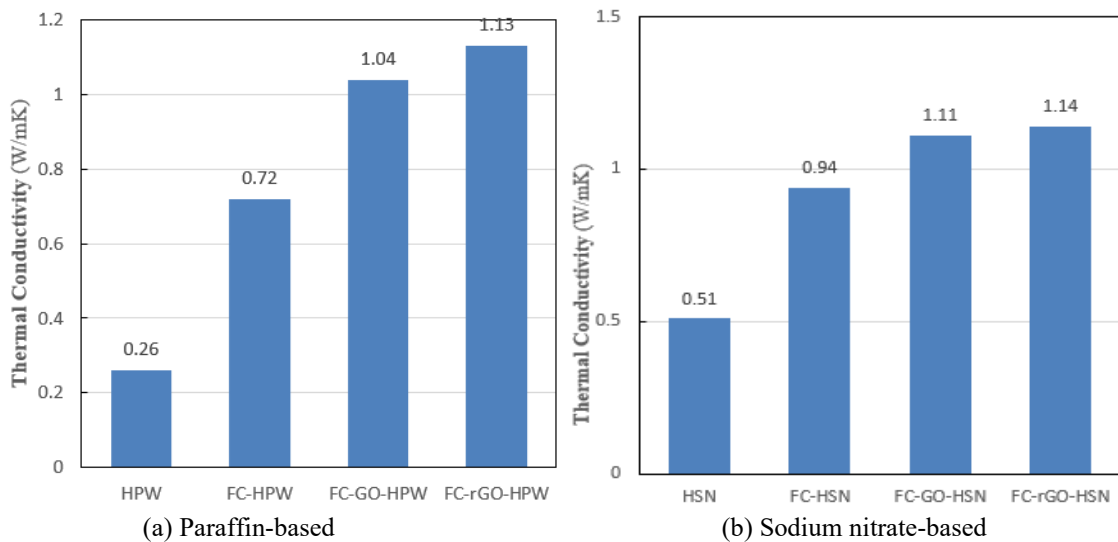
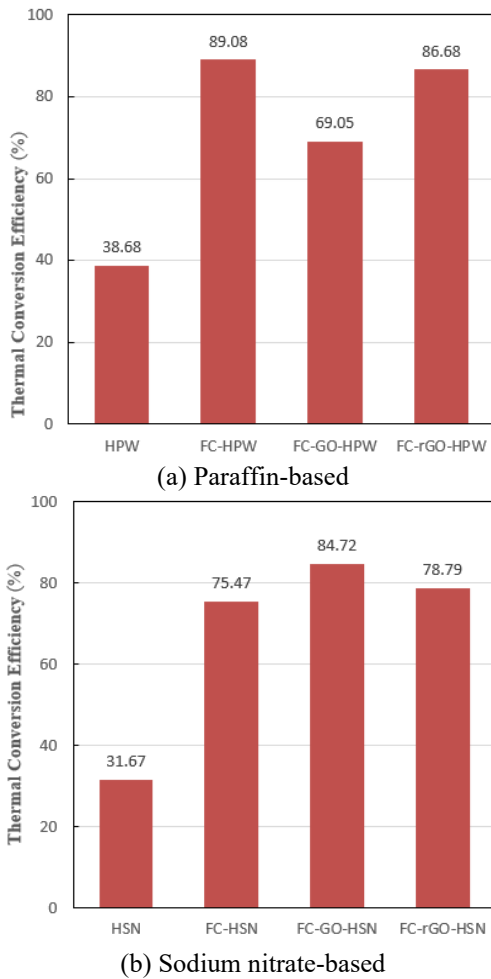


Figure 5. Thermal conductivity of paraffin-based and sodium nitrate-based green building materials

Figure 5 shows the thermal conversion efficiency of paraffin-based and sodium nitrate-based green building materials. In the figure, lipophilic paraffin and hydrophilic sodium nitrate are represented by HPW and HSN, respectively, with foam copper as the carrier represented by FC, and

graphene derivatives graphene oxide and reduced graphene oxide as surface modifiers, represented by GO and rGO, respectively. For paraffin-based green building materials, the experimental data in Figure 5 show that the thermal conductivity of unmodified HPW is 0.26W/m·K, while the

