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Thermal Performance of Phase Change Material Wallboard with Typical Structure: Artificial Controlled Condition Experimental Investigation

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Phase change material (PCM) integrated with building envelopes could enhance thermal storage performance of building envelopes significantly. Due to the variable physical property of PCM, the thermal performance of PCM envelopes is different from traditional envelopes such as clay brick and concrete wall. In the present paper, the thermal performance of PCM envelopes are experimentally investigated in an artificial climate chamber. The experimental PCM wallboard is made by PCM layer, concrete layer and insulation layer, which could reflect the real envelopes structure in typical office buildings in Western China. The thermal performance of the wallboard with different material layer locations is compared, and the thickness of PCM layer is optimized. During the experiments, the PCM wallboard is under double-sides heat effect, including periodic outdoor air temperature fluctuation and indoor heat source. Two indicators named thermal inertia index and coefficient of heat accumulation of interior surface are introduced as the key parameters to evaluate the thermal storage performance of the PCM envelopes. The results show that, under double-sides periodic thermal effect, the indoor air temperature is mainly affected by the coefficient of heat accumulation of interior surface of the PCM wallboard. However, the increment of the thermal inertia index of the whole wallboard has little influence on the indoor thermal environment under double-sides periodic thermal effect.

1. Introduction

The temperature and heat flux on the interior surface of building envelopes are critical for the indoor thermal environment (Yang et al., 2018). And the thermal storage performance of the building envelopes is especially important for the temperature and heat flux on the interior surface (Givoni, 1998). As a result, improving thermal storage performance of building envelopes is an ideal approach to obtain a stable indoor thermal environment and reduce building energy consumption (Liu et al., 2020). As a kind of materials with large thermal storage capacity, phase change material (PCM) integrated with building envelopes has been proved that is a potential method to improve indoor thermal environment (Zhang et al., 2006). However, due to its variable physical properties, the thermal performance of PCM envelopes is different from traditional envelopes such as brick or concrete wall (Liu et al., 2020). The thermal storage performance of PCM envelopes and its effects on the indoor thermal environment have aroused widespread attention (Kuznik et al., 2011).
The thermal storage performance of PCM envelopes are influenced by various parameters. There are many investigations have been carried out. On the one hand, a part of recent studies aims to reveal the key parameters on the thermal storage performance of PCM wallboards under the one-side thermal effect. The thermal performance of the PCM wallboard under the one-side thermal effect with temperature linear rising and falling were conducted by Kuznik et al. (2009). The influences of ventilation and solar radiation on the PCM wallboard were obtained by Xie et al. (2018). The proper phase change temperature and narrow phase change range should be chosen. On the other hand, many studies were carried out under the double-sides thermal effect. These studies were usually conducted under the actual climate conditions. The energy efficiency of PCM envelopes is the focus in the most of these investigations. Lin et al. (2005) investigated the energy saving effect

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of the PCM plates integrated with under-floor electric heating systems in winter. And the energy efficiency of PCM envelopes in summer are investigated by Barzin et al. (2015). More than 73 % of electricity reduction was observed. There were some studies have conducted under double-sides periodic thermal effect for its key parameters. A simplified method calculating the thermal storage coefficient of PCM was proposed by Ling et al. (2016). The influence of thermophysical properties of PCM were compared by Li et al. (2019). The parameters included the thermal conductivity, phase change enthalpy and phase change temperature. The results showed that the thermal conductivity has priority over other parameters. And the increase in the thickness of the PCM leaded to less improvement of thermal storage performance of PCM envelopes.
From above discussions, it can be found that the recent studies of the thermal storage performance and its influence parameters of PCM envelopes are mainly conducted under one-side thermal effect. However, the building envelopes are usually under double-sides thermal effect including outdoor climate conditions and indoor thermal environment. In the previous study, Liu et al. (2020) established a numerical model to analyze the optimization of the position and thickness of the PCM layer integrated with structural insulated panel (SIP). The present work aims to investigate the thermal storage performance and key influencing factors of the typical envelope structure combined with the structural layer (including concrete and insulation layer) under double-sides periodic thermal effect. The experimental conditions with different material layer orders and different PCM layer thicknesses are compared. The indicators named thermal inertia index and coefficient of heat accumulation of interior surface are introduced as the key parameters to evaluate the thermal storage performance of the PCM envelopes. This work could provide references for the improvement on the thermal storage of PCM envelopes.

