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Experimental Study on Thermal Performance Improvement of Building Envelopes Integrated with Phase Change Materials in an Air-conditioned Room

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Abstract

Phase change materials (PCMs) are used to decrease the indoor temperature swing, keep the indoor environment comfortable and increase energy efficiency of buildings by enhancing the thermal storage capacity of building walls. This paper studied the thermal performance of the PCM wall and the reference wall when the air-condition ran continuously and intermittently through experiment. An experimental building with these two kinds of wall units was chosen, and the inner surface temperature and heat flow were measured. Results showed that the PCMs reduced the inner surface temperature 1°C and the inner surface heat flow about 40% during continuous air conditioning. Otherwise, when the air-condition ran intermittently by the working schedule, the cold releasing time of PCM wall was 2 hours longer than the reference wall. The PCMs can improved the thermal performance of building envelope significantly.

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Keywords: Phase change material; Building envelope; Thermal performance; Indoor thermal environ-ment; Energy efficiency

1. Introduction

Integrating phase change materials with building envelope is able to reduce energy consumption, improve indoor thermal comfort and shift the peak electricity load. Compared with sensible heat storage system, latent heat storage system with PCMs has higher energy storage density while requiring smaller masses and volumes of material, so that

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PCMs are widely used in the heat storage of building envelopes. PCMs absorb heat while changing from solid to liquid with the increasing temperature and release heat while changing from liquid to solid with the decreasing temperature. Integrating PCMs with building envelope can increase the heat capacity to use the renewable and non-renewable energy rationally. Wang et al. [1] evaluated the thermal performance of ultrathin envelope integrated with PCMs by aid of numerical simulation for PCM heat conductivity coefficient, phase change heat, phase-transition temperature and PCM layer position. Feng and Liang [2] built experimental rooms with phase change wall and ordinary wall, and used household air-condition for cooling. Results showed that the indoor air temperature of room with phase change wall was 1°C or 2°C lower than that of room with ordinary wall, and heat flow was reduced by the phase change wall. Yan et al [3] studied the thermal properties of the PCM wall formed by different methods, and found out that the surface temperature and heat flow through the PCM walls prepared by different methods were lower than that of traditional wall. Castell et al [4] did comparison experiments on two cubicles integrated with different PCMs, and results showed that PCMs could reduce the peak temperature by up 1°C, while reducing the air conditioning energy consumption by 15% in summer. Kuznik and Virgone [5] did experiments on the indoor thermal environments of PCM room and ordinary room in summer, winter and the transition seasons. Experimental results showed that the phase change wall could reduce the indoor temperature fluctuations. Behzadi and Faril [6] did computer simulations on PCMs impregnated in building materials, and carried out that the use of PCMs could effectively reduce the daily fluctuations of indoor air temperature to 4°C and maintain it at the desired comfort level for a long period without air conditioning. Lei et al [7] studied the energy performance of building envelopes integrated with PCMs for cooling load reduction in tropical cli-mate through simulations. The results showed that PCMs could effectively reduce heat gains through building envelopes throughout the whole year.

Existing studies show that PCMs can significantly improve indoor thermal environment in buildings with natural ventilation or continuous air conditioning. However, the thermal performance of PCM wall during continuous air conditioning and intermittent air conditioning are different. This paper presents an experimental study about the inner surface temperature and heat flow of the PCM wall and the reference wall when air condition runs continuously and intermittently. The results can provide theoretical guidance for indoor thermal environment regulation through improving thermal performance of building envelope by integrating with PCMs.

2. Methods

A dynamic test experimental building was built in Sichuan University to study the thermal performance improvement of building envelopes integrated with PCMs, as shown in Figure 1. There were two rooms in the building, and the size of which were both 3.5m (length)×3.0m (width)×2.2m (height). The PCM wall unit and the reference wall unit were embedded in the north external wall of Room1 (Fig. 1(b)). The two wall units with size of 600mm×600mm×260mm were in the same indoor and outdoor environment, which made the test results more comparable. Supported by steel frames, the two wall units were surrounded by 80mm EPS to reduce the heat transfer between units, ensuring one-dimensional heat transfer in the central area of each one. A split air conditioner (KFR-35GW/HFJ+3) was installed on Room 1's south wall.