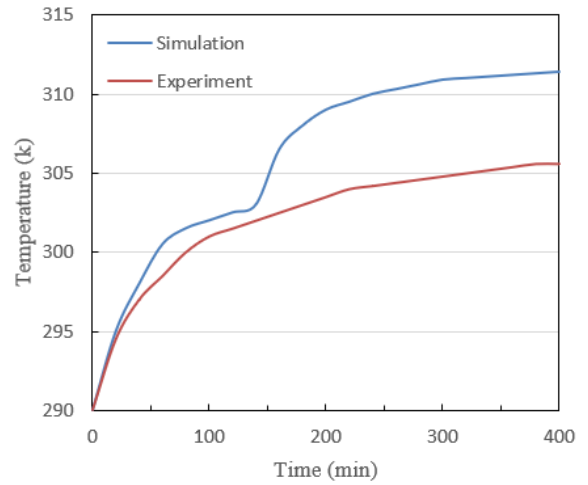
thermal conductivity of materials treated with foam copper carriers and surface modifiers FC-HPW, FC-GO-HPW, and FC-rGO-HPW increase to  $0.72\text{W/m}\cdot\text{K}$ ,  $1.04\text{W/m}\cdot\text{K}$ , and  $1.13\text{W/m}\cdot\text{K}$ , respectively. Similarly, the thermal conductivity of sodium nitrate-based materials increased from  $0.51\text{W/m}\cdot\text{K}$  for unmodified HSN to  $0.94\text{W/m}\cdot\text{K}$  for FC-HSN,  $1.11\text{W/m}\cdot\text{K}$  for FC-GO-HSN, and  $1.14\text{W/m}\cdot\text{K}$  for FC-rGO-HSN. This indicates that the use of foam copper as a carrier and the application of graphene and its derivatives as surface modifiers significantly improve the thermal conductivity of the materials. By analyzing the thermal conductivity, it can be concluded that the thermal conductivity of lipophilic paraffin and hydrophilic sodium nitrate is significantly improved after modification with foam copper and graphene derivatives. This modification strategy increases the thermal conductivity of the material, optimizing the thermal performance of the PCM, making them more efficient in storing and releasing heat.



**Figure 6.** Thermal conversion efficiency of paraffin-based and sodium nitrate-based green building materials

The experimental results in Figure 6 show that the thermal conversion efficiency of paraffin-based green building materials significantly increases when foam copper (FC) is used as the carrier, from 38.68% for the original HPW material to 89.08% for FC-HPW. When graphene oxide (GO) and reduced graphene oxide (rGO) are added as surface modifiers, the thermal conversion efficiency reaches 69.05% and 86.68%, respectively. Similarly, the thermal conversion efficiency of sodium nitrate-based materials also significantly increased from 31.67% for the original HSN material to 75.47% when

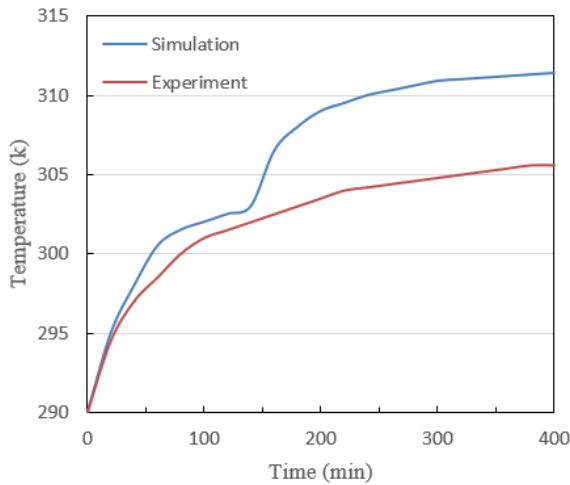
foam copper was used as the carrier. When GO and rGO were added as surface modifiers, the thermal conversion efficiency further increased to 84.72% and 78.79%. These experimental results indicate that the use of foam copper as a carrier and the addition of graphene derivatives as modifiers can significantly improve the thermal conversion efficiency of phase change thermal storage green building materials. This improvement is of great significance for optimizing the thermal performance of building materials, particularly in practical applications where it can significantly enhance building energy efficiency and reduce energy consumption.



**Figure 7.** Simulation and experimental temperatures inside the wall test block of green building materials

Figure 7 shows the comparison between the simulated and experimental temperatures inside the wall test block of green building materials at different time points. In the initial 0 to 100 minutes, the heating trends of the simulated and experimental temperatures are basically consistent, with the simulated temperature slightly higher than the experimental temperature. For example, at 100 minutes, the simulated temperature is  $300^\circ\text{C}$ , while the experimental temperature is close to  $298.7^\circ\text{C}$ . In the subsequent time period (100 minutes to 400 minutes), the difference between the simulated and experimental temperatures gradually becomes apparent. For example, at 200 minutes, the simulated temperature is  $306.5^\circ\text{C}$ , while the experimental temperature is  $299.3^\circ\text{C}$ . At 300 minutes, the simulated temperature reaches  $311.3^\circ\text{C}$ , while the experimental temperature is  $306^\circ\text{C}$ . Overall, although the trends of the heating curves are consistent, the simulated temperature is slightly higher than the experimental temperature, especially in the later period (after 300 minutes), where the simulated temperature is more noticeably higher than the experimental temperature. This may reflect the model's overestimation of some thermodynamic effects during the phase change thermal storage process. By analyzing the data of simulated and experimental temperatures, it can be concluded that despite some deviations, the thermal performance heat transfer model of phase change thermal storage green building materials constructed in this paper can better capture the trend of temperature changes during the experiment. This indicates that the model is accurate in overall trend and can effectively reflect the heat conduction characteristics of building materials during the phase change thermal storage process. The deviations may be due to differences between the model simplifications and the actual

experimental conditions, especially in the thermodynamic properties at high temperatures, where the model may not fully capture all complex physical processes.



