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Design and Experimental Study of Thermally Self-Regulating Building Envelopes Based on Energy-Storage Phase Change Materials

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ABSTRACT

With the intensifying global energy crisis and climate change, enhancing energy efficiency and indoor thermal comfort has become a key objective in modern building design. Traditional building envelope systems often lack sufficient thermal insulation, making them ineffective at mitigating indoor temperature fluctuations and resulting in increased energy consumption. Thermally self-regulating building envelopes designed with phase change materials (PCMs) offer a promising solution. By utilizing the latent heat exchange during the phase transition process, these materials can buffer indoor temperature variations, thereby reducing energy demand and improving occupant comfort. Thus, the study of PCM-based self-regulating building envelopes holds significant theoretical and practical value. Although extensive research has been conducted on the application of PCMs in buildings, existing approaches and models often involve simplifications that overlook the dynamic nature of the building's thermal environment, limiting their practical effectiveness. Some studies have established the thermal physical models of materials but fail to fully incorporate the thermal balance equations of the wall surface, indoor air, and the overall building system, compromising the accuracy of heat flow predictions. This paper focuses on the design of thermally self-regulating building envelopes based on PCMs and proposes two main research directions: (1) establishing physical and mathematical models for self-regulating envelope structures, and (2) formulating comprehensive thermal balance equations for the wall surface, indoor air, and the building as a whole. The findings aim to provide new theoretical support for energy-efficient building design and promote the broader application of PCMs in the construction industry.

1. INTRODUCTION

With the increasingly severe global climate change and energy crisis, building energy conservation has become an important topic in modern building design [1, 2]. Especially in terms of temperature regulation, how to effectively reduce building energy consumption and improve comfort [3-5] has become one of the hotspots in the field of building research. The thermal insulation performance of traditional building envelope structures can no longer meet the growing energy demand and comfort requirements [6, 7]. To cope with this challenge, thermally self-regulating building envelope structures based on PCMs have emerged [8, 9]. PCMs can absorb or release heat during temperature fluctuations, effectively regulating indoor temperature, reducing the energy consumption of air conditioning and heating systems, and thus improving the energy utilization efficiency of buildings.

Thermally self-regulating building envelope structures based on PCMs can not only effectively improve the thermal environment of buildings but also have important significance in energy conservation and emission reduction, as well as in improving comfort. With the increasing global demand for building energy conservation and low-carbon environmental protection, exploring envelope structure design based on PCMs has become an important research direction. As a carrier for thermal energy storage, PCMs can undergo physical phase changes within a certain temperature range [10-13], thereby alleviating indoor temperature fluctuations to a certain extent and ensuring that indoor temperature remains within a comfortable range. Therefore, the research on thermally self-regulating building envelope structures based on PCMs has important theoretical significance and application value.

However, although many studies have been conducted on the application of PCMs in buildings, there are still some deficiencies in existing research methods and models [14, 15]. On the one hand, many studies only consider the thermal physical properties of materials and ignore the complexity and dynamic changes of the overall thermal environment of buildings, resulting in oversimplified models that lack practical guidance value [16, 17]. On the other hand, although some studies have established heat transfer models, they have not fully considered the thermal balance equations of the wall surface, indoor air, and the overall building envelope structure, leading to inaccurate predictions of heat flow and limited applicability of the models [18, 19]. Therefore, the limitations of existing research methods in practical applications are still significant and need further improvement.

In response to these problems, this paper will design thermally self-regulating building envelope structures based on PCMs, and carry out research on physical and mathematical models. The main research contents of this paper include two aspects: firstly, to establish physical and mathematical models of thermally self-regulating building envelope structures based on PCMs; secondly, to establish thermal balance equations for the wall surface, indoor air, and the overall building envelope structure. These studies will provide theoretical support for more accurate temperature control design, promote the practical application of PCMs in buildings, and provide new ideas and methods for optimizing building energy efficiency.

2. PCM-BASED THERMAL ENVELOPE MODELING

The core advantage of PCMs lies in their ability to absorb or release a large amount of heat through physical phase change processes during temperature fluctuations, thereby balancing indoor temperature changes. Therefore, correctly establishing the physical and mathematical models of thermally self-regulating envelope structures based on PCMs is the key. The physical model can accurately describe the phase change characteristics of materials at different temperatures, the variation of thermal conductivity, and their influence on heat conduction, convection, and other heat transfer processes, thus helping researchers predict the thermal behavior of envelope structures under different environmental conditions. Through the establishment of a physical model, the energy storage and release processes of PCMs in envelope structures can be systematically understood and simulated, providing a theoretical basis for subsequent experimental research and practical applications. The establishment of a mathematical model is a further quantification and analysis of the physical model, which can provide more practical computational tools in engineering practice. Thermally self-regulating envelope structures based on PCMs will face complex heat transfer problems in application, especially the thermal balance among wall surface, indoor air, and the overall building, which is difficult to solve solely through intuitive experience. Through mathematical models, the heat transfer process can be expressed in the form of equations, thereby quantitatively analyzing the thermal performance of the envelope structure.

2.1 Physical model

The core feature of the thermally self-regulating building envelope structure studied in this paper is the application of PCMs. This type of material can effectively absorb and release heat through the phase change process, thereby regulating the temperature fluctuations within the envelope structure and achieving the effect of energy efficiency regulation. In order to construct an accurate physical model, it is first necessary to consider the unique properties of PCMs, such as phase change temperature, latent heat, and thermal conductivity, and combine them with the complex dynamic effects in the heat conduction process.

