Research Article

A Parametric Investigation on Energy-Saving Effect of Solar Building Based on Double Phase Change Material Layer Wallboard

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In order to further understand the thermal performance of the double phase change material (PCM) layer wallboard, the wallboard model was established and a comprehensively numerical parametric investigation was carried out. The variation laws of inner wall temperature rise and the heat flux transferred under different phase transition temperatures and thermal conductivities are presented in detail. The main results show that the temperature of the inside wall for case 2 can be reduced by about 1.5 K further compared to that for case 1. About 83% of the heat transferred from the outside is absorbed by the PCM layer in case 2. Reducing the phase transition temperature of the PCM layer can decrease the inside wall temperature to a certain extent in the period of high temperature. The utilization of double PCM layers shows much more performance compared to that of the single PCM layer case, and the temperature of the inside wall can be reduced by 2 K further.

1. Introduction

Energy demand has been increasing quickly with the development of economy. And the conventional fossil energy sources such as oil, coal, and gas are limited. Their use leads to climate changes and environmental pollution [1]. Building energy consumption has become a serious problem due to a large amount of energy that is consumed by the heating, ventilation, and air conditioning system of buildings every day. According to [2], about 40% of the world's total energy was used for buildings and more than 30% of the primary energy consumed in buildings is for the heating and air conditioning system. Therefore, some energy-saving and environment-friendly techniques have been investigated in recent years. Thermal energy storage techniques used in buildings to decrease the energy consumption were considered an effective way [3, 4]. Thermal energy storage can be divided into sensible heat storage, latent heat storage, and chemical energy storage. And among them, the latent heat storage has

received considerable attention in comparison with the other two methods attributed to the obvious advantages of latent heat storage using phase change material (PCM), like high energy storage density and narrow operating temperature range [5, 6]. Furthermore, PCM can store and release a large amount of latent heat during the process of melting and solidifying in its narrow phase transition range [7, 8].

In the past two decades, researches on the application of PCM in building energy conservation can be divided into two categories. One is combining the PCM with the active air conditional system where the PCM system serves as the heat source or cold source of the air conditioning system to increase the refrigerating efficiency or the heat efficiency [9, 10]. For instance, Tyagi et al. [11] designed and experimentally studied the thermal performance of a PCM-based building thermal management system for cool energy storage. The other is the usage in the passive heat insulation and preservation system, comprising the combination of PCM and building materials to obtain novel energy

FIGURE 1: Schematics of the resident house and enlargement of the analysis region with structure mesh.

conservation building materials and directly inserting shape-stabilized PCM into the enclosure structure of the building [12–14]. The first category of PCM application needs to be considered early in the design process of the air conditioning system and also needs later maintenance. However, the second one is concentrated on the design of new building material, like coating material with phase change function, insulation wallboard, and brick with PCM encapsulated in it, and is a way to enhance the ability of the building itself to adapt to the climate. Therefore, it is widely of concern to scholars. Li et al. [15] compared the thermal performance of lightweight buildings with and without a PCM layer attached to the inside wallboard and found that the energy consumption to maintain comfortable temperature can be reduced by 40–70%. Ramakrishnan et al. [16] numerically investigated the thermal control effect of building fabrics integrated with PCM under extreme heatwave periods. The result shows that the indoor heat stress risks can be reduced effectively without the function of an air conditioner. Meanwhile, Thiele et al. [17] constructed a numerical model based on a modified admittance model to evaluate the thermal performance of building envelopes integrated with PCM whose result turns to agree well with that of the existing finite element simulations. Zhu et al. [18, 19] put forward a new structure of wallboards with double shape-stabilized PCM, proposed a related simplified dynamic model, and then used it to analyze energy performance of office building under different conditions. However, the model and related analysis are concentrated on the whole system and overall efficiency. The heat transfer process and the influence of the PCM parameters on the heat transfer law are also quite important for the actual design and need to be further understood.