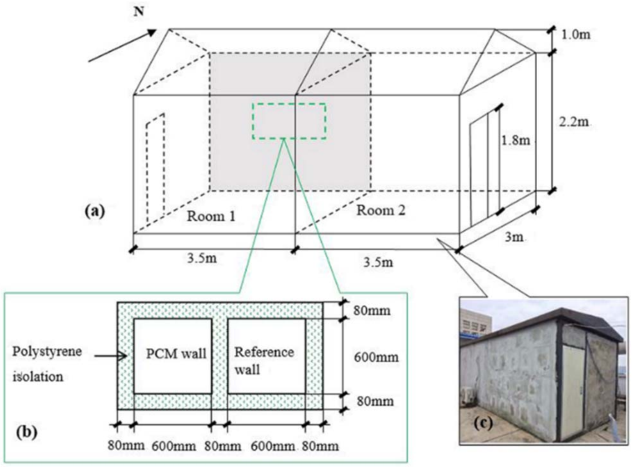


Fig. 1. The experimental system ((a) sketch map of the experiment test building; (b) experimental wall units; (c) architectural appearance).

In order to study the influence of PCMs on building envelope thermal performance, this paper chose the PCM wall unit and the reference wall unit as the research object. Fig. 2 shows the schematic structures of walls. From the inner side to the outer side, the PCM wall consisted of one layer of cement mortar of 10mm, one layer of PCMs of 20mm, one layer of solid brick of 220mm and one layer of cement mortar of 10mm. From the inner side to the outer side, the reference wall consisted of one layer of cement mortar of 10mm, one layer of solid brick of 240mm and one layer of cement mortar of 10mm. The physical properties of each layer of material are shown in Table 1. The phase-transition temperature range of the PCM is from 18°C to 26°C, which has phase change latent heat of 178.5kJ/kg. The thermal conductivity coefficient of the cement mortar in Table 1 was measured by the steady heat flow method in laboratory.

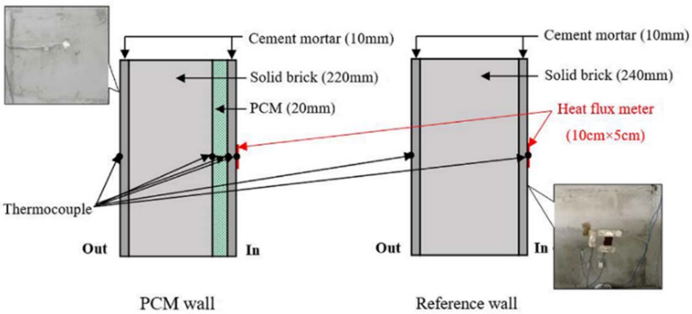


Fig. 2. The schematic structures and measurement distributions of walls.

Table 1. Physical properties of each layer.

Material	Density (kg/m^3)	Thermal conductivity ($W/(m \cdot K)$)	Specific heat ($kJ/kg \cdot K$)
Cement mortar	1406	0.3505	1.05
Solid brick	1536	0.7505	0.523
PCM	1300	0.25(phase change), 0.5(solid or liquid)	1.785

For the test wall units, thermocouples were arranged at the center of the inner and outer sur-faces to measure the surface temperatures, and heat flow meters were arranged at the center of the inner surfaces to measure the heat flow of the inner surfaces. One thermocouple was located 20cm from the inner surface of the wall to measure the indoor air temperature near the wall, while another sensor was arranged 20cm from external surface of the wall and 1.5m above the ground to measure the outdoor air temperature near the wall. In addition, there were thermocouples on the central area of both sides of PCM layer. The detailed measurement arrangements are shown in Fig. 2.

T-type thermocouples (with accuracy of 2%) and heat flow meters (JTC08A with accuracy of 5%) were used to measure the temperature and heat flow. All measurement data were recorded by a JTRG-II building thermal temperature automatic tester. The measurements of the variations of temperature and heat flow under different air conditioning conditions were carried out every 1 minute from June 2015 to August 2015. The cooling thermostat setting was adjust to 16°C for summer space cooling to ensure the phase change of PCMs.