In the construction of the physical model, the heat conduction process must first be simplified. Since the heat transfer of thermally self-regulating envelope structures based on PCMs in practical applications is a three-dimensional unsteady process, directly solving this complex problem is very difficult. Therefore, by reasonably simplifying the heat transfer process, the problem becomes more solvable. Considering the unsteady characteristics of the phase change process in most practical cases, the problem is first simplified by assuming that heat transfer in the envelope structure occurs only in the one-dimensional direction along its thickness, ignoring excess factors such as surface heat convection. In this way, the problem can be transformed from a complex three-dimensional heat conduction problem into a more manageable one-dimensional heat conduction problem. Figure 1 shows a schematic diagram of the heat transfer principle of the thermally self-regulating building envelope structure based on PCMs.

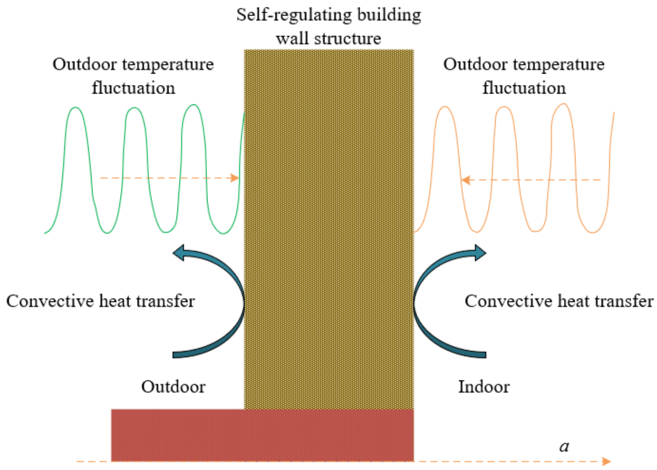

Figure 1. Schematic diagram of heat transfer principle of thermally self-regulating building envelope structure based on PCMs

Table 1. Thermal physical parameters of PCMs in thermally self-regulating building envelope structure

Parameters	PCMs
Phase Change Temperature	22,25,28
Latent Heat	90,110,130
Phase Change Range	1
Specific Heat	2
Thermal Conductivity	0.1,0.2,0.5,1
Density	830
Envelope Thickness	15,20,25,30

Secondly, regarding the physical properties of the thermally self-regulating building envelope structure based on PCMs, it is necessary to clarify how it exhibits thermal performance different from traditional building materials in the heat transfer process. PCMs have obvious nonlinear characteristics and exhibit latent heat properties during the absorption and release of heat. This makes the phase change process not only a simple heat conduction process but also a complex process involving phase change temperature and latent heat absorption/release. In this context, when establishing the physical model, these factors must be considered for their profound impact on the heat transfer process. That is to say, the thermal conductivity of PCMs changes significantly near the phase change temperature, and the latent heat during the phase change process must also be accurately reflected in the model in order to simulate the temperature response of the envelope structure under different thermal loads. Table 1 shows the thermal physical parameters of PCMs in the thermally self-regulating building envelope structure.

Usually, the solution of transient heat transfer problems relies on the numerical solution of the heat conduction equation, especially when considering PCMs. The heat conduction equation needs to incorporate the thermal physical parameters related to phase change. By introducing parameters such as phase change temperature, latent heat, and thermal conductivity of the PCM into the heat conduction equation, it is possible to accurately describe the temperature variation of the envelope structure at different time points and under different environmental conditions. At this point, the fluctuation of wall surface temperature as a boundary condition is of great significance to the calculation of the entire heat conduction process. Furthermore, through the method combining numerical simulation and experimental verification, the influence of different parameters on the heat storage performance of the envelope structure can be deeply analyzed. For example, the variation of phase change temperature directly affects the thermal response speed of the envelope structure, while the magnitude of latent heat determines the energy conversion efficiency during the heat storage and release process. Thermal conductivity and envelope structure thickness affect the speed and uniformity of heat propagation within the envelope structure. The variation of these parameters will directly affect the thermal management effect and energy-saving performance of the envelope structure.

2.2 Mathematical model

The thermal characteristics of PCMs are manifested in the absorption or release of a large amount of latent heat within the phase change temperature range, resulting in insignificant temperature changes. This makes traditional heat conduction models unable to effectively describe the thermal behavior of PCMs. To solve this problem, this paper chooses to apply the apparent heat capacity method to the solution of phase change problems. The main advantage of this method is that it treats latent heat as a large apparent heat capacity within the phase change temperature range, reconstructs the linear partition function of heat capacity, and transforms the complex energy conservation equation into a nonlinear heat conduction equation that is easy to solve through this function. This method not only simplifies the calculation process but also effectively solves the evolution problem of temperature and phase change interface during the phase change process, thereby providing reliable numerical support for predicting the thermal performance of the thermally self-regulating envelope structure.

The unique characteristics of PCMs enable them to absorb or release heat through physical phase change processes during temperature changes. This unsteady heat transfer process causes the temperature distribution of the envelope structure to change over time and space. To solve this problem, the construction of the heat transfer control equation needs to consider the latent heat effect of PCMs and the nonlinear characteristics in the heat conduction process. The heat transfer behavior based on PCMs can be described by combining the energy conservation equation with the phase change interface conditions of the PCM, thus deriving the unsteady heat transfer equation describing the heat conduction process of the envelope structure. This equation introduces physical parameters such as heat capacity, thermal conductivity, and phase change temperature, and can accurately reflect the temperature variation of the envelope structure under different thermal loads. Specifically, suppose latent heat is denoted by G_o, density by σ, time by s, temperature by S, phase change range by ΔS, the coordinate in the direction of the plate thickness by a, equivalent thermal conductivity, solid phase thermal conductivity, and liquid phase thermal conductivity by j_r, j_t, and j_m respectively, phase change temperature by S_l, equivalent specific heat, solid phase specific heat, and liquid phase specific heat by z_r, z_t, and z_m respectively. The following expression gives the unsteady heat transfer control equation of the thermally self-regulating building envelope structure based on PCMs:

$$\sigma z_r \frac{\partial S}{\partial s} = j_r \frac{\partial^2 S}{\partial a^2} \tag{1}$$