In this paper, in order to further explore the heat transfer law and thermal performance of the double PCM layer wallboard put forward by Zhu et al. [18] under different conditions, the wallboard model was established and a comprehensively parametric numerical investigation was carried out. The variation law of temperature rise at the inner side of the wall and the heat flux transferred under different phase transition temperatures, thermal conductivities, and arrangements of PCMs are presented and discussed in detail in the following sections.

2. Model and Methodology

2.1. Model Description. Figure 1 shows the schematics of the resident house and enlargement of the analysis region with structure mesh. The performance of the wall determines the economic and energy-saving efficiency of the whole building to a great extent. Therefore, the wallboard is the key research object. The structure of the wallboard is presented in the enlarged view clearly. As shown in Figure 2, three cases of wallboard with different layer combinations were designed and compared. Case 1 represents the convection wallboard with insulation material only. The insulation layer outside is replaced by the PCM layer in case 2, and both insulation layers are replaced by PCM layers in case 3. The dimensions and thermo-physical properties of these two layers and the concrete can be seen in Table 1.

2.2. Numerical Simulation. With the development of computer technology, numerical study as an effective means of research involving design, analysis, and optimization is being developed quickly. In this exploration, commercial

FIGURE 2: Schematics of the building wallboard with/without PCM.

computational fluid dynamics package, FLUENT 14.0, was utilized. The mesh density and the computational parameters such as time step and number of iterations per time step were evaluated by checking the dependency of the total heat transfer flux on models with various mesh quantities and different computational parameters. The time step was set to 10 seconds, and the number of iterations per time step was 50. The pressure-based 1st-order implicit algorithm for this unsteady problem was considered. Some assumptions were made in the following simulation work. The specific heat, the phase transition temperature, and the thermal conductivity of PCMs were constant. Also, the PCMs utilized were isotropic and homogenous. The volume change of the PCM during phase transition was ignored.

The energy conservation equation for the concrete region can be presented as follows:

$$\frac{\partial}{\partial \tau} (\rho_c c_{pc} t_c) = \nabla \cdot (\lambda_c \nabla t_c), \quad (1)$$

where ρ_c , c_{pc} , and λ_c are the density, heat capacity, and thermal conductivity of the concrete, respectively. The enthalpy-porosity model was adopted to model the phase changing process in this work. The liquid fraction is computed at each iteration, based on an enthalpy balance. The energy equation of PCM can be expressed as follows [20]:

$$\begin{aligned} \rho \frac{\partial H}{\partial \tau} &= k \nabla^2 H + S, \quad H = H_0 + \Delta H, \\ H_0 &= H_{\text{ref}} + \int_{T_{\text{ref}}}^T C_{p_{\text{pcm}}} dT, \quad C_{p_{\text{pcm}}} = \begin{cases} C_{ps_{\text{pcm}}}, & T < T_m, \\ C_{pl_{\text{pcm}}}, & T > T_m, \end{cases} \\ \Delta H &= \beta \gamma, \quad \beta = \begin{cases} 0, & T < T_m, \\ 1, & T > T_m, \end{cases} \end{aligned} \quad (2)$$

where H represents the total enthalpy of PCM, H_0 is the sensible enthalpy, ΔH is the latent heat, β is the liquid fraction, and T_m is the phase transition temperature.

$$q_s''(t) = \begin{cases} q_{s,\text{max}} \cos\left(\frac{\pi t}{43200} - \pi\right), & 6:00 \text{ am} \leq t \leq 6:00 \text{ pm}, \\ 0, & 6:00 \text{ pm} < t \leq 6:00 \text{ am}, \end{cases} \quad (3)$$

$$\begin{aligned} q_{\text{ave}}'' &= \frac{\int q_s''(t) dt}{12 \times 3600} = \frac{\int q_{s,\text{max}} \cos\left(\frac{\pi t}{43200} - \pi\right) dt}{12 \times 3600} \\ &= \frac{q_{s,\text{max}} \int \cos\left(\frac{\pi t}{43200} - \pi\right) dt}{12 \times 3600}. \end{aligned} \quad (4)$$