3. Results

3.1. The experiment results during continuous air conditioning

The measurement about continuous air conditioning was carried out from 16:00 June 2nd 2015 to 11:00 June 7th 2015. Fig. 3 presents the variations of indoor and outdoor air temperature from June 4th to June 5th. During the test period, the minimum outdoor air temperature was 19.25°C, and the maximum was 36.10°C. The outdoor air temperature difference between day and night was around 12-16°C. Although the air conditioning temperature was set at 16°C during the experiment, the indoor air temperature was changing like sawtooth wave be-cause the air condition lacked of frequency conversion and the cooling power was larger than the need. The compressor stopped working when the indoor air temperature reached the set temperature, and ran when the indoor air temperature was higher than the set temperature. The indoor air temperature during the continuous air conditioning changed between 13.4°C to 17°C, and the average value was 15.4°C. Owing to the outdoor air temperature fluctuations, the indoor air temperature presented cyclical fluctuations. The indoor air temperature in-creased significantly during 16:00-20:00 every day, and the fluctuations delayed 1 hour com-pared to the outdoor air temperature because of the thermal inertia of building envelope.

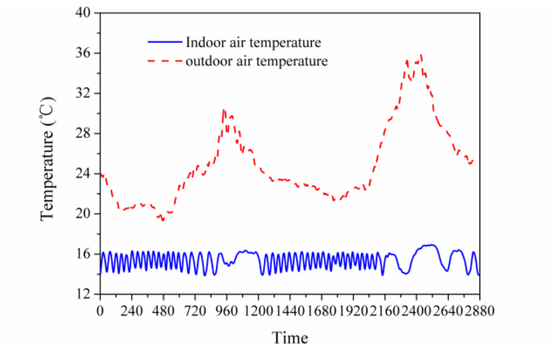


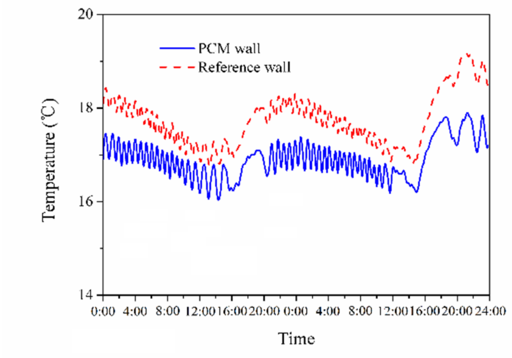
Fig. 3. The variations of indoor and outdoor air temperatures from June 4th to June 5th.

Fig. 4 presents the variations of inner surface temperature and heat flow during continuous air conditioning. During the measurement, the inner surface temperature of the PCM wall was lower than the reference wall. The average inner surface temperature of the PCM wall was 16.91°C, while that of the reference wall was 17.75°C. The PCMs could reduce the inner sur-face temperature about 1°C. During continuous air conditioning, the walls' inner surface temperature fluctuations were different, and the inner surface temperature fluctuation of reference wall was large because it was weak of resisting the outdoor air temperature fluctuations. Table 2 shows that the fluctuation amplitude of reference wall's inner surface temperature was 2.5°C, while it of PCM wall's was 1.9°C. With latent heat storage of PCMs, the PCM wall can effectively prevent the heat transferred from the outdoor to indoor, and achieve heat attenuation as well as temperature delayed.

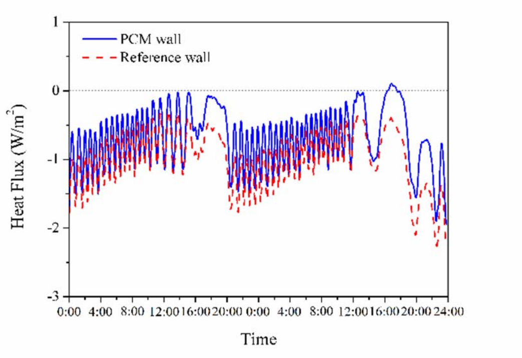
The negative value of heat flow in Fig. 4(b) means that heat was transferred out of the wall's inner surface, because the inner surface temperature was higher than the indoor air temperature. The inner surface heat flow of PCM wall was significantly lower than the reference wall, and the PCM wall with excellent energy saving potential could reduce the inner surface heat flow about 40%.