The equivalent specific heat and thermal conductivity of PCMs are functions of temperature and are respectively expressed as:

$$z_r = \begin{cases} z_t, S < (S_l - \Delta S) \\ \dfrac{G_o}{2\Delta S} + \dfrac{z_t + z_m}{2}, (S_l - \Delta S) \le S \le (S_l + \Delta S) \\ z_m, S > (S_l + \Delta S) \end{cases} \tag{2}$$

$$j_r = \begin{cases} j_t, S < (S_l - \Delta S) \\ j_t + \dfrac{j_m - j_t}{2\Delta S}\left[S - (S_l - \Delta S)\right], \\ (S_l - \Delta S) \le S \le (S_l + \Delta S) \\ j_m, S > (S_l + \Delta S) \end{cases} \tag{3}$$

Assuming the convective heat transfer coefficients on the outer and inner surfaces are represented by g_{OUT} and g_{IN}, the outdoor and indoor temperatures are represented by S_{OUT} and S_{IN}, and the surface temperatures of the exterior and interior sides of the enclosure structure are represented by $S_{q,OUT}$ and $S_{q,IN}$ respectively. The initial temperature is represented by S_0. The initial conditions are:

$$S(a,s)|_{s=0} = S_0 \tag{4}$$

$$g_{OUT}\left(S_{OUT} - S_{q,OUT}\right) = -j \frac{\partial S}{\partial a}|_{a=0} \tag{5}$$

$$g_{IN}\left(S_{IN} - S_{q,IN}\right) = j_r \frac{\partial S}{\partial a}|_{a=M} \tag{6}$$

2.3 Boundary conditions

For enclosure structures based on PCMs, the temperature variations on the outer and inner boundaries are affected by fluctuations in outdoor and indoor temperatures. The characteristics of PCMs endow them with a unique way of responding to such temperature fluctuations. In the model, it is assumed that the outer side of the enclosure structure is subjected to a sine wave temperature variation with a 24-hour period, an initial phase of 20℃, and an amplitude of 20℃, simulating the temperature variation of the external environment. A notable characteristic of PCMs is their capacity to absorb or release a large amount of heat within the phase change temperature range. Therefore, when setting the boundary condition for the outer side, the periodic fluctuation of the wall surface temperature must be considered, and it is assumed that this external temperature wave is transmitted to the inner surface through the thermal resistance effect of the enclosure structure.

The temperature condition on the inner side boundary is affected by the fluctuation of indoor air temperature. It is assumed that the indoor temperature is a sine wave with a 24-hour period, an initial phase of 15°C, and an amplitude of 10°C. This assumption reflects that the amplitude of indoor temperature variation is smaller and the initial phase is different compared to the external environment. For enclosure structures based on PCMs, there is an instantaneous temperature difference between the inner and outer boundaries. Due to this temperature difference, convective heat transfer will occur. This heat exchange process influences the temperature change of the wall's inner surface, leading to attenuation and delay of the temperature wave. In order to accurately describe the thermal response of the enclosure structure, the inner temperature wave set in the boundary conditions considers the attenuation effect of the temperature wave and assumes that the heat exchange between the inner surface and the indoor air is realized through convection. In addition, thermal physical parameters of the enclosure structure itself, such as phase change temperature, specific heat, and thermal conductivity, will affect the internal heat conduction and phase change process of the enclosure structure under the action of these boundary conditions, and thus further affect the overall temperature distribution and thermal performance.

3. ENVELOPE THERMAL BALANCE EQUATIONS

The unique thermal properties of PCMs, such as their significant absorption or release of heat during the phase change process, provide the enclosure structure with a strong adjustment ability in response to external temperature changes. In order to accurately simulate and predict the thermal performance of this self-adjusting enclosure structure, it is necessary to take into account the heat transfer processes of the wall surface, indoor air, and the entire building, and establish the corresponding thermal balance equations. The heat exchange process between the wall surface and indoor air includes not only thermal conduction, but also radiative and convective heat transfer. The interior of the enclosure structure is affected by the heat absorption and release of the PCM. Therefore, the establishment of thermal balance equations helps to comprehensively reflect these heat exchange and energy storage processes, reveal the thermal response characteristics of the enclosure structure under different environmental conditions, and thus provide theoretical support for the design and optimization of self-adjusting enclosure structures.

3.1 Heat balance equation

The inner surface of the wall is affected by various heat transfer mechanisms, including heat conduction, direct radiation, mutual radiation between inner wall surfaces, and convective heat transfer with indoor air. Among these heat transfer modes, heat conduction and convective heat transfer with indoor air are the main influencing factors, while the effect of mutual radiation between inner wall surfaces is relatively weak. Therefore, the heat balance equation mainly considers the former.

Among the influencing factors, the amount of heat conduction refers to the heat transfer between the inner surface of the wall and the interior of the envelope structure. For self-regulating building envelope structures based on PCMs, the PCMs inside the envelope will change the thermal conductivity of the structure during the heat absorption and release process. Therefore, the heat conduction process needs to consider the thermal physical parameters of the material, especially the sensible heat and latent heat effects of the PCM at different temperatures. The radiant heat received by the inner surface of the wall mainly comes from solar radiation through windows or other external surfaces. Since the external wall of the building is usually exposed to sunlight, the transfer of external radiant heat to the inner surface of the wall cannot be ignored. For envelope structures based on PCMs, these radiant heat quantities will affect the temperature change of the PCM, and further regulate the heat storage and release process of the envelope structure. In this process, the radiation absorption of the wall surface is closely related to the heat storage capacity of the material. Especially during periods of strong sunlight, the envelope structure may rapidly absorb heat, promote the phase change process of the material, and thereby affect the change of the inner surface temperature. The convective heat transfer between the inner surface of the wall and the indoor air is also an important part of the heat balance equation. The temperature fluctuation of indoor air will cause a change in the temperature difference between it and the wall surface, and this temperature difference carries out heat exchange through the convective heat transfer mechanism. For envelope structures based on PCMs, the temperature change of the wall surface is not only determined by external radiation and heat conduction, but also affected by indoor air temperature fluctuations. As the indoor air temperature changes, the temperature of the wall surface will also fluctuate accordingly, thereby affecting the rate of heat exchange.

