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Investigation into the Self-Regulating Temperature Mechanism and Energy-Saving Performance of Phase Change Energy Storage Materials in Building Walls

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ABSTRACT

With the global energy crisis and environmental issues becoming increasingly severe, building energy efficiency has emerged as a key societal concern. Phase change energy storage materials (PCMs) are gaining prominence in the field of building energy conservation due to their ability to absorb and release large amounts of latent heat during temperature fluctuations, thereby achieving a self-regulating temperature effect. Although numerous studies have explored the properties of PCMs and their applications in buildings, most have focused on optimizing material performance and conducting tests in laboratory settings, often overlooking the complex thermal dynamics in real-world building environments. This study establishes a mathematical model of PCMs in building walls, defines the initial and boundary conditions, and conducts error analysis to systematically investigate the self-regulating temperature mechanism and the energy-saving effects of these materials. The findings of this research will provide new theoretical support and practical references for the advancement of building energy-saving technologies.

1. INTRODUCTION

With the increasing severity of the global energy crisis and environmental issues, building energy conservation has become a focal point of societal concern. The proportion of energy consumption by buildings in the total global energy consumption is increasing year by year, particularly in the areas of heating and cooling, which account for a significant portion [1-5]. To effectively reduce building energy consumption, many new materials and technologies have been introduced into the field of building energy conservation [6, 7]. Among them, PCMs have gradually attracted the attention and application of researchers due to their ability to effectively absorb and release large amounts of latent heat during temperature changes, thereby achieving a self-regulating temperature effect.

The application of PCMs in building walls can not only absorb solar radiation during the day and release it at night to regulate indoor temperature, reduce air conditioning load, and improve indoor thermal comfort, but also effectively reduce the energy consumption of buildings and decrease carbon dioxide emissions [8-10]. Therefore, studying the self-regulating temperature mechanism and energy-saving effects of PCMs in building walls is of great significance for promoting the development of building energy-saving technologies and also provides theoretical and practical basis for achieving green buildings and sustainable development [11, 12].

Although many studies have explored the properties of PCMs and their applications in buildings, most studies have mainly focused on optimizing material performance and conducting tests in laboratory environments [13-16]. Existing research often overlooks the complex thermal environment of buildings and actual usage conditions in practical applications, lacking systematic studies on the dynamic thermal performance of PCMs in building walls [17, 18]. Meanwhile, traditional experimental research methods have the drawbacks of being time-consuming, costly, and having poor repeatability, making it difficult to widely promote and apply them [19-21]. Therefore, it is necessary to use mathematical models for simulation analysis, combined with actual conditions, to systematically study the thermal performance and energy-saving effects of PCMs in building walls.

The main research content of this paper includes three parts: First, establishing a mathematical model of PCMs in building walls, revealing the self-regulating temperature mechanism through theoretical analysis and numerical simulation; Second, determining the initial and boundary conditions of the model, and conducting simulation analysis based on the actual building environment; third, performing error analysis to verify the accuracy and reliability of the model. By systematically studying the thermal performance and energy-saving effects of PCMs in building walls, this research not only enhances existing theories but also provides reference for practical engineering applications. This study will provide new ideas and methods for the development of building energy-saving technologies, with important academic and practical value.

2. SELF-REGULATING TEMPERATURE AND ENERGY-SAVING MECHANISM

The working principle of PCMs is based on their ability to absorb or release a large amount of latent heat during the phase change process. When the ambient temperature changes to the phase change temperature of the PCMs, the PCMs undergo a phase transition, such as from a solid state to a liquid state or from a liquid state to a solid state. During this process, the heat absorbed or released by the material is referred to as latent heat. When the ambient temperature rises to the melting point of the PCMs, the PCMs begin to absorb heat and melt, changing from a solid state to a liquid state. During this process, the PCMs absorb a large amount of heat, but the temperature remains nearly constant. This helps to stabilize the surrounding environment's temperature and prevent further temperature rise. When the ambient temperature drops to the freezing point of the PCMs, the PCMs release the stored heat and solidifies, changing from a liquid state to a solid state. During this process, the PCMs release a large amount of heat, but the temperature remains nearly constant. This helps to maintain the surrounding environment's temperature during cold periods, preventing a sharp temperature drop.

The application of PCMs in building walls can utilize their phase change properties to achieve temperature regulation and energy-saving effects. Specifically, PCMs are typically embedded in building materials, such as wall panels, gypsum boards, or coatings, to form an energy storage system. This system can regulate indoor temperature throughout the day by absorbing and releasing heat. During the daytime in summer, when the outside temperature is high and solar radiation is intense, buildings are prone to overheating. The PCMs embedded in the wall absorbs heat and undergoes phase change as the temperature rises, preventing a sharp increase in indoor temperature. This process not only improves living comfort but also reduces the frequency of air conditioning use and energy consumption. During nighttime in summer or cold periods in winter, when the outside temperature is low, the indoor temperature tends to drop. At this time, the PCMs release the heat stored during the day and undergoes reverse phase change, helping to maintain indoor temperature stability and reducing the use of heating equipment, thereby saving energy.

Since PCMs can absorb and release a large amount of heat during the phase change process, they can balance the temperature fluctuations inside the building, reducing the operating time and frequency of air conditioning and heating equipment. This directly lowers the building's energy consumption and improves energy efficiency. When air conditioning and heating systems operate under high loads, their efficiency usually decreases, and the wear and failure rate of the equipment increases. By regulating the temperature, PCMs enable these systems to operate under more stable loads, improving the operating efficiency of the equipment and extending its service life. Meanwhile, PCMs are passive energy-saving materials that can function without additional energy input. By integrating with the building structure, PCMs utilize its physical properties to achieve temperature regulation, further enhancing the building's passive energy-saving effect. The reasonable application of PCMs in building design can reduce reliance on traditional cooling and heating systems and optimize the building's overall energy strategy. For example, embedding PCMs in walls can reduce the wall's heat transfer coefficient, improve the wall's thermal insulation performance, and thereby increase the overall energy efficiency of the building.