2. Experimental setup

2.1 Experimental conditions

The experiments are conducted in the experimental system which is composed of a climate chamber, controlled system, data acquisition system and a test chamber (Figure 1). The air temperature in the climate chamber could be adjusted from -10 °C to 50 °C and the relative humidity from 10 % to 90 %. A test chamber with replaceable wallboards is located in the climate chamber as a reduced-scale building model. The extruded polystyrene (EPS) panels with 100 mm are adopted as the envelope of the test chamber. One of the adiabatic wallboards is replaced by a PCM wallboard and the wallboards are tightly sealed.

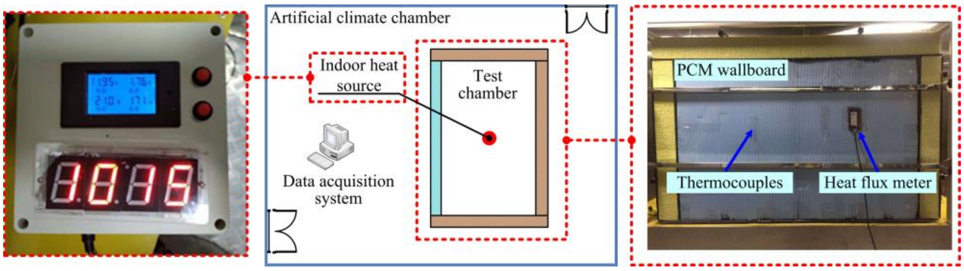


Figure 1: Diagram of experimental system

2.2 Presentation of the PCM wallboard with typical structure

The wallboards with two types comparative settings are investigated in the present work: 1) the wallboards with different material layers arrangements, the orders of the material layers from the exterior side to the interior side are listed in Table 1; 2) the wallboards with different PCM layer thickness including 25 mm, 50 mm and 75 mm.The material of insulation layer is EPS. Concrete is adopted as structural layer material. The PCM layer is made by the PCM panels which integrated with macro-encapsulated PCM and phenolic aldehyde. $Na_2SO_4{\cdot}10H_2O$ is chosen as the base material of macro encapsulated PCM with 25 °C of phase change temperature. The physical parameters of wallboard materials are listed in Table 2.

Table 1: The different material layers arrangements of the PCM wallboards

Experimental conditions	Material layers arrangements (from the exterior side to the interior side)
Arrangement 1	PCM layer (25 mm), structural layer (50 mm), insulation layer (30 mm)
Arrangement 2	Insulation layer (30 mm), structural layer (50 mm), PCM layer (25 mm)
Arrangement 3	Insulation layer (30 mm), PCM layer (25 mm), structural layer (50 mm)

Table 2: Physical parameters of PCM wallboard materials

Materials	ρ/kg·m^{-3}	λ/W·m^{-1}·°C^{-1}	c/kJ·kg^{-1}·°C^{-1}	ΔH/kJ·kg^{-1}
Extruded polystyrene	30	0.0376	1.2	-
Concrete	1,100	0.5	1.05	-
Phenolic aldehyde	60	0.034	1.38	-
Phase change material	1,464	0.56	-	131.2

2.3 The setting of experimental conditions

During the experiment, the PCM wallboard are under double-side periodic thermal effects with the period of 24 h. Based on the dry-bulb temperature curves of July in Xi'an, China, the outdoor air temperature curve is set as Figure 2(a). A halogen lamp is located in the test chamber as the internal heat source simulator. Figure 2(b) illustrates the power of internal heat source in each hour. The experiments start at the 9th hour of a cycle.