Under the influence of the above factors, the establishment of the heat balance equation on the inner surface of the wall needs to consider the above heat effects. By establishing a heat transfer model based on PCMs, the heat exchange process between the inner surface of the wall and indoor air can be accurately described. Specifically, it is assumed that the heat gained by the u-th inner surface under the temperature difference on both sides is denoted by $w_{u(v)}$, the inner surface temperatures of the u-th and j-th envelope structures are denoted by $s_{u(v)}$, $s_{j(v)}$, the indoor air temperature at time v is denoted by $s_e(v)$, the total number of inner wall surfaces of the envelope structure in the room is denoted by V, the blackbody radiation constant is denoted by Z_y, the system emissivity between the u-th and j-th envelope wall surfaces is denoted by V_u, i.e., $\gamma_{uj}=\gamma_u\gamma_j$, the radiation angle coefficient from the u-th wall surface to the j-th wall surface is denoted by θ_{uj}, the radiant heat from solar radiation and various internal disturbances directly received by the u-th inner wall surface is denoted by $w^e_u(v)$, and the convective heat transfer coefficient of the u-th wall surface is denoted by β^z_u. The specific expression is as follows:

$$\begin{aligned} & w_u(v)+w_u^e(v) \\ & +\sum_{u=1}^{V_u} Z_y \gamma_{uj} \theta_{uj}\left[\left(\frac{S_j(v)}{100}\right)^4-\left(\frac{S_u(v)}{100}\right)^4\right] \\ & +\beta_u^z\left[s_e(v)-s_u(v)\right]=0 \end{aligned} \tag{7}$$

When only focusing on convective heat transfer between indoor air and the envelope structure itself, the expression is:

$$w_u(v)+\beta_u^z\left[s_e(v)-s_u(v)\right]+w_u^e(v)=0 \quad (8)$$

3.2 Indoor air heat balance equation

The temperature variation of indoor air is affected by various factors, including external environmental temperature, wall surface temperature, indoor heat sources, and heat exchange between indoor air and the envelope structure. In passive heating buildings without active equipment, the temperature regulation of indoor air mainly relies on the heat storage and heat transfer performance of the building envelope structure. Therefore, the indoor air heat balance equation needs to comprehensively consider the supply of heat sources, the storage and release of heat, and the heat exchange effect of the envelope structure. In self-regulating envelope structures based on PCMs, the envelope not only has thermal conductivity regulation function, but can also absorb and release a large amount of heat through the phase change process, thereby maintaining indoor temperature stability in environments with large temperature fluctuations. Figure 2 shows the temperature variation curve of the inner and outer sides of the phase change wall.

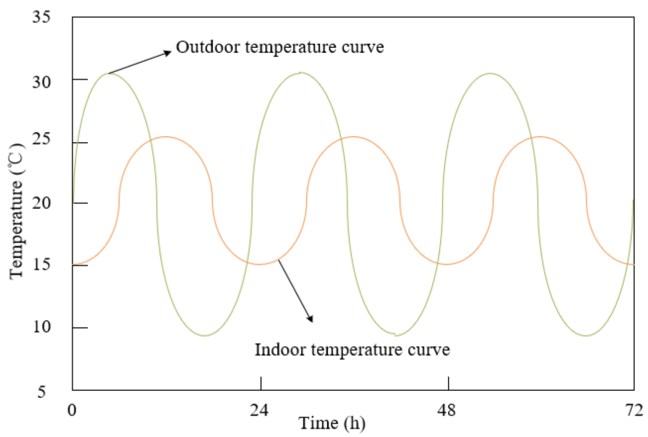

Figure 2. Temperature variation curve of inner and outer sides of phase change wall

Specifically, the heat balance equation of indoor air generally includes heat conduction, convective heat transfer, radiation exchange, and heat input from external heat sources. For self-regulating envelope structures based on PCMs, the temperature change of the wall surface directly affects the fluctuation of indoor air temperature, especially under conditions of large external temperature variations. The envelope structure regulates indoor temperature through the heat absorption and release process of the PCM, thereby mitigating drastic indoor temperature fluctuations. The convective heat transfer between the air and the envelope structure is an important component of the indoor air heat balance and is influenced by air flow and temperature gradients. As heat is exchanged between the indoor air and the wall surface, the temperature of indoor air will change accordingly. Therefore, the indoor air heat balance equation needs to establish the heat exchange relationship between air temperature and wall surface temperature, considering how the characteristics of PCMs affect the thermal response of the envelope structure. It is assumed that the area of the j-th inner wall surface of the envelope is denoted by Dj, the convective heat transfer coefficient of the j-th wall surface is denoted by $\beta^z{}_u$, the specific heat capacity per unit volume of air is denoted by $(z\sigma)_x$, the room volume is denoted by N, the outdoor air temperature is denoted by $s_x(v)$, and the air infiltration at time v is denoted by $M_x(v)$, then the expression is:

$$\begin{aligned}&\sum_{u=1}^{V_u} D_j\beta_j^z\left[s_j(v)-s_e(v)\right]\\&+M_x(v)(z\sigma)_x\left[s_x(v)-s_e(v)\right]/3.6\\&=N(z\sigma)_x\frac{s_e(n)-s_e(v-1)}{3.6\times\Delta\pi}\end{aligned} \quad (9)$$