3. MATHEMATICAL MODEL

The application of PCMs in building walls is a highly promising technology that can regulate indoor temperature by absorbing and releasing latent heat. However, the realization of this process requires overcoming a series of complex challenges related to phase change heat transfer. The phase change process in building walls involves heat conduction within the solid phase, heat conduction and convection within the liquid phase, and the absorption or release of latent heat during the phase change, all of which constitute a complex multi-physical field coupling system. In this process, the movement of the phase interface, also known as the Stefan problem, is a major challenge. Since the phase change temperature is not a precisely fixed value, the phase interface often manifests as a fuzzy mushy zone of solid and liquid phases, which makes solving the phase change heat transfer problem more difficult. Moreover, as the phase change process progresses, the material may undergo melting and solidification, accompanied by natural convection in the liquid phase region and the mushy characteristics of the solid-liquid two-phase region, further complicating the analysis and calculation of the heat transfer process.

The use of PCMs in building walls also requires consideration of their performance in real building environments, particularly the heat exchange with the wall structure and external environment. This involves accurately modeling the initial and boundary conditions to reflect the real temperature gradients and environmental changes. The volume change during the phase change process can also affect the physical stability and thermal performance of the wall, which must be carefully considered. Therefore, the study of the phase change heat transfer mechanism of PCMs in building walls needs to particularly focus on the dynamic behavior and coupling effects of the phase interface, as well as the impact of natural convection and structural changes on the heat transfer process. Solving these challenges not only helps to enhance the energy-saving effects of the material but also provides important theoretical support for optimizing the thermal environment of buildings.

In this paper, the enthalpy-porous medium method and the Solidification/Melting model are used to solve the melting/solidification problem of PCMs in building walls, to study their self-regulating temperature mechanism and energy-saving effects. The enthalpy-porous medium method treats the phase change enthalpy as a source term in the energy equation and solves the momentum and energy equations of the solid-liquid two phases of PCMs in the fixed grid region of the building wall, effectively solving the energy transfer problem at the solid-liquid two-phase interface of PCMs. At the same time, the mushy zone model of the solid-liquid phase interface of PCMs is regarded as a porous medium region, and the different phase fractions are represented by the liquid phase fraction, thereby handling the discontinuous changes in the physical properties of the solid-liquid two phases of PCMs. In addition, the Solidification/Melting model is used to effectively simulate the complex phase change heat transfer process, particularly the energy exchange and dynamic changes at the interface between different phases.

To study the self-regulating temperature mechanism and energy-saving effects of PCMs in building walls, this paper adopts a simplified three-dimensional model for the melting and solidification process of the energy storage unit. Since the energy storage unit in building walls has symmetry, to reduce computation time and resource consumption, only half of the structure is used to establish a physical model in the three-dimensional coordinate system. This simplified model can effectively describe the energy exchange between the solid and liquid phases, natural convection, and dynamic changes of the phase interface during the phase change process. In the solidification process, a physical model without fins is first established, and structured mesh generation is performed using ICEM-CFD software. This method accurately simulates the internal heat transfer and phase change process of the material and obtains the evolution of the phase change interface over time. To further explore the effect of fins on the phase change process, a physical model with fins is also established, and structured mesh generation is similarly performed to compare the heat transfer efficiency and energy-saving effects under different structures. For the melting process of the energy storage unit, a corresponding physical model is established, and mesh generation is performed for the computational domain. Through numerical simulation of the simplified model, the heat transfer behavior of PCMs in real building environments can be effectively studied, particularly the self-regulating temperature capability of the material during the melting and solidification processes.

To study the self-regulating temperature mechanism and energy-saving effects of PCMs in building walls, a series of assumptions were made for the three-dimensional model of the melting and solidification processes to ensure the effectiveness and convenience of numerical calculations, and to maintain consistency with the thermal storage units used in experiments. The specific assumptions are as follows:

(1) Neglecting shell thickness and contact thermal resistance: In practical applications, shell thickness and contact thermal resistance may affect heat transfer. However, to simplify the calculations, this paper assumes that these factors are neglected, focusing on the heat transfer characteristics of the phase change energy storage material itself.

(2) No heat loss in the thermal storage unit, external wall surface insulated: It is assumed that there is no heat loss in the thermal storage unit during the entire phase change process, and the external wall surface is insulated. This assumption simplifies the calculations and focuses on the heat transfer process within the phase change material, avoiding the influence of the external environment on the results.

(3) Constant inlet temperature of the heat transfer fluid: To simplify the model and ensure the stability of the calculations, it is assumed that the inlet temperature of the heat transfer fluid remains constant. This helps to clarify the impact of the heat transfer fluid on the system during the melting and solidification processes of the phase change material.

(4) Both the heat transfer fluid and liquid paraffin are incompressible fluids, satisfying the Boussinesq assumption: In the actual phase change heat transfer process, changes in fluid density may affect buoyancy and flow characteristics. This paper assumes that both the heat transfer fluid and liquid paraffin are incompressible fluids, satisfying the Boussinesq assumption, which considers density changes only in the buoyancy term, while other physical parameters remain constant. This assumption simplifies the solution of the fluid dynamics equations and improves computational efficiency.

To study the self-regulating temperature mechanism and energy-saving effects of PCMs in building walls, this paper constructs detailed steps in the three-dimensional model of the melting/solidification process, focusing on the following aspects.