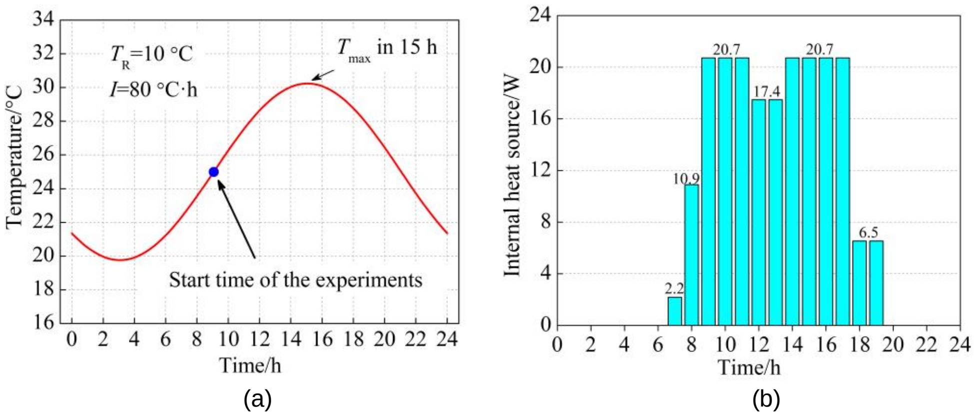


Figure 2: Experimental conditions: (a) outdoor air temperature; (b) power of indoor heat source

2.4 Measurement devices

The K-type thermocouples are adopted to measure the surface temperature of the PCM wallboard and the interior/exterior air temperature of the test chamber. The HOBO® four channels thermometers record the temperature data with 1 min record interval. In both interior and exterior surfaces of the PCM wallboard, the heat flux meters are arranged for measuring the heat flux data and recorded by Keithley® data acquisition.

3. Results and discussion

3.1 Key parameters of thermal storage performance of the PCM envelopes

The thermal storage performance of the wall is the key to reducing the temperature fluctuation of the interior surface. Thermal inertia index (D) is introduced to characterize the thermal storage performance of walls. For one material layer of the wall, D is defined as:

$$D = RS \tag{1}$$

where R is the thermal resistance of the material layer, m^2·°C·W^{-1}; S is the heat storage coefficient of the material, W·m^{-2}·°C^{-1}. For the wall combined of multiple layers of homogeneous materials, the thermal resistance is the sum of the thermal resistances of the individual material layers:

$$D = D_1 + D_2 + \cdots + D_n \tag{2}$$

where D_1, D_2…D_n are the thermal inertia index of each material layer of the wall, dimensionless. The coefficient of heat accumulation of interior surface (Y_i) is adopted as one of the key design parameters of the wall thermal storage performance. The coefficient of heat accumulation of interior surface is defined as the ratio between the heat flux amplitude and the temperature amplitude of the interior surface:

$$Y_i = \frac{A_q}{A_t} \tag{3}$$

where A_q is the heat flux amplitude on the interior surface of the wall, W·m^{-2}; A_t is the temperature amplitude on the interior surface of the wall, °C.

3.2 Thermal performance of the PCM wallboard under double-side periodic thermal effects

Figure 3 shows the temperature and heat flux curves in different locations of the PCM wallboard. The temperatures of indoor air and interior surface are affected significantly by internal heat source. The maximum temperature of indoor air is 34.0 °C, and is 32.7 °C in interior surface. The maximum temperature appears at 6:00 p.m. (in the 9-th h of a temperature cycle). When the internal heat source reduces to 0 W·m^{-2}, the temperature changes of indoor air/interior surface from rising to falling. The result shows that the effect of the internal heat source on the indoor thermal environment has a cumulative effect and is reflected in the indoor air temperature and the internal surface temperature. Due to the thermal storage performance of the PCM layer and the structural layer, the temperature amplitude is reduced from 3.5 °C on $T_{in, sur}$ to 1.2 °C on $T_{insu\text{-}stru}$, and the time of the temperature peak occurs delayed by 1.8 h. The amplitude of $q_{ex, sur}$ is significantly larger than the amplitude if $q_{in, sur}$. It can be seen that the effects of material layers with different thermal storage performance, on temperature waves are significantly different. It is necessary to investigate the influence of different arrangement order of the material layer on the thermal storage performance of the PCM wallboard.