Assuming the room volume is denoted by n and the room's air change rate is denoted by v_j, $M_x(v)$ can be determined based on the following equation:

$$M_x(v)=v_jN \quad (10)$$

3.3 The overall thermal balance equation set

The overall thermal balance equation set for building enclosure structures includes the inner and outer surface thermal balance equations of opaque envelope structures and the indoor air thermal balance equation. The heat exchange process of the inner surface of the wall is influenced by various factors. In addition to heat conduction, radiation, and convective heat exchange, the PCMs in the enclosure structure can absorb and release a large amount of heat during the phase change process. Therefore, the enclosure structure can not only regulate indoor temperature fluctuations but also affect indoor air temperature through the phase change energy storage effect. The unique properties of PCMs enable the enclosure structure to absorb solar radiation heat during the day and release it at night, thereby smoothing indoor temperature variations. The overall thermal balance equation set for the building enclosure structure integrates these heat exchange processes to establish the heat flow relationship among the wall surface, indoor air, and the entire building. However, due to the complexity of the involved heat exchange processes and the large computational workload, manually solving these equations is prone to errors. Therefore, in actual research, the use of building simulation software DesignBuilder for numerical calculations has become a common and effective practice. DesignBuilder software can simulate the heat exchange processes of various components inside the building, including the heat storage and release characteristics of PCMs in the enclosure structure. The specific expression is as follows:

$$\begin{cases}w_u(v)+\beta_u^z\left[s_e(v)-s_u(v)\right]+w_u^e(v)=0\\\sum_{u=1}^{V_u} D_j\beta_j^z\left[s_j(v)-s_e(v)\right]\\+M_x(v)(z\sigma)_x\left[s_x(v)-s_e(v)\right]/3.6\\=N(z\sigma)_e\frac{s_e(v)-s_e(v-1)}{3.6\times\Delta\pi}\end{cases} \quad (11)$$

In the specific process of self-temperature-regulating building envelope structure based on PCMs, it is necessary to fully consider the characteristics of PCMs, especially their phase change temperature and phase change latent heat under different temperature conditions. PCMs can absorb or release a large amount of heat in environments with large temperature fluctuations, regulating indoor environmental temperature. Therefore, in envelope structure design, it is necessary to select an appropriate phase change temperature range to ensure that the PCMs undergo frequent phase change processes within the indoor normal temperature variation range, thereby maximizing their heat regulation capacity. In addition, the thermal conductivity, density, and specific heat capacity of PCMs must also be considered, as these parameters directly affect the thermal response speed and efficiency of the envelope structure. The design of the envelope structure should ensure the uniform distribution of PCMs and good combination with other building materials to optimize the heat conduction and convective heat exchange processes, ensuring that the envelope structure can fully exert its energy storage and temperature regulation functions during the heat absorption and release process.

Furthermore, based on the establishment of the thermal balance equation set, the design of the envelope structure also needs to balance the building's thermal load, indoor air flow, and thermal comfort. Through numerical simulation and analysis, it is possible to predict the thermal response of the envelope structure under different external environments, thereby adjusting the thickness of the envelope structure, the type and distribution method of PCMs, and the selection of external building materials. The design should select suitable types of PCMs and layered structures according to different climate conditions, indoor activity patterns, and building usage requirements. For example, in cold climate regions, choosing high-phase-change-temperature PCMs can improve the heat release efficiency at night, while in warm climates, low-phase-change-temperature PCMs can be used to meet the demand for rising indoor temperatures during the day. Through this method, buildings can maintain a comfortable indoor temperature without relying on traditional air conditioning or heating equipment, reducing energy consumption.

4. EXPERIMENTAL RESULTS AND ANALYSIS

Tables 2, 3, and 4 respectively show the floor, wall, and roof construction methods and thermal parameters. As seen from Table 2, the floor construction contains multiple layers, among which the most important is the PCM layer. Its thickness is not directly given, but its thermal parameters (thermal conductivity of 0.5 W/(m·°C), density of 850 kJ/m³, specific heat capacity of 2 kJ/kg·°C, and latent heat of 108 kJ/kg) play a key role in the floor's thermal storage performance. Through the application of this material, heat can be absorbed during the day and released at night to maintain indoor temperature stability and reduce the impact of temperature fluctuations on comfort. In addition, the EPS insulation layer above the floor (60mm thick, thermal conductivity of 0.04 W/(m·°C)) provides a low thermal conductivity, which can effectively reduce ground heat loss to the outside, further enhancing the building's thermal effect. Other layers in the floor, such as cement mortar and decorative layers, serve basic structural support and insulation functions, with thermal conductivities of 0.92 W/(m·°C) and 0.16 W/(m·°C) respectively, reflecting relatively high and low thermal performance.

As shown in Table 3, the wall structure also combines the advantages of PCMs and traditional building materials. The wall's PCM layer (similar to the floor, with a thermal conductivity of 0.52 W/(m·°C), density of 850 kJ/m³, specific heat capacity of 2 kJ/kg·°C, and latent heat of 108 kJ/kg) is critical for regulating wall temperature. The porous brick layer in the wall is 240mm thick with a thermal conductivity of 0.38 W/(m·°C), which helps increase the wall's thermal resistance and reduce rapid heat loss. At the same time, both the outer and inner layers of the wall are cement mortar layers with a thickness of 25mm and relatively high thermal conductivity (0.92 W/(m·°C)), which helps provide structural strength. However, compared to other insulation materials, their thermal insulation performance is relatively poor. Therefore, the excellent heat storage performance of the PCM can effectively make up for the high thermal conductivity of traditional materials, achieving better indoor temperature regulation effects.