For the heat transfer fluid, it is first necessary to establish the continuity equation to describe the mass conservation of the fluid. This equation ensures that the fluid's mass does not change during the heat transfer process, forming the foundation of the entire model and ensuring the correct simulation of fluid flow during heat transfer. Assuming that the density, velocity vector, specific heat, thermal conductivity, and expansion coefficient of the heat transfer fluid and paraffin are represented by ϑ_d, ϑ, i_d, i, Z_o, j, and α, respectively, the calculation formula is:

$$\frac{\partial \vartheta_d}{\partial s} + \nabla \cdot \left(\vartheta_d i_d \right) = 0 \tag{1}$$

Next, the momentum equation is established to describe the flow behavior of the fluid around the phase change energy storage material. For the heat transfer fluid, since the Rayleigh number is less than 10^9, the standard laminar flow model is used for calculations. This model is suitable for natural convection scenarios, ensuring accurate simulation of fluid flow under low-speed conditions.

$$\frac{\partial \vartheta_d i_d}{\partial s} + \nabla \cdot \left(\vartheta_d i_d i_d \right) = -\nabla O + \nabla \cdot \left(\vartheta_d \nabla i_d \right) + \left(\vartheta_d - \vartheta_0 \right) h \tag{2}$$

For the phase change material, since it undergoes phase transitions during melting and solidification, the momentum equation needs to consider the flow characteristics of the solid-liquid two-phase region and accurately describe the dynamic changes of the solid-liquid interface. The mushy zone constant is represented by X_{MU}, the reference temperature by S_{RE}, the enthalpy value at the reference temperature by g_{RE}, the total enthalpy by G, and the liquid phase fraction of the phase change material by ε. The calculation formula is:

$$\begin{aligned} &\frac{\partial \vartheta i}{\partial s} + \nabla \cdot \left(\vartheta i \right) = -\nabla o + \nabla \cdot \left(\omega \nabla i \right) \\ &+ \left(\vartheta - \vartheta_0 \right) h + \frac{\left(1-\varepsilon\right)^2}{\left(\varepsilon^3 + \gamma\right)} i X_{MU} \end{aligned} \tag{3}$$

The energy equation is the core equation describing heat transfer, used to simulate the temperature changes that PCMs undergo during the melting and solidification processes. This equation needs to account for the material's thermal conductivity and latent heat characteristics, appropriately handling the absorption and release of energy during the solid-liquid phase transition. Additionally, the energy equation needs to be closely coupled with the continuity equation and momentum equation to ensure that the mutual influence between heat transfer and fluid flow is accurately reflected.

$$\left(\vartheta - \vartheta_0 \right) h = -\vartheta_0 \alpha \left(S - S_0 \right) \tag{4}$$

$$\frac{\partial \vartheta G}{\partial s} + \nabla \cdot \left(\vartheta i G \right) = \nabla \cdot \left(j \nabla S \right) \tag{5}$$

$$G = g + \varepsilon M \tag{6}$$

$$g = g_{RE} + \int_{S_{RE}}^{S} Z_o fS \tag{7}$$

In the simulation of phase change materials, the liquid phase fraction ε is an important parameter used to describe the proportion of solid and liquid phases during the melting and solidification processes. By using the liquid phase fraction, the distribution of the material's phases at different time points can be dynamically reflected. This step represents the liquid phase fraction through a field variable, thereby simplifying the explicit solution of the solid-liquid interface and accurately simulating the evolution of the phase interface over time. The introduction of this parameter makes the simulation of the phase change process more intuitive and accurate.

$$\varepsilon = \begin{cases} 1 & S \geq S_m \\ \dfrac{S - S_t}{S_m - S_t} & S_T < S < S_m \\ 0 & S \leq S_T \end{cases} \tag{8}$$

4. INITIAL AND BOUNDARY CONDITIONS

Figure 1 shows a three-dimensional schematic diagram of the experimental platform for the melting/solidification process in building walls. When studying the three-dimensional model of the melting/solidification process of PCMs in building walls, to reveal their self-regulating temperature mechanism and energy-saving effects, this paper first sets the initial and boundary conditions for the solidification process in detail. The following are the initial and boundary conditions for the model during the solidification process. At the initial moment (s=0), the temperatures of both the phase change material and the heat transfer fluid are constants, where the temperature of the phase change material is set to S_{PC}=S_0=361K, and the temperature of the heat transfer fluid is set to S_{AI}=S_1=356K. Since S_1<S_0, this setting ensures that at the start, the temperature gradient causes the phase change material to begin transferring heat to the heat transfer fluid, thereby initiating the solidification process. Figure 2 shows a schematic diagram of the phase change layer arrangement during the experiment in this paper.

Regarding the boundary conditions, for the adiabatic surfaces in the thermal storage unit, all surfaces except the coupling surface in contact with the heat transfer fluid are set as adiabatic surfaces. This means that these surfaces do not allow heat transfer, ensuring that all heat exchange occurs only through the coupling surface in contact with the heat transfer fluid. This setting simulates the actual application scenario where the thermal storage unit is isolated from the external environment, making the computational model more realistic.

$$\left.\frac{\partial S}{\partial c}\right|_{W-A} = 0 \tag{9}$$

The coupling surface of the thermal storage unit is the only surface that exchanges heat with the heat transfer fluid. During the period when s > 0, the phase change material inside the thermal storage unit exchanges heat with the external heat transfer fluid through this coupling surface. This setting ensures that during the solidification process, the phase change material transfers heat to the heat transfer fluid through the coupling surface, gradually lowering its temperature and undergoing phase change. Accurate simulation of this process is crucial for studying the self-regulating temperature mechanism and energy-saving effects of phase change materials in building walls.