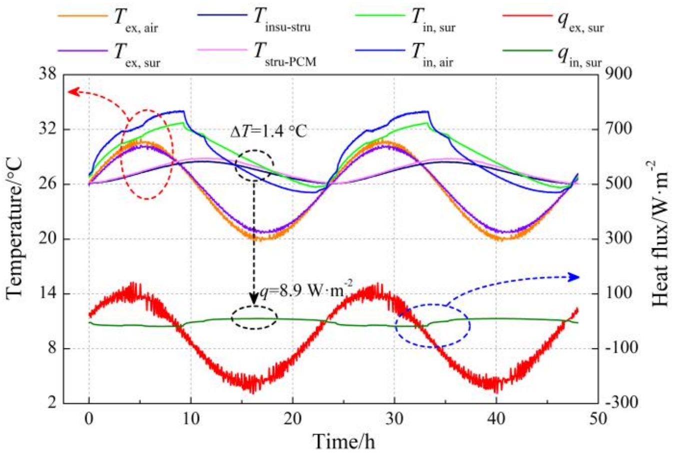


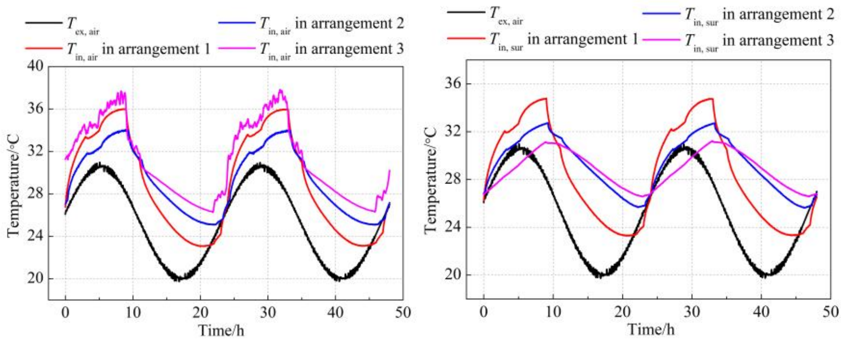
Figure 3: Temperature and heat flux of the PCM wallboard under double-sides periodic thermal effect

3.3 Thermal performance of PCM wallboard with different material layer orders

The interior surface temperature and indoor air temperatures of the PCM wallboards with different material layer orders are illustrated in Figure 4. For the PCM wallboard with arrangement 1, the interior surface temperature peak and amplitude are greater than the other two comparative conditions. These results indicate that the PCM wallboard with the insulation layer on the indoor side is not conducive to the thermal storage performance. For the PCM wallboard with arrangement 1, the maximum interior surface temperature is 31.1 °C with 2.3 °C amplitude. And the maximum temperature and amplitude in the interior surface of the PCM wallboard with arrangement 2 are 32.7 °C and 3.5 °C. However, the PCM wallboards with different material layers arranged in order have an approximate time of peak temperature on the interior surface. It can be seen from Figure 4b, the peak indoor air temperature of the test chamber adopted the PCM wallboard with the PCM layer on the indoor side and insulation layer on the outdoor side is the lowest of the comparative conditions. The peak temperature is 33.9 °C with 4.4 °C of temperature amplitude. Compared with the condition of the PCM wallboard with arrangement 3, the maximum temperature is reduced by 3.1 °C, the amplitude is reduced by 0.9 °C. In order to reduce the overheating of indoor air temperature in the afternoon, the PCM wallboard with the PCM layer on the indoor side and insulation layer on the outdoor side is a reasonable method.