The external boundary condition is based on the total solar radiation of the Xuzhou area, which can be seen in Figure 3 [21]. The average solar radiation (q_{ave}'') of the Xuzhou area in June is about 385.8 W/m^2 , and the maximum daily solar radiation can be observed through (4). Boundary conditions at the top and bottom of the model are thermal isolation. The sun radiation reaches the left side to heat the wall, and the convection heat transfer exists at the same time to cool the wall. But the heat flux and radiation cannot appear in the boundary condition at the same time to complete the numerical solution. Therefore, after simplification, the left boundary condition is time-dependent temperature boundary, which is described as follows:

$$\begin{aligned} x &= 0, \\ -k \frac{\partial T}{\partial n} &= T(\tau) = \Delta T_{\text{max}} + T_{\text{ini}} \sin\left(\frac{\pi t}{60000}\right). \end{aligned} \quad (5)$$

The right side boundary conditions are mixed boundary conditions. The right side of the wall heats the air inside by radiation and convection synchronously, which can be described as follows:

$$\begin{aligned} x &= x_3, \\ -k_i \frac{\partial T}{\partial n} &= h_i (T_{\text{wi}} - T_{\text{ai}}) + \varepsilon \sigma (T_{\text{wi}}^4 - T_{\text{ai}}^4). \end{aligned} \quad (6)$$

A parametric study was undertaken to investigate the influence of phase transition temperature of PCM and thermal conductivities of PCM and the thermal control effect of the double PCM layers compared to other two cases.

3. Result and Discussion

The aim of this work was to investigate a special kind of wallboard with two PCM layers attached both sides of the concrete wall for heat insulation and energy saving. Temperature variation of the outside wall with time in summer is exhibited in Figure 4. As the figure shows, the temperature of the outside wall increases to 325 K linearly with a relatively high rate of rise before 10:00 am, and the tendency of temperature rising gradually reduces from 10:00 am to 02:00 pm. The highest temperature of the outside wall in one solar day is up to about 338 K at 02:00 pm. After 02:00 pm, the temperature of the outside wall gradually decreases to 330 K (at 06:00 pm). This variation trend of the outside wall

TABLE 1: Thermo-physical properties of the wallboard materials [18].

Materials	c_p (kJ/kg·°C)	λ (W/m·°C)	ρ (kg/m ³)	L (kJ/kg)	T_m (°C)	D (m)
Concrete	0.8	2.1	2400	—	—	0.24
Insulation	2.0	0.2	850	—	—	0.03
PCM 1/PCM 2	2.0	0.1~2	850	200	26~29	0.03

FIGURE 3: Total solar radiation of the Xuzhou area in different months.

temperature can reflect well the actual temperature condition of a solar day in the Xuzhou area in summer.

Figure 5 presents the temperature variation and the heat flux of the inside wall for different cases. As shown in Figure 5(a), the temperature of case 1 and case 2 has little change before 10:00 am, keeping a temperature of 299 K, and after 10:00 am, the temperature of case 1 gradually increases to 300 K, while that of case 2 has only little variation until 02:00 pm. After 02:00 pm, variation of temperature rising of case 1 has a significant improvement and case 2 starts a temperature rising with a similar tendency with that of case 1, and the temperatures of case 1 and case 2 are, respectively, 302 K and 300 K. As the wall is without any heat insulation layer or PCM layer, the temperature of the inside wall rises promptly after 09:00 am and finally rises to 312 K at 06:00 pm. In summary, the function of the insulation layer and PCM layer can both greatly retard the velocity of temperature diffusion, and the inside wall temperature can be decreased by more than 10 K. Case 2 has a certain advantage over case 1, which is attributed to the phase change endothermic behavior of the PCM layer. When the outside insulation layer was replaced by the PCM layer, the temperature of the inside wall can be reduced by about 1.5 K further. As shown in Figure 5(b), the heat flux is positive in the morning, indicating that the wall absorbs the air heat in the room, for the reason that the temperature of external air is set larger than the initial temperature of the wall in the simulation process. The heat flux of case 2 begins to turn negative, and the heat began to go through the wall completely until about 04:00 pm. It can be concluded from area C and area A in Figure 5(b) that the heat transferred into the indoor can be reduced about

FIGURE 4: Temperature variation of the outside wall at different moments in summer.