$$i_d = i = 0, S_0 = S_1, -j_{PC}\frac{\partial S_{PC}}{\partial v} = -j_{AI}\frac{\partial S_{AI}}{\partial v} \tag{10}$$

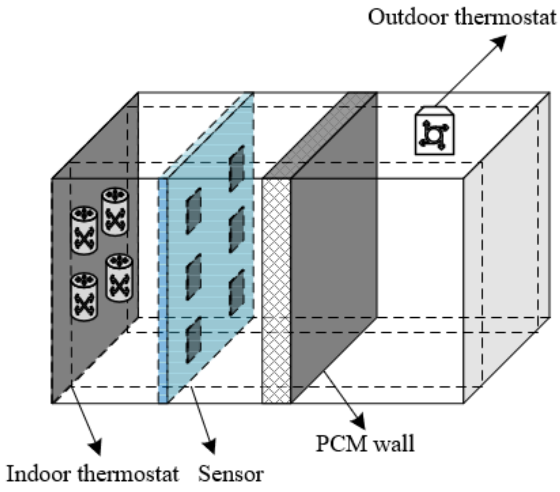

Figure 1. Three-dimensional schematic diagram of the experimental platform for the melting/solidification process in building walls

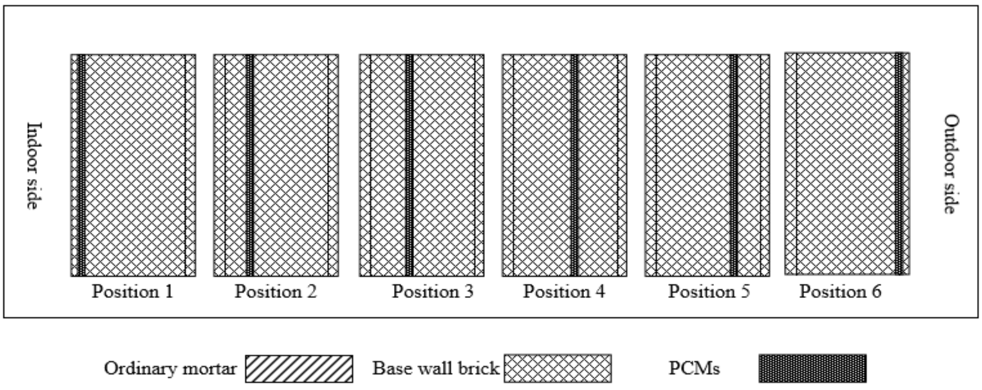

Figure 2. Schematic diagram of the phase change layer arrangement

The initial and boundary conditions during the melting process are detailed as follows. At the initial moment (s=0), the temperatures of both the phase change material and the heat transfer fluid are constants, where the temperature of the phase change material is set to $S_{PC}=S_3=301K$, and the temperature of the heat transfer fluid is set to $S_{AI}=S_4=359K$. Since S_4 is higher than S_3, this setting ensures that at the start, the temperature gradient causes the heat transfer fluid to transfer heat to the phase change material, thereby initiating the melting process.

In the thermal storage unit, all external wall surfaces except the coupling surface in contact with the heat transfer fluid are set as adiabatic surfaces. This means that these surfaces do not allow heat transfer, ensuring that all heat exchange occurs only through the coupling surface in contact with the heat transfer fluid. This setting simulates the actual application scenario where the thermal storage unit is isolated from the external environment, making the computational model more realistic.

$$\left.\frac{\partial S}{\partial z}\right|_{WA} = 0 \tag{11}$$

The coupling surface of the thermal storage unit is the only surface that exchanges heat with the phase change material. During the period when t>0, the phase change material inside the thermal storage unit exchanges heat with the heat transfer fluid inside the U-shaped tube wall through this coupling surface. This setting ensures that during the melting process, the phase change material absorbs heat from the heat transfer fluid through the coupling surface, gradually increasing its temperature and undergoing phase change. Accurate simulation of this process is crucial for studying the self-regulating temperature mechanism and energy-saving effects of phase change materials in building walls.

$$i_d = i = 0, -j_{PC}\frac{\partial S_{PC}}{\partial v} = -j_{WA}\frac{\partial S_{WA}}{\partial v} \tag{12}$$

5. MEASUREMENT ERROR

In the study of the self-regulating temperature mechanism and energy-saving effects of PCMs in building walls, accurate measurement of temperature and flow rate is crucial, as errors in these measurements directly affect the accuracy of phase change heat transfer calculations. Therefore, analyzing the errors in temperature measurement and circulating water flow rate measurement is a key step in ensuring the reliability of experimental data.

Figure 3 shows the distribution of sensors in the phase change wall. In this experiment, temperature measurement was performed using T-type thermocouples. The maximum absolute error of the T-type thermocouple measurement is 0.3℃, which means that the error in a single measurement will not exceed 0.3℃ throughout the entire temperature measurement process. Considering that the temperature measurement range in the experiment is greater than 80℃, the relatively large temperature difference helps to more accurately capture the temperature changes during the phase change process. However, the maximum relative error in temperature measurement is a critical parameter to consider, as it directly impacts the calculation of the temperature gradient, thereby affecting the accuracy of the phase change heat transfer model. Although the single measurement error is relatively small, cumulative errors over multiple measurement points and long-term monitoring may impact the experimental results. Therefore, it is necessary to consider this error range in the experimental design and to perform error correction and data smoothing during data processing to improve the accuracy of temperature measurements.