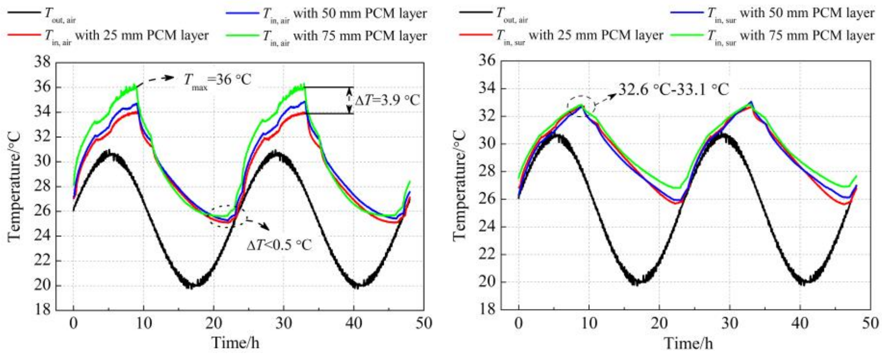
3.4 Thermal performance of PCM wallboard with different PCM layer thickness

Figure 5 shows the interior surface temperature of the PCM wallboard and the indoor air temperature of the test chamber. The PCM wallboards in the comparison experiment adopted the PCM layer thicknesses of 25 mm, 50 mm and 75 mm. The arrangement 2 is adopted. As shown in Figure 5(a), the peak temperatures and temperature amplitude of the interior surface of the three conditions are close, and the time delay with different PCM layer thicknesses are close. Increasing the thickness of the PCM layer has little effect on the interior surface temperature. The indoor air temperatures of test chamber in different comparative conditions are illustrated in Figure 5(b). The temperature amplitude of indoor air in the test chamber adopted 75 mm PCM layer wallboard is 5.2 °C, which is higher than the temperature amplitude of indoor air in the test chamber adopted 25 mm PCM layer wallboard with 4.4 °C. This phenomenon is mainly because the PCM adopted in the experiment is a combination of macro-encapsulated PCM and phenolic board. While increasing the thickness of the PCM layer, phenolic boards with thermal insulation are also increasing. The combined effect of the two reduces the thermal storage capacity of the PCM wall to the indoor thermal environment.



(a) (b)

Figure 4: Temperature of the PCM wallboard with different material layer orders: (a) interior surface temperature; (b) indoor air temperature



(a) (b)

Figure 5: Temperature of the PCM wallboard with different PCM layer thicknesses: (a) interior surface temperature; (b) indoor air temperature

3.5 Thermal performance of PCM wallboard with different PCM layer thickness

The calculation results of the coefficient of heat accumulation of interior surface are listed in the Table 3. When the interior surface is the insulation material, the value of Y_i decreases significantly. For the indoor thermal environment, the insulation material located on the interior surface of the wall can be considered that the thermal storage performance of the wall has little impact on the indoor thermal environment, and the wall has a lightweight characteristic. It can be found that the most important factor that affects Y_i is the material on the interior surface of the wallboard, and increasing the thickness of the PCM layer has little effect on Y_i. It can be found that Y_i can more accurately reflect the influence of the wall thermal storage performance change on the indoor thermal environment than using the value of thermal inertia index. For the PCM envelopes under the double-sides periodic thermal effect, compared to using only thermal inertia index, using Y_i as a key parameter could accurately reflect the thermal storage performance.

Table 3: Statistics of the coefficient of heat accumulation of interior surface

Material layer orders (from outside to inside)	PCM (25 mm) Stru (50 mm) Insu (30 mm)	Insu (30 mm) PCM (25 mm) Stru (50 mm)	Insu (30 mm) Stru (50 mm) PCM (25 mm)	Insu (30 mm) Stru (50 mm) PCM (50 mm)	Insu (30 mm) Stru (50 mm) PCM (75 mm)
Y_i/W·m^{-2}·°C^{-1}	1.3	5.8	4.1	3.8	5.6