As shown in Table 4, the roof structure involves multiple insulation and heat insulation layers. First, the cement mortar layer is 21mm thick and has high thermal conductivity (0.92 W/(m·°C)), but it mainly serves as a load-bearing material and does not directly affect heat flow. Next is the asphalt waterproof layer, with a thickness of 12mm and thermal conductivity of 0.16 W/(m·°C), which provides a certain degree of insulation. The cement expanded perlite layer and the EPS insulation layer are the key insulation layers. Among them, the EPS insulation layer is 91mm thick with a thermal conductivity of 0.04 W/(m·°C), which can effectively prevent heat loss from the roof and enhance insulation performance. The reinforced concrete layer (102mm thick, thermal conductivity of 1.69 W/(m·°C)) mainly provides structural support for the roof. Its relatively high thermal conductivity means that its thermal insulation performance is poor and thus does not play an important regulatory role in heat transfer.

The design of the self-temperature-regulating building enclosure structure based on PCMs in this paper highlights the important role of PCMs in improving the thermal performance of buildings. The self-temperature-regulating building envelope structure based on PCMs uses the regulation effect of PCMs during temperature fluctuations to effectively improve building energy efficiency, reduce energy waste, and increase indoor comfort. The differences in thermal performance between different material layers and the energy storage characteristics of PCMs complement each other, making the building envelope structure not only have good insulation performance but also able to regulate and balance the indoor thermal environment. In the design, the configuration and thickness of PCMs should be reasonably selected and combined with appropriate insulation layers to achieve the best energy-saving and comfort effect.

Figure 3 shows the indoor temperature variation data under different phase change temperatures of the phase change floor. According to the data in Figure 3, the indoor temperature minimum and maximum values corresponding to the phase change floor exhibit a certain pattern under different phase change temperatures. In the phase change temperature settings of 19–23°C, the minimum indoor temperatures are all around 12–13°C, and the maximum temperatures are stable around 21–22°C. This indicates that under different phase change temperature settings, the indoor temperature fluctuation range is relatively stable without significant hot or cold changes. This relatively stable indoor temperature variation fully reflects the effectiveness of the self-temperature-regulating building envelope structure design based on PCMs. PCMs can absorb or release heat during temperature changes and regulate indoor temperature through their phase change process. The experimental data showing minor indoor temperature fluctuations indicate that the material effectively suppresses sharp indoor temperature swings and can maintain the indoor temperature in a relatively comfortable and stable range. This proves that the self-temperature-regulating building envelope structure design based on PCMs has the ability to stably regulate indoor temperature in practical applications and can create a more suitable thermal environment indoors.

Table 2. Floor construction method and thermal parameters

Material Layer	Thickness (mm)	Thermal Conductivity (W/(m·°C))	Density (kJ/m³)	Specific Heat Capacity (kJ/kg·°C)	Latent Heat (kJ/kg)
Decorative Layer	12	0.16	900	2	\
Cement Mortar	12	0.92	1750	1.12	\
PCM	\	0.5	850	2	108
EPS Insulation Layer	60	0.04	18	1.3	\

Table 3. Wall construction method and thermal parameters

Material Layer	Thickness (mm)	Thermal Conductivity (W/(m·°C))	Density (kJ/m³)	Specific Heat Capacity (kJ/kg·°C)	Latent Heat (kJ/kg)
Cement Mortar	25	0.92	1750	1.12	\
EPS Insulation Layer	60	0.04	18	1.3	\
Perforated Brick	240	0.38	1150	1.16	\
PCM	\	0.52	850	2	108
Cement Mortar	25	0.92	1750	1.12	

Table 4. Roof construction method and thermal parameters

Material Layer	Thickness (mm)	Thermal Conductivity (W/(m·°C))	Density (kJ/m³)	Specific Heat Capacity (kJ/kg·°C)
Cement Mortar	21	0.92	1750	1.12
Asphalt Waterproof Layer	12	0.16	620	1.36
Cement Mortar	22	0.92	1750	1.12
Cement Expanded Perlite	41	0.22	620	1.21
EPS Insulation Layer	91	0.04	18	1.3
Cement Mortar	21	0.92	1750	1.12
Reinforced Concrete	102	1.69	2450	0.91

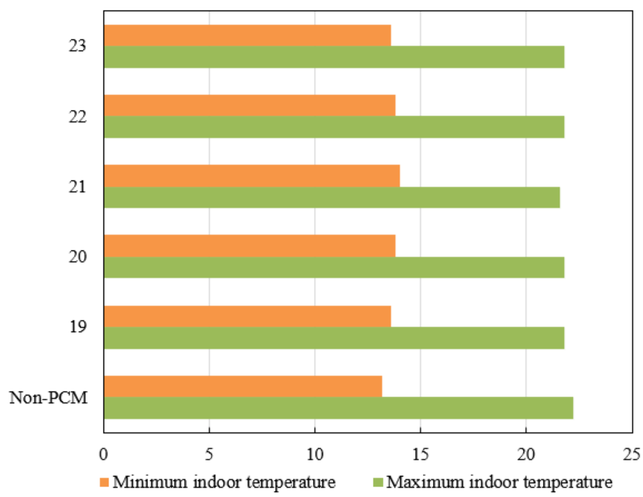

Figure 3. Indoor temperature variation under different phase change temperatures of the phase change floor

Figure 4 shows the indoor temperature variation when PCMs are added to two walls. Observing the data in Figure 4, when PCMs are added to the east and south walls, the west and south walls, or the east and west walls, the indoor temperature minimum values are approximately between 10–12°C, and the maximum indoor temperature values are all stable around 20°C. In contrast, without PCMs, the minimum indoor temperature values are also between 10–12°C, and the maximum values are also around 20°C. This shows that under the condition of adding PCMs to different wall combinations, the indoor maximum temperature remains stable and is not significantly different from that without PCM, and the minimum temperature also does not show obvious deterioration. From the above experimental data, it can be seen that the self-temperature-regulating building envelope structure design based on PCMs is effective. After adding PCMs to different walls, the indoor temperature can be maintained in a relatively stable state. Especially the stability of the maximum temperature indicates that PCMs effectively suppress excessive indoor temperature rise. When the external ambient temperature changes, they can absorb or release heat through their phase change process to regulate the indoor temperature and avoid extreme high-temperature situations.