$$\frac{\sigma S}{\Delta S} \le 0.375\% \tag{13}$$

The flow rate of the circulating hot water during the energy storage process was measured using an SA10-15 electromagnetic flowmeter. The measurement accuracy of this flowmeter is 2.0%, and the range is between 50 and 250 L/h. This range covers the expected flow range in the experiment, ensuring the applicability of the flowmeter. An accuracy of 2.0% means that the maximum absolute error at the maximum range will reach 5 L/h. This level of error has a significant impact on the heat balance calculation of the entire system, as accurate flow measurement is fundamental to calculating the heat transfer amount. To reduce the impact of this error on the experimental results, the average of multiple measurements can be taken to reduce random errors, and error correction methods can be applied during data analysis to enhance the reliability and accuracy of the data. The maximum absolute error calculation formula is:

$$\sigma N = (250-50)\times 2.0\% = 4M/g \tag{14}$$

The maximum measurement error of the circulating water flow rate can be calculated by the following formula:

$$\frac{\sigma N}{\Delta N} \le 4.45\% \tag{15}$$

In addition to the aforementioned direct measurement errors, indirect measurement error analysis is also crucial. In the study of PCMs, the main measurement variables include temperature, circulating water flow rate, and time. Temperature is usually measured by thermocouples, the circulating water flow rate by electromagnetic flowmeters, and time is a relatively simple but crucial variable. Furthermore, we need to understand how these errors are propagated through calculations to the final indirect measurement results. Indirect measurement error analysis helps us identify the degree of influence each variable has on the final result. Let the indirect measurement b be a function of the direct measurements a_1, a_2, ..., a_v, with the functional expression represented by $b = d\ (a_1, a_2, ..., a_v)$. The absolute errors of the direct measurements a_1, a_2, ..., a_v are denoted by Δa_1, Δa_2, ..., Δa_v, and the absolute error of the indirect measurement b is denoted by Δb. The error transfer coefficient is represented by $_i\partial d/\partial a_u$, and the absolute error of the indirect measurement b can be calculated by the following formula:

$$\begin{aligned}\Delta b &= \sqrt{\left(\frac{\partial d}{\partial a_1}\Delta a_1\right)^2 + \left(\frac{\partial d}{\partial a_2}\Delta a_2\right)^2 + \cdots + \left(\frac{\partial d}{\partial a_v}\Delta a_v\right)^2} \\ &= \sqrt{\sum_{u=1}^{v}\left(\frac{\partial d}{\partial a_u}\Delta a_u\right)^2}\end{aligned} \tag{16}$$

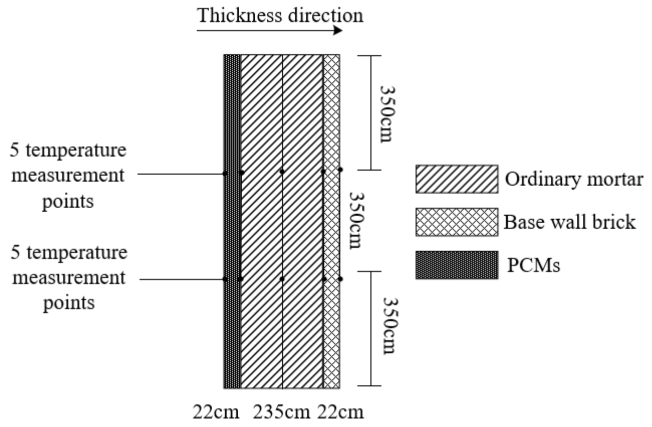

Figure 3. Distribution of sensors in the phase change wall

The relative error of *b* can be calculated by the following formula:

$$\frac{\Delta b}{b}=\sqrt{\left(\frac{\partial d}{\partial a_1}\Delta a_1\right)^2+\left(\frac{\partial d}{\partial a_2}\Delta a_2\right)^2+\cdots+\left(\frac{\partial d}{\partial a_v}\Delta a_v\right)^2} \qquad (17)$$

6. EXPERIMENTAL RESULTS AND ANALYSIS

According to the data in Figure 4, the variation in bottom surface temperature and liquid fraction over time demonstrates the temperature regulation effects of different contents of PCMs. The bottom surface temperature gradually increases over time, but the higher the PCM content, the slower the temperature rise. Specifically, when the PCM content is 20%, the bottom surface temperature is only 40℃ at 1000 minutes, significantly lower than the 55.5℃ observed with 0% PCM content. Additionally, the liquid fraction increases with time, and the higher the PCM content, the faster the liquid fraction rises and reaches equilibrium in a shorter time. For example, the liquid fraction of 20% PCM approaches 0.93 at around 400 minutes, while 5% PCM reaches a similar value at around 600 minutes. Compared to low PCM content, higher PCM content exhibits stronger heat absorption and storage capabilities.

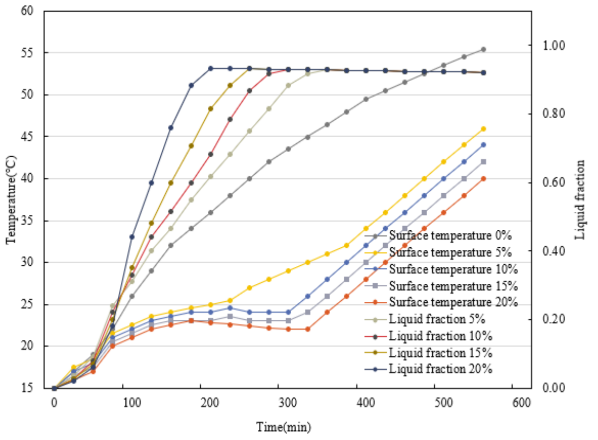

Figure 4. Variation trends of the bottom surface temperature and liquid fraction of PCMs in building walls over time

According to the data in Figure 5, as time increases, the top surface temperature rises under different PCM contents, but the higher the content, the slower the temperature rise. For example, the surface temperature of 0% PCM reaches 70℃ at 500 minutes, while 20% PCM only reaches 45℃. This indicates that the higher the PCM content, the more significant its temperature regulation effect. The liquid fraction data further supports this point, showing the heat absorption during the phase change process with different PCM contents. The liquid fraction of 5% PCM is 0.92 at 500 minutes, while 20% PCM reaches 0.93 at 400 minutes and stabilizes. This shows that high PCM content absorbs more heat and completes the phase change in a shorter time, thereby maintaining a stable surface temperature over a longer period.