98% by the function of the PCM layer and insulation layer. It can also be deduced that about 83% of the heat transferred from the outside is absorbed by the PCM layer through comparing area B and area C.

Figure 6 shows the temperature contours of the wallboard at 06:00 pm for three different cases obviously. The temperature distribution exhibits uniform gradient in the concrete wall case, in which the double layers are replaced by the concrete. It can be seen from case 1 and case 2 that the overall average temperature of the concrete wall in case 2 is obviously lower than that in case 1 for the reason that PCM can absorb large amount of latent heat under lower and stable temperature region, the heat transfer driving force and temperature difference are relatively weak, and less heat gets across the border to the concrete wall.

3.1. The Effect of Phase Transition Temperature of the PCM Layer. Figure 7 presents temperature variation and heat flux of the inside wall for case 2 under different phase transition temperatures (from 299.15 K to 302.15 K). As shown in Figure 7(a), the temperature under different phase transition times is identical before 10:00 am and after 04:00 pm. In the middle range of the solar day, the temperature difference under different phase transition temperatures increases firstly and then decreases. When time goes after 02:00 pm, the temperature difference under different phase transition temperatures decreases in contrast. The temperature of the inside wall under different phase transition temperatures is identical again at 04:00 pm, and the final identical temperature is about 301 K, increasing about 2.7 K. As shown in Figure 7(b), heat flux of the inside wall is also identical under

FIGURE 5: Temperature variation and heat flux of the inside wall under different cases.

FIGURE 6: Temperature contour of the wallboard at 06:00 pm under different cases.

different transition temperatures before 10:00 am. When time is over 10:00 am, heat flux of the inside wall is higher under lower phase transition temperature, which is opposite to temperature. Heat flux of the inside wall under different phase transition temperatures is identical at the end. It can also be seen that heat flux decreases from 11.2 W/m^2 to -7 W/m^2 . Actually, heat flux decreases from 11.2 W/m^2 to 0 W/m^2 , and then it increases to 7 W/m^2 with the opposite heat transfer direction. In summary, reducing the phase transition temperature of the PCM layer can decrease the inside wall temperature to a certain degree in the middle period of

a solar day; however, the heat transferred into the indoor in the whole daytime is almost not affected by the phase transition temperature.

3.2. The Effect of Thermal Conductivity of PCM. Figure 8 exhibits the temperature variation and heat flux of the inside wall for case 2 under different thermal conductivities of PCM. As shown in Figure 8(a), the temperature of the inside wall has little change before 10:00 am, keeping a temperature of 299 K, though the thermal conductivity of PCM is changed. After 10:00 am, the temperature of the inside wall gradually increases and the final temperatures are 303.2 K, 305.4 K, and 307.4 K while the thermal conductivities of PCM are $0.4 \text{ W/(m}\cdot\text{K)}$, $0.8 \text{ W/(m}\cdot\text{K)}$, and $2 \text{ W/(m}\cdot\text{K)}$, respectively. As the thermal conductivity of PCM reaches $0.2 \text{ W/(m}\cdot\text{K)}$, the rising trend of the inside wall temperature becomes obvious after 02:00 pm, and the final temperature rises to 301 K. However, the temperature of the inside wall has little change during the whole solar day when the thermal conductivity of PCM is as low as $0.1 \text{ W/(m}\cdot\text{K)}$. It is obvious that decreasing the thermal conductivity of the PCM layer is beneficial to heat insulation and energy saving. Less heat can be transferred to the indoor. As shown in Figure 8(b), heat flux is almost stable around 5 W/m^2 and flows toward the outside before 10:00 am. And after 10:00 am, heat flux gradually reverses its direction and reaches about 22.5 W/m^2 , 37.9 W/m^2 , and 52.3 W/m^2 at 06:00 pm as the thermal conductivities of PCM are $0.4 \text{ W/(m}\cdot\text{K)}$, $0.8 \text{ W/(m}\cdot\text{K)}$, and $2 \text{ W/(m}\cdot\text{K)}$, respectively. Figure 9 shows the phase change ratio of the PCM layer for case 2 under different thermal conductivities. It can be found that when the thermal conductivity is $2 \text{ W/(m}\cdot\text{K)}$, the PCM melts entirely in almost 7200 s, while it takes 4.5 times longer to melt the PCM layer with a thermal conductivity of $0.1 \text{ W/(m}\cdot\text{K)}$.