Figure 5 intuitively shows the indoor temperature variation under different phase change envelope structure designs. According to the data in Figure 5, without PCMs, the indoor temperature minimum and maximum values vary within a certain range. When only the floor adds PCMs, three wall surfaces add PCMs, or both the floor and three wall surfaces add PCMs, the minimum indoor temperature values are all around 12–13°C, and the maximum values are all stable around 21–22°C. This shows that under different phase change envelope structure designs, indoor temperature fluctuation is relatively stable without large rises or falls. These data strongly demonstrate the effectiveness of the self-temperature-regulating building envelope structure design based on PCMs. PCMs in different envelope structure design applications can all play a role in regulating indoor temperature. Through their phase change process, they absorb or release heat and effectively suppress drastic indoor temperature fluctuations, keeping the indoor temperature in a relatively comfortable and stable range. Whether only the floor is added, or the combination of walls and floor is added with PCMs, indoor thermal environment optimization can be achieved, proving that this design can create stable and suitable indoor temperature conditions in practical applications and has significant practical value.

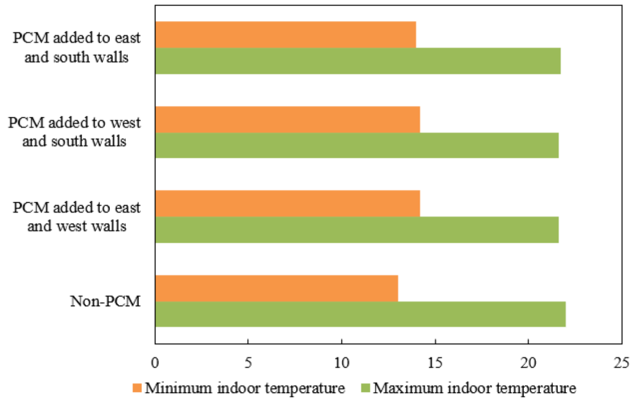

Figure 4. Indoor temperature variation when PCMs are added to two walls

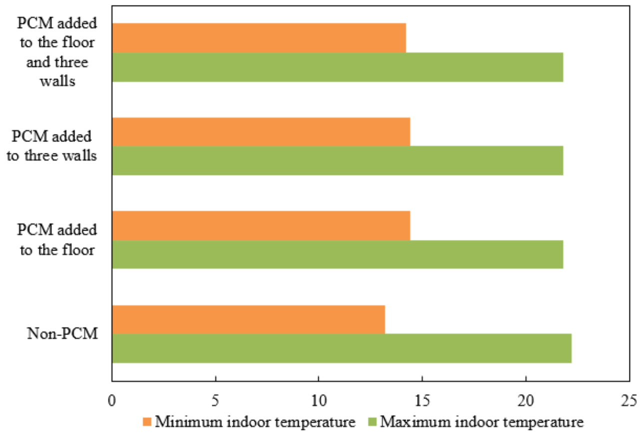

Figure 5. Indoor temperature variation under different phase change envelope structure designs

Figure 6 intuitively shows the indoor temperature variation under different thicknesses of PCMs in the floor. According to the data in Figure 6, when the floor uses different thicknesses of PCMs, the minimum indoor temperature is approximately between 12–13°C, and the maximum indoor temperature is stable around 21–22°C. Compared with the condition without PCMs, the indoor temperature fluctuation range under different thicknesses of PCMs is relatively stable, and no large temperature swings occurred. Among them, when the thickness varies from 10mm to 40mm, the minimum and maximum indoor temperature values do not show significant increasing or decreasing trends. These data fully demonstrate the effectiveness of the self-temperature-regulating building envelope structure design based on PCMs. Although the floor PCM thickness varies, indoor temperature can be kept relatively stable, indicating that PCMs can effectively regulate indoor heat through their phase change characteristics. Regardless of thickness, they can absorb or release heat during temperature changes and suppress drastic indoor temperature fluctuations, keeping the indoor temperature in a more comfortable range.

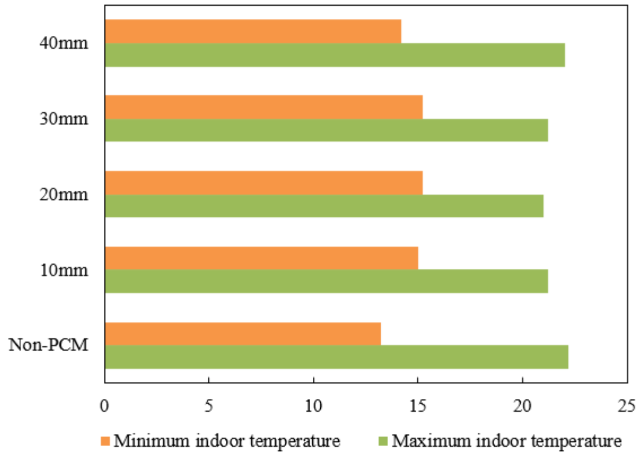

Figure 6. Indoor temperature variation under different thicknesses of PCMs in the floor