The experimental results clearly show that increasing the PCM content can significantly reduce the rate of temperature rise on the surface of building walls, thereby achieving effective temperature regulation. This is because PCMs absorb a large amount of latent heat during the phase change process, maintaining a stable temperature near the phase change temperature and reducing heat transfer to the interior. The variation trend of the liquid fraction shows that PCMs continuously absorb heat during the phase change process and gradually reaches a saturated state, indicating that PCMs can balance temperature changes over a long period, thereby reducing the need for air conditioning and heating systems. Through this self-regulating temperature mechanism, PCMs can significantly save energy in building walls, optimize energy use, and improve overall building energy efficiency.

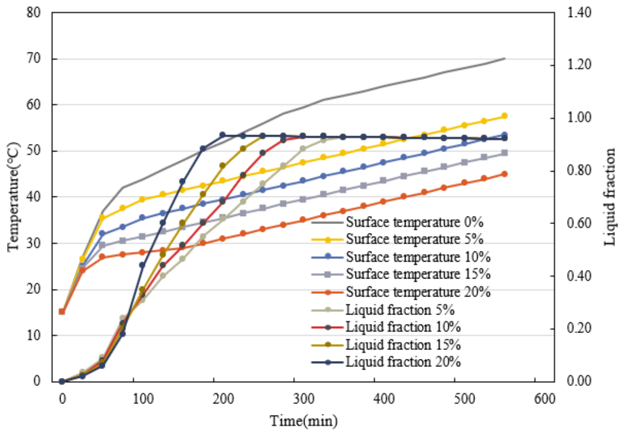

Figure 5. Variation trends of the top surface temperature and liquid fraction of PCMs in building walls over time

According to the data in Table 1, different types of building walls exhibit different temperature regulation effects in temperature simulation calculations. The external wall surface temperature of ordinary walls fluctuates between a maximum of 42.6℃ and a minimum of 26.5℃, while the internal wall surface temperature fluctuates between a maximum of 27.8℃ and a minimum of 26.8℃. In contrast, the external wall surface temperature of the exterior PCM wall fluctuates between a maximum of 42.4℃ and a minimum of 26.3℃, and the internal wall surface temperature fluctuates between a maximum of 27.3℃ and a minimum of 26.5℃. The external wall surface temperature of the sandwich PCM wall fluctuates between a maximum of 42.2℃ and a minimum of 26.2℃, and the internal wall surface temperature fluctuates between a maximum of 27.5℃ and a minimum of 27.2℃. The external wall surface temperature of the interior PCM wall fluctuates between a maximum of 42.3℃ and a minimum of 27.4℃, and the internal wall surface temperature fluctuates between a maximum of 27.2℃ and a minimum of 27.3℃. These data indicate that PCMs can significantly reduce temperature fluctuations on the internal and external surfaces of walls, with the temperature regulation effect of the sandwich PCM wall being the most significant.

According to the data in Table 2, different types of building walls show significant differences in temperature attenuation factors and peak delay times. The external wall surface amplitude of the ordinary wall is 15.4°C, the internal wall surface amplitude is 1.12°C, the attenuation factor is 14.2, and the delay time is 9.4 hours. In contrast, the external wall surface amplitude of the exterior PCM wall is 15.2°C, the internal wall surface amplitude decreases to 0.65°C, the attenuation factor increases to 23.2, and the delay time extends to 11.4 hours, with an attenuation increase of 68.2% and a delay increase of 2 hours. The external wall surface amplitude of the sandwich PCM wall is 15.3°C, the internal wall surface amplitude further decreases to 0.58°C, the attenuation factor reaches 25.6, and the delay time is also 11.4 hours, with an attenuation increase of 86.5% and a delay increase of 3 hours. The external wall surface amplitude of the interior PCM wall is 15.6°C, and the internal wall surface amplitude is the lowest at only 0.44°C, with the highest attenuation factor of 34.2 and the longest delay time of 12.25 hours, with an attenuation increase of 144.2% and a delay increase of 2.68 hours. These data indicate that PCMs can significantly increase the temperature attenuation factor and peak delay time of walls, with the effect being most significant in interior PCM walls.

According to the data in Table 3, there are significant differences in the heat storage coefficient of the external wall surface among different types of building walls. The heat flux density amplitude of the ordinary wall is 75.26 W/m^2, the temperature amplitude is 7.66°C, and the heat storage coefficient is 9.85 $W/(m^2\cdot K)$. The heat flux density amplitude of the exterior PCM wall is 76.24 W/m^2, the temperature amplitude decreases to 6.45°C, and the heat storage coefficient increases to 11.23 $W/(m^2\cdot K)$, which is an increase of 20.1% compared to the ordinary wall. The heat flux density amplitude of the sandwich PCM wall is 75.36 W/m^2, the temperature amplitude is 7.85°C, and the heat storage coefficient is 9.87 $W/(m^2\cdot K)$, with an increase of -0.2%. The heat flux density amplitude of the interior PCM wall is 75.85 W/m^2, the temperature amplitude is 7.69°C, and the heat storage coefficient is 9.65 $W/(m^2\cdot K)$, with an increase of -0.1%. These data indicate that the exterior PCM wall significantly improves the heat storage coefficient, while the heat storage coefficients of the sandwich and interior PCM walls are not much different from that of the ordinary wall.