**Figure 8.** Simulated average temperature and experimental average temperature at the top of the wall test block of green building materials

From Figure 8, it can be seen that the trends in the changes of the simulated average temperature and the experimental average temperature at the top of the wall test block of green building materials at different time points. The initial temperature is 290°C. At 100 minutes, the simulated temperature is 295°C, while the experimental temperature is slightly lower at 294.5°C. As time progresses, at 200 minutes, the simulated temperature is 298°C, and the experimental temperature is 297°C, showing a trend of uniform heating for both. At 300 minutes, the simulated temperature is 300.5°C, and the experimental temperature is 298.5°C. By 400 minutes, the simulated temperature reaches 311.4°C, while the experimental temperature is 305.6°C. Overall, the simulated temperature is generally higher than the experimental temperature, especially after 300 minutes, where the difference between the two becomes significantly larger, with the simulated temperature consistently higher than the experimental temperature, and the increase is more pronounced. By analyzing the data of the simulated average temperature and the experimental average temperature, it can be concluded that despite some deviations, the thermal performance heat transfer model of phase change thermal storage green building materials constructed in this paper can better reflect the trend of temperature changes in actual experiments. The existence of deviations may be due to the simplifications of the model in some thermodynamic effects, particularly in high-temperature regions, where the model may overestimate the rate of heat conduction. However, the overall consistency of the trend indicates that the model has a certain degree of accuracy in capturing temperature changes. This validates the effectiveness of the model and provides important theoretical and experimental evidence for optimizing the thermal performance of green building materials. The study in this paper not only proves the application prospects of phase change thermal storage materials in green buildings but also provides directions and methods for further improving the thermal performance of these materials, promoting the development of green building technology.

## 5. CONCLUSION

This paper systematically optimized the thermal performance of green building materials through a research approach based on thermodynamic principles. The research content mainly includes two parts: firstly, constructing control equations for the phase change thermal storage process of green building materials and analyzing the thermodynamic characteristics during the phase change process in detail; secondly, conducting an in-depth analysis of the heat transfer process in phase change thermal storage green building materials to explore their thermal performance in practical applications. Experimental results show that the temperature and heat flux changes of green building materials with different thicknesses of the phase change layer vary significantly over time, revealing the heat conduction characteristics of the materials during the heat storage and release process. The thermal conductivity of paraffin-based and sodium nitrate-based green building materials significantly improved after adding surface modifiers (GO and rGO), indicating the important role of material modification in optimizing thermal performance. Additionally, the changes in thermal conversion efficiency of paraffin-based and sodium nitrate-based materials under different modification conditions also show significant improvements, especially when using foam copper as the carrier, where the thermal conversion efficiency significantly increases. The simulated temperature and experimental temperature data of the interior and top of the green building material wall test block further validated the effectiveness of the control equations. Although there is some deviation between the simulation results and the experimental data, the overall trend is consistent, proving the reliability of the model in reflecting actual temperature changes.

The research in this paper provides important theoretical and experimental evidence for improving the energy efficiency of green buildings by systematically analyzing and optimizing the thermal performance of green building materials. By constructing and validating control equations for the phase change thermal storage process and conducting an in-depth study of the thermal conductivity and thermal conversion efficiency of the materials, this paper not only validated the application prospects of phase change thermal storage materials in green buildings but also provides scientific guidance for further improving the thermal performance of these materials. The research results indicate that the choice of surface modifiers and carrier materials has a significant impact on optimizing the thermal performance of materials, which is of great reference value for the future development of high-efficiency green building materials.

Despite the significant research results achieved in this paper, there are still some limitations. Firstly, the deviation between the simulation and experimental results suggests that the simplification of the model in some thermodynamic effects may need further improvement. Secondly, this research mainly focuses on the thermal performance optimization of specific materials. Future research should consider more types of PCM and their combinations to explore a wider range of application scenarios. Additionally, this paper does not comprehensively cover the long-term performance of green building materials under different environmental conditions. Future research should strengthen the study of the long-term stability and durability of materials in actual building applications. Overall, future research directions should include further optimization



of the model, expansion of material types and combinations, and research on long-term performance under different environmental conditions to comprehensively enhance the thermal performance and application prospects of green building materials.

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