3.3. The Effect of Double PCM Layers. In order to further increase the energy-saving capacity of the wallboard, the

FIGURE 7: Temperature variation and heat flux of the inside wall for case 2 under different phase transition temperatures.

FIGURE 8: Temperature variation and heat flux of the inside wall for case 2 under different thermal conductivities of PCM.

FIGURE 9: Phase change ratio of the PCM layer for case 2 under different thermal conductivities.

right insulation layer is also replaced by the PCM layer, and the PCM has the same thermal physical property as the left layer. Figure 10 presents the temperature variation and heat flux of the inside wall for case 3. It can be observed that the temperature curve for case 3 increases first and becomes stable almost the whole day. The temperature can be stabilized at about 299.15 K. The wallboard with double PCM layers shows much better thermal performance compared to the single PCM layer case, and the temperature of the inside wall can be reduced by 2 K further. The inner wall almost can exclude the interference from external environment. As shown in Figure 10(b), the heat flux for case 3 is positive in the whole daytime. The heat outside cannot be transferred to the indoor, which is the reason why the temperature of the inside wall can be stable. Figure 11 illustrates the phase change ratio of each PCM layer for case 3. The phase change ratio of PCM 1 is on the rise before 12:00 pm, but that of PCM 2 remains constant until 02:00 pm. It can be seen that PCM 1 just takes 21600 s to melt totally. However, the phase

FIGURE 10: Temperature variation and heat flux of the inside wall for case 3.

FIGURE 11: Phase change ratio of each PCM layer for case 3.

change ratio of PCM 2 is still under 0.2 at the end of the solar day.

4. Conclusion

In order to further understand the heat transfer law and thermal performance of the double PCM layer wallboard under different conditions, a comprehensively parametric numerical investigation was carried out. The variation law of temperature rise at the inner side of the wall and the heat flux flowed through under different phase transition temperatures, thermal conductivities, and arrangements of PCMs are presented and discussed in detail. The main conclusions can thus be summarized as follows:

- (1) The function of the insulation layer and PCM layer can both greatly retard the velocity of temperature

diffusion, and the inside wall temperature can be decreased by more than 10 K. About 83% of the heat transferred from the outside is absorbed by the PCM layer in case 2.

- (2) Reducing the phase transition temperature of the PCM layer can decrease the inside wall temperature to a certain degree in the period of high temperature. Increasing the thermal conductivity of the PCM layer is not beneficial to heat insulation and energy saving. More heat can be transferred to the indoor easily.
- (3) The utilization of the double PCM layer shows much more performance compared to that of the single PCM layer case, and the temperature of the inside wall can be reduced by 2 K further.

Nomenclature

T :	Temperature (K)
ΔT :	Temperature difference (K)
c_p :	Specific heat (J/(kg·K))
H :	Enthalpy (J kg ⁻¹)
ΔH :	Latent heat of PCM (J kg ⁻¹)
ΔT :	Temperature increase (K)
k :	Thermal conductivity (W/(m·K))
q :	Heat flux (W/m ²)
β :	Liquid volume fraction
τ :	Time (s)
ρ :	Density (kg/m ³)
ε :	Emissivity
σ :	Stefan-Boltzmann constant.

Subscripts

w:	Wall
wi:	Wall inside
a:	Air

ai: Air inside
 ini: Initial
 c: Concrete
 ave: Average
 ref: Reference
 m: Melting.

Acronyms

PCM: Phase change material.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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