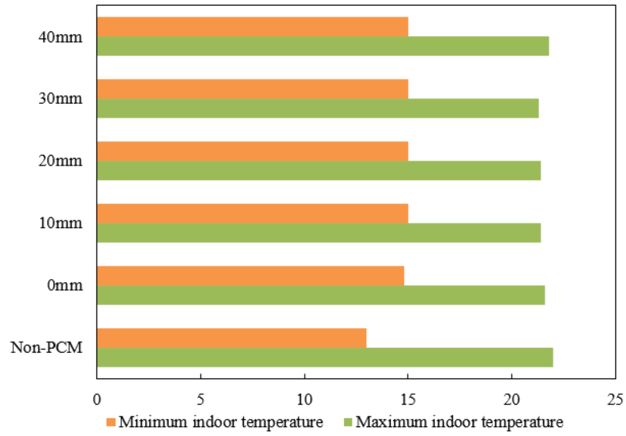

Figure 7. Indoor temperature variation under different thicknesses of PCMs in the east wall

Figure 7 shows the indoor temperature variation under different thicknesses of PCMs in the east wall. Observing the data in Figure 7, when the thickness of the PCM in the east wall increases from 0mm to 40mm, the minimum indoor temperature fluctuates between 12–14°C, and the maximum indoor temperature remains stable around 21–22°C. Compared with the situation without PCMs, with the increase in PCM thickness, the minimum indoor temperature does not show a significant decreasing trend, and the maximum value also does not show large changes. The overall temperature fluctuation range is relatively stable. The above experimental data strongly prove the effectiveness of the self-temperature-regulating building envelope structure design based on PCMs. Although the thickness of the PCM in the east wall is different, the indoor temperature can be maintained relatively stable, indicating that PCMs can effectively regulate indoor heat based on their phase change characteristics. When the external temperature changes, PCMs of different thicknesses can absorb or release heat, suppressing large fluctuations in indoor temperature and keeping the indoor temperature in a comfortable range. This demonstrates that the design has the ability to stably regulate indoor temperature in practical applications and can create a more suitable thermal environment indoors, highlighting the important significance and practical value of the self-temperature-regulating building envelope structure design based on PCMs in building thermal environment control.

From the building heating energy consumption variation chart shown in Figure 8, it can be clearly seen that over time, there is a significant difference in building heating energy consumption between non-phase change and phase change conditions. The non-phase change curve (blue) shows greater fluctuation, and the heating energy consumption value shows significant ups and downs at different time points, with some time points even reaching about 4 W/m²; while the phase change curve (red) fluctuates relatively gently, with most values concentrated between 0–2 W/m², which is significantly lower than the peak energy consumption in the non-phase change condition. The above data fully reflect the effectiveness of the self-temperature-regulating building envelope structure design based on PCMs. PCMs can effectively reduce building heating energy consumption fluctuations and keep energy consumption at a relatively low and stable level. This is because PCMs can absorb or release heat through their phase change process during temperature changes, reducing indoor temperature fluctuations, and thereby reducing energy consumption caused by frequent adjustment of the heating system. Compared with non-phase change conditions, the design based on PCMs performs outstandingly in energy saving and can utilize energy more efficiently, providing a feasible and effective way for building energy saving, proving that this design has important value in practical applications for reducing building energy consumption and improving energy use efficiency.

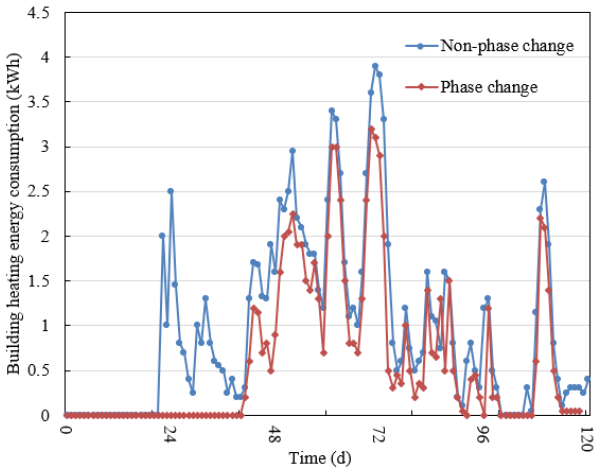

Figure 8. Building heating energy consumption variation

5. CONCLUSION

This paper focuses on the "Design and Experimental Research on Self-Temperature-Regulating Building Envelope Structure Based on PCMs", and the main research content includes establishing the physical and mathematical model of the self-temperature-regulating building envelope structure based on PCMs, as well as establishing thermal balance equations for wall surfaces, indoor air, and the whole building envelope structure. The research results show that PCMs are effective in regulating indoor temperature and reducing building heating energy consumption. Under different phase change temperatures and different envelope structure application scenarios (such as different wall combinations, different thicknesses of floors and walls, etc.), the indoor temperature fluctuation range is relatively stable and can be maintained in a comfortable range. At the same time, compared with the non-phase change condition, PCMs can significantly reduce building heating energy consumption fluctuations and keep energy consumption at a low level, highlighting their important value in building energy conservation.

However, this study also has certain limitations. The experiments were only carried out under specific conditions, while the actual building environment is more complex and variable. Factors such as different regional climate differences, building orientation, and surrounding environment may affect the performance of PCMs. In addition, the research on the long-term durability and economic cost-effectiveness of PCMs is not yet sufficient. Future research directions can start by expanding practical application scenarios, conducting application research in different climate zones and different building types, and further verifying and optimizing the performance of PCMs. At the same time, efforts should be made to strengthen research on the long-term performance and cost-effectiveness of PCMs, and to explore more efficient, economical, and environmentally friendly PCMs and application schemes, promoting the wide application of self-temperature-regulating building envelope structures based on PCMs in the field of architecture.

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