Table 2. The inner surface temperature fluctuations during continuous air conditioning.

Wall type	Maximum value (°C)	Minimum value (°C)	Fluctuation amplitude (°C)
PCM wall	17.9	16	1.9
Reference wall	19.2	16.7	2.5



(a) Inner surface temperature



(b) Inner surface heat flux

Fig. 4. The variations of inner surface temperature and heat flow during continuous air conditioning.

3.2. The experiment results of intermittent air conditioning

The intermittent air conditioning means that residents open air conditions to adjust indoor air temperature in an individual room, which can reduce the air conditioning time and area to a large extent [8-9]. Because the heating equipment starts and stops frequently during intermittent heating, the building envelopes are always storing and releasing heat while the indoor environment is changing. The thermal performance of building envelope during intermittent air conditioning is much different from the continuous air conditioning. The intermittent operation condition in this paper refers to one of the typical work schedules in office building [10], namely opening air condition during 8:00-18:00 and closing in other times. The measurement was carried out from 0:00 July 31st 2015 to 24:00 July 1st 2015.

Fig. 5 shows the variations of the indoor and outdoor air temperatures during intermittent air conditioning. With the change of the air condition operation, the indoor air temperature changes significantly. The indoor air temperature dropped quickly to the lower limit of the setting temperature 20 minutes after start. The compressor was then suspended off because the air condition power was very large. When the indoor air temperature rose to the upper limit of the setting temperature, the compressor started working and the indoor air temperature decreased again. As a result, there was a cycle of reciprocating fluctuations. The indoor air temperature was relatively stable in 4 hours after cooling, and it rose rapidly after the air conditioning was off. The indoor air temperature increased to the normal level in about 1 hour after stopping cooling.

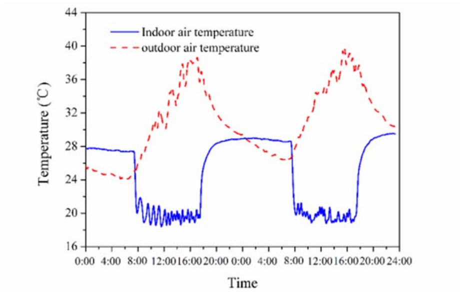


Fig. 5. The variations of indoor and outdoor air temperature during intermittent air conditioning.

Fig. 6 presents the variations of the inner surface temperatures during intermittent air conditioning. The wall inner surface temperature decreased as the indoor air temperature decreased with air conditioning on, but its cooling rate was much lower than that of the indoor air temperature. The wall's inner part is storing cold. However, the inner surface temperature of two walls changed very fast in the first 30 minutes after cooling, and the drop rate became slowly after that. The inner surface temperature stayed stable in 4 hours after air conditioning, which indicated that the cold storage of wall units had reached saturation. During the air conditioning operation time, the inner surface temperature of the PCM wall changed more rapidly than the reference wall, and the inner surface temperature of the PCM wall was about 1.5°C lower than the reference wall, which was more favorable to the indoor thermal environment during intermittent air conditioning.

After the air conditioning was off, the wall's inner surface temperatures increased exponentially as the indoor air temperature increased. The indoor air temperature rose to higher than the inner surfaces temperature in 30 minutes after closing the air condition, which means the walls began to release the cold which was stored during the air conditioning time to the in-door environment. The inner surface temperature of the reference wall rose higher than the air temperature at around 20:00-21:00, which means the cold releasing was completed. The inner surface temperature of the PCM wall rose higher than the air temperature at around 23:00-23:30, and cold releasing was completed. Because of the latent heat storage of PCMs when phase changing, the cold stored by the PCM wall was larger than the reference wall, so the cold releasing time of the PCM wall was about 2 hours longer than the reference wall. Moreover, the PCM wall's inner surface temperature was lower than the reference wall during the air conditioning suspension time, which was more beneficial in maintaining the indoor thermal environment in the comfortable range.