The experimental results show that the exterior PCM wall performs best in improving the heat storage performance of walls, mainly due to the effective absorption and release of heat by the phase change energy storage material at the external wall surface, significantly reducing the temperature amplitude and thereby increasing the heat storage coefficient. The exterior PCM wall, through the thermal capacity effect of the phase change material, absorbs solar radiation heat during the day and releases heat at night, thereby significantly increasing the heat storage coefficient by 20.1% compared to the ordinary wall. The sandwich and interior PCM walls, due to the deeper position of the phase change material and the longer heat transfer path, do not perform as well in heat storage as the exterior PCM wall but still help to mitigate temperature fluctuations to some extent. This mechanism suggests that the application of PCMs in building walls can effectively improve heat storage performance, thereby enhancing building energy efficiency, reducing energy consumption, and achieving sustainable building design. By reasonably configuring the position and content of PCMs, the thermal performance of building walls is optimized, which helps improve indoor comfort and energy utilization efficiency.

According to the data in Table 4, the application of different thicknesses of phase change energy storage material layers in building walls shows different peak-valley heat flux density attenuation rates. The 5 mm thickness phase change layer, at suitable phase change temperatures of 26°C, 28°C, and 30°C, has a maximum peak-valley heat flux density attenuation rate of 75.6%. The attenuation rate increases to 87.6% for the 10 mm thickness phase change layer at suitable phase change temperatures of 28°C, 30°C, and 32°C. The 15 mm thickness phase change layer, at suitable phase change temperatures of 26°C, 28°C, and 30°C, further increases the attenuation rate to 92.3%. The 20 mm thickness phase change layer, at suitable phase change temperatures of 28°C, 30°C, and 32°C, achieves an attenuation rate of 95.4%. The 25 mm thickness phase change layer, at the same suitable temperatures, has an attenuation rate of 96.3%. The 30 mm thickness phase change layer, at suitable phase change temperatures of 28°C, 30°C, and 32°C, has the highest attenuation rate of 97.5%. These data indicate that as the thickness of the phase change layer increases, the peak-valley heat flux density attenuation rate significantly improves.

Table 1. Summary of temperature simulation calculation results for different types of building walls

Wall Type	Comprehensive Air Temperature		External Wall Surface Temperature		Internal Wall Surface Temperature	
	Max	Min	Max	Min	Max	Min
Ordinary wall	42.3°C	25.1°C	42.6°C	26.5°C	27.8°C	26.8°C
Exterior PCM wall			42.4°C	26.3°C	27.3°C	26.5°C
Sandwich PCM wall			42.2°C	26.2°C	27.5°C	27.2°C
Interior PCM wall			42.3°C	27.4°C	27.2°C	27.3°C

Table 2. Summary of temperature attenuation factors and peak delay time calculation results for different types of building walls

Wall Type	External Wall Surface Amplitude (°C)	Internal Wall Surface Amplitude (°C)	Attenuation Factor	Delay Time	Attenuation Increase	Delay Increase
Ordinary wall	15.4	1.12	14.2	9.4h	-	-
Exterior PCM wall	15.2	0.65	23.2	11.4h	68.2%	2h
Sandwich PCM wall	15.3	0.58	25.6	11.4h	86.5%	3h
Interior PCM wall	15.6	0.44	34.2	12.25h	144.2%	2.68h

Table 3. Summary of heat storage coefficient calculation results for the external wall surface of different types of building walls

Wall Type	External Wall Heat Flux Density Amplitude (W/m²)	External Wall Surface Temperature Amplitude (℃)	Heat Storage Coefficient W/(m²·K)	Increase
Ordinary wall	75.26	7.66	9.85	/
Exterior PCM wall	76.24	6.45	11.23	20.1%
Sandwich PCM wall	75.36	7.85	9.87	-0.2%
Interior PCM wall	75.85	7.69	9.65	-0.1%

Table 4. Summary of optimal combinations of phase change layer thickness and building walls for PCMs

Phase Change Layer Thickness	Suitable Phase Change Temperature	Maximum Peak-Valley Heat Flux Density Attenuation Rate
5 mm	26℃, 28℃, 30℃	75.6%
10 mm	28℃, 30℃, 32℃	87.6%
15 mm	26℃, 28℃, 30℃	92.3%
20 mm	28℃, 30℃, 32℃	95.4%
25 mm	28℃, 30℃, 32℃	96.3%
30 mm	28℃, 30℃, 32℃	97.5%

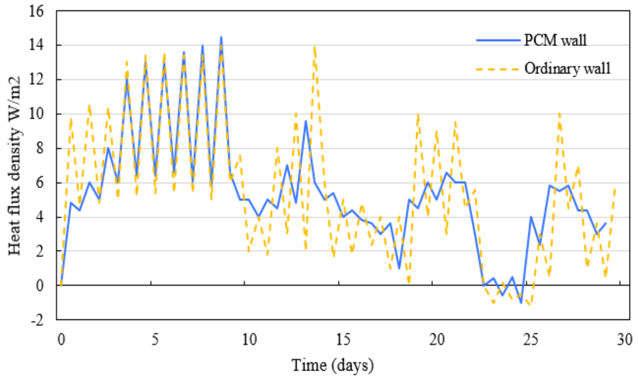

Figure 6. Comparison of the change in heat flux density on the inner wall surface of building walls during summer