4. Conclusions

The thermal storage performance of the PCM wallboard under the double-sides periodic thermal effect are experimentally investigated in the present study. The main results are showed as follows: (1) Under the double-sides periodic thermal effect, due to the cumulative effect of the heat in indoor thermal environment, the overheating phenomenon of the indoor air temperature in the test chamber appeared obviously. The temperature amplitude is the smallest at the interface between the insulation layer and the structural layer with 1.2 °C. (2) Under double-sides periodic thermal effect, compared with increasing the thickness of the PCM layer, optimizing the order of the material layers can significantly improve the thermal storage performance of the PCM wallboard. The PCM wallboard with material layer order of insulation layer on the outdoor side and PCM layer on the indoor side is a reasonable method for improving its thermal storage performance. The maximum indoor air temperature is reduced by 3.1 °C, the amplitude is reduced by 0.9 °C. Compared with increasing the thermal storage capacity of the wallboard, the effect on the indoor thermal environment is more significant by improving the thermal storage performance on the interior surface of the wallboard. (3) The coefficient of heat accumulation of interior surface can be adopted as a key parameter to evaluate the thermal storage performance on the interior surface of PCM envelopes under double-sides periodic thermal effect. The present experiments are carried out under artificial controlled conditions and have reliable experimental data. The proposed parameters can provide a reference for the thermal design of PCM envelopes.

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References

Barzin R., Chen J.J., Young B.R., Farid M.M., 2015, Application of PCM energy storage in combination with night ventilation for space cooling, Applied Energy, 158, 412-421.

Givoni B., 1998, Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods, Energy and Buildings, 28(1), 25-32.

Kuznik F., Virgone J., 2009, Experimental assessment of a phase change material for wall building use. Applied Energy, 86, 2038-2046.

Kuznik F., David D., Johannes K., Roux J.J., 2011, A review on phase change materials integrated in building walls, Renewable and Sustainable Energy Reviews, 15(1), 379-391.

Ling H.S., Chen C., Qin H., Wei S., Lin J., Li N., Zhang M.X., Yu N., Li Y., 2016, Indicators evaluating thermal inertia performance of envelops with phase change material, Energy and Buildings, 122, 175-184.

Liu J., Liu Y., Yang L., Liu T., Zhang C., Dong H., 2020, Climatic and seasonal suitability of phase change materials coupled with night ventilation for office buildings in Western China, Renewable Energy, 147(1), 356-373.

Lin K.P., Zhang Y.P., Xu X., Di H.F., Yang R., Qin P.H., 2005, Experimental study of under-floor electric heating system with shape-stabilized PCM plates, Energy and Buildings, 37(3), 215-220.

Liu T., Liu Y., Yang L., Liu J., Qiao Y.H., Yan D., 2020, Impacts of pcm location and thickness on dynamic thermal characteristics of external walls for residential buildings, Environmental Science and Engineering, 3, 127-135.

Liu Y., Wang M.Y., Cui H.Z., Yang L., Liu J.P., 2020, Micro-/macro-level optimization of phase change material panel in building envelope, Energy, 195, 116932.

Li Z.X., Abdullah A., Rostamzadeh M., Kalbasi R., Shahsavar Amin, Afrand M., 2019, Heat transfer reduction in buildings by embedding phase change material in multi-layer walls: Effects of repositioning, thermophysical properties and thickness of PCM, Energy Conversion and Management, 195, 43-56.

Xie J.C., Wang W., Sang P.F., Liu J.P., 2018, Experimental and numerical study of thermal performance of the PCM wall with solar radiation, Construction and Building Materials, 177, 443-456.

Yang L., Qiao Y.H., Liu Y., Zhang X.R., Zhang C., Liu J.P., 2018, A kind of PCMs-based lightweight wallboards: Artificial controlled condition experiments and thermal design method investigation, Building and Environment, 144, 194-207.

Zhang Y.P., Lin K.P., Zhang Q.L., Di H.F., 2006, Ideal thermophysical properties for free-cooling (or heating) buildings with constant thermal physical property material, Energy and Buildings, 38, 1164-1170.