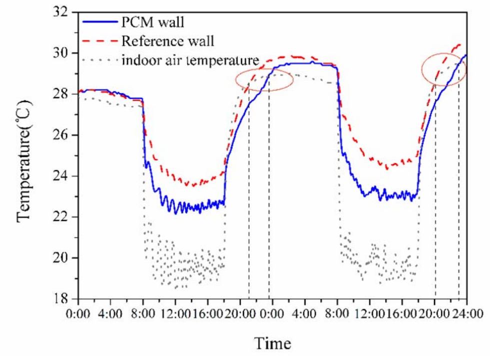


Fig. 6. The variations of the inner surface temperatures during intermittent air conditioning.

4. Discussion

When the air condition runs continuously, the PCMs were in the phase change state because the temperatures of both sides of PCM layer were in the range of 18-26°C (Fig. 7). The building envelope integrated with PCMs provide a higher thermal inertia to the building that, combined with thermal insulation can reduce the energy consumption by absorbing the heat gains and reducing the heat flow.

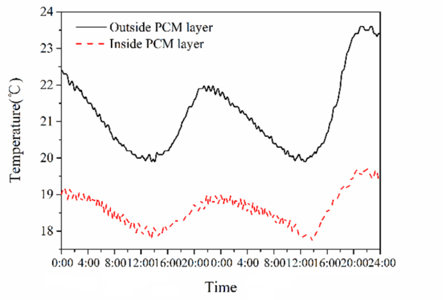


Fig. 7. The temperatures of both sides of PCM layer during continuous air conditioning.

However, during intermittent air conditioning, some of the cold transferred into the inner sur-face was stored by the wall, while the other was lose to the outdoor environment through the wall. As for the PCM wall, with decreasing temperature the PCMs changed from liquid to solid and stored cold, and with the increasing temperature after stopping air conditioning the PCMs changed from solid to liquid and released cold. Fig. 8 presents the inside and outside temperatures of the PCM layer and the temperature difference between them. Owing to that the outdoor air temperature was higher than the indoor air temperature in summer, the heat was always transferred from outside to inside, and the outside temperature of PCM layer was higher than the inside. The inside and outside temperatures of the PCM wall were higher than the phase transition temperature before air conditioning, indicating that the PCM layer acted as an insulation. The inside temperature of the PCM layer decreased quickly after cooling, and the temperature difference increased which means PCM layer was storing cold. After the suspension of air conditioning, the temperature difference between the two sides of the PCM layer decreased, and it reached relative stable in 6-7 hours (around 0:00), which indicated the end of the PCMs exothermic process. During the intermittent air conditioning, the phase change wall can absorb more cold, and release it to the indoor environment after stop cooling. Therefore, the air conditioning time and energy consumption can be reduced to a certain ex-tent through reasonably controlling the air conditioning process when the indoor air temperature is maintained in the comfort range by the rational use of PCM wall's exothermic process.

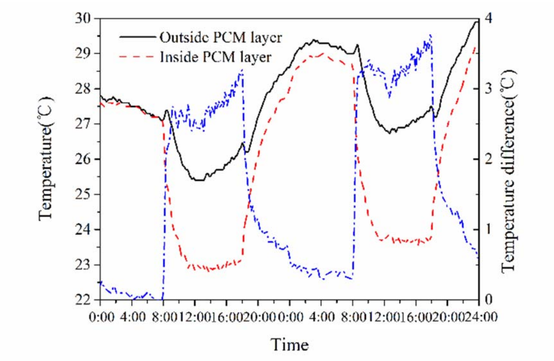


Fig. 8. The temperatures of both sides of PCM layer during intermittent air conditioning

5. Conclusions

This paper studied the thermal performance improvement of building envelope by PCMs when air condition run continuously and intermittently. The results showed that the PCMs could reduce the inner surface temperature 1°C and the inner surface heat flow about 40% during continuous air conditioning. When the air condition ran intermittently by the working schedule, the PCMs could also reduce the inner surface temperature 1°C, and the cold releasing time of PCM wall was 2 hours longer than the reference wall. The PCMs can improve the thermal performance of building envelope significantly.

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