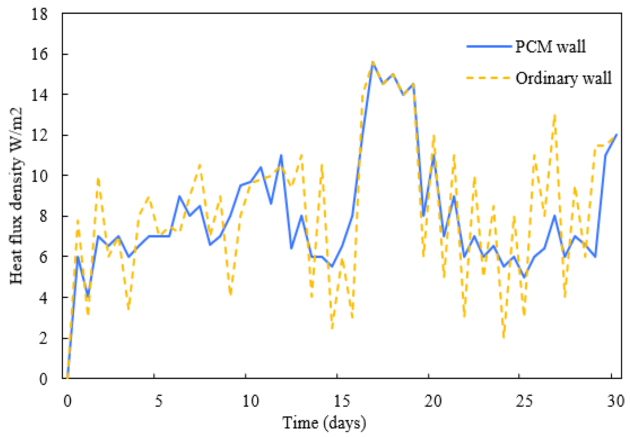

Figure 7. Comparison of the change in heat flux density on the inner wall surface of building walls during winter

According to the data shown in Figure 6, the change in heat flux density on the inner wall surface of building walls during summer was compared between the PCM wall and the ordinary wall over a period of 25 days. The heat flux density on the inner wall surface of the PCM wall was relatively low in the first few days, for example, 4.8 W/m² on the 5th day, while the ordinary wall had a heat flux density as high as 9.8 W/m² on the same day. Over time, the heat flux density fluctuations of the PCM wall remained small, generally between 4-6 W/m², for example, 4.4 W/m² on the 10th day, 6 W/m² on the 15th day, and 5 W/m² on the 20th day. In contrast, the heat flux density fluctuations of the ordinary wall were larger, with data ranging between 2-14 W/m², for example, 4.6 W/m² on the 10th day, 10.6 W/m² on the 15th day, and 4.8 W/m² on the 20th day. The PCM wall exhibited relatively stable heat flux density throughout the period, while the ordinary wall showed more pronounced fluctuations in heat flux density.

According to the data shown in Figure 7, the change in heat flux density on the inner wall surface of building walls during winter was compared between the PCM wall and the ordinary wall over a period of 30 days. The heat flux density on the inner wall surface of the PCM wall was relatively stable in the first few days, for example, 6 W/m² on the 5th day, while the ordinary wall had a heat flux density of 7.8 W/m² on the same day. Over time, the heat flux density fluctuations of the PCM wall remained small, mainly between 5-15.6 W/m², for example, 4 W/m² on the 10th day, 7 W/m² on the 15th day, and 8.6 W/m² on the 20th day. In contrast, the heat flux density fluctuations of the ordinary wall were larger, with data ranging between 2-15.6 W/m², for example, 3 W/m² on the 10th day, 10 W/m² on the 15th day, and 10 W/m² on the 20th day. The PCM wall exhibited relatively stable heat flux density throughout the period, while the ordinary wall showed more pronounced fluctuations in heat flux density.

The experimental results indicate that the application of PCMs in building walls during winter significantly reduced the fluctuations in heat flux density on the inner wall surface, thereby effectively stabilizing the indoor temperature. This is due to the phase change material's ability to absorb and release large amounts of heat during the phase change process, maintaining a relatively stable heat flux density on the inner wall surface through the self-regulating temperature mechanism. The PCM wall exhibited smaller fluctuations in heat flux density throughout the experiment, reflecting its better thermal stability, while the ordinary wall showed larger fluctuations, indicating poorer thermal stability. The phase change material, by absorbing heat during the day and gradually releasing it at night, reduced the sudden rise and fall of indoor temperature, enhancing the thermal comfort of the building. Furthermore, the application of phase change materials can reduce the frequency and load of heating systems, thus achieving energy-saving effects. Overall, the application of PCMs in building walls not only improves the thermal comfort of buildings but also significantly increases energy efficiency, offering broad promotion value.

7. CONCLUSION

This paper established a mathematical model of PCMs in building walls, combined with theoretical analysis and numerical simulation, to reveal the self-regulating temperature mechanism of PCMs. The experimental results include the trends of temperature and liquid fraction changes on the bottom and top surfaces of PCMs in building walls at different times, as well as the temperature simulation calculation results for different types of building walls. Through the summary analysis of the optimal combination of phase change layer thickness and suitable phase change temperature, it was found that PCMs can significantly reduce the fluctuations in heat flux density on the inner wall surface of building walls, thereby effectively improving the stability and comfort of indoor temperature. In addition, the comparative analysis of the heat flux density on the inner wall surface of building walls during summer and winter further verified the significant energy-saving effects of PCMs. This study reveals that the application of PCMs in building walls can significantly regulate indoor temperature by absorbing and releasing heat, reducing temperature fluctuations, improving thermal comfort, and reducing energy consumption. The experimental data and simulation results provide experimental evidence supporting the potential application value of phase change materials in energy-saving building design. The application of PCMs can reduce the load on air conditioning and heating systems, thereby reducing energy consumption and achieving the goal of energy conservation and environmental protection.

Although this study revealed the significant effects of PCMs in building walls, there are certain limitations in the research. Firstly, the experimental conditions and simulation environment may not fully reflect the complexity and diversity of actual building environments. In addition, this study focused primarily on phase change materials with specific thicknesses and temperature ranges, and did not comprehensively cover the diversity of material properties and application conditions. Future research can further explore the effects of different phase change materials and broader application conditions. Future studies should further expand the scope of research on PCMs, including different types and compositions of phase change materials, as well as their application effects under different climate conditions and building types. Additionally, the thickness and phase change temperature of phase change materials can be further optimized to find more efficient and economical material combinations. Through long-term testing in actual building environments, the long-term stability and energy-saving effects of PCMs in different application scenarios can be verified. Furthermore, research should focus on how to combine intelligent control systems to further enhance the temperature regulation effect of phase change materials, achieving more efficient building energy-saving goals.

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