Experimental study of thermal characteristics for a novel ventilation roof with composite phase change material (VRCPCM)

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Abstract. A phase change material particle (PCMP) was prepared by vacuum adsorption method, with the binary eutectic mixture of myristic acid and tetradecanol as phase change material (PCM) and expanded vermiculite (EVM) as porous adsorption materials. Then PCMPs were pressed into composite phase change plates (CPCP) for the outside layer of roof to store the heat passively. The active cooling storage was provided by the cold water in the seamless steel pipe and the iron box containing binary eutectic mixture of lauric acid and tetradecanol on the indoor side. Combined with the ventilation roof, a novel ventilation roof with composite phase change material experimental hut was constructed. The cold storage performance test was conducted under the two strategies which were regularly opened ventilation layer at certain time and timing cooling while regularly opened ventilation layer. The first strategy result showed that CPCP effectively reduced the temperature of the outer surface of the roof and the ventilation layer was turned on at night, which could effectively reduce the indoor air peak temperature. The second strategy result under the active cooling condition showed that the indoor PCM could absorb the heat of the indoor air and reduce the indoor temperature and the indoor temperature fluctuation range.

1. Introduction
In recent years, phase change materials have become more and more widely used. Heat storage is an important means to improve energy efficiency [1]. The heat storage of buildings can achieve by sensible heat and latent heat (PCMs and other thermal inertial materials) [2]. Latent heat storage is considered to be the most efficient thermal energy storage technology [3, 4]. The application of phase change energy storage technology in buildings can improve thermal comfort and reduce indoor temperature fluctuations and building energy consumption.

This study used the vacuum adsorption method to adsorb the PCM into the porous building materials to form phase change material particle. And then PCMPs were compressed by mold pressing method to obtain CPCP which was laid on the outer surface of the roof. Under the roof, the experimental hut provided with a ventilation air layer which was transparent to the north and south, and the air layer and the indoor air were insulated by the low-temperature phase change plate. This study not only used phase change energy storage technology, but also combined ventilation to regulate indoor thermal environment by using natural energy. Therefore, the content of this study has important practical significance in the field of buildings energy efficiency.

2. Preparation and analysis
2.1. Preparation of composite phase change plates (CPCP)
2.1.1. Selection of materials. Experimental studies were performed at Tianjin, China, which has a hot and dry summer. According to the Ref. [5], the suitable phase change temperature for PCM used in outside layer is 33–35 °C. Tetradecanol (TD, purity ≥98%, melting point 43.05 °C) and myristic acid
MA, purity \( \geq 99\% \), melting point 54.74 °C) were selected in this experiment. A binary eutectic mixture was prepared with a mass ratio of TD:MA=69.65:30.35 and applied as outdoor side PCM.

PCM is in a liquid phase after being melted, and is not suitable for direct use in construction components. In this experiment, expanded vermiculite (EVMT, purchased from Xingxian Xinlei Mineral Powder Processing Factory) was selected as the porous material to adsorb the PCM to prepare PCMP, and then it can be combined with the building envelope.

### 2.1.2. Preparation of composite phase change plate (CPCP)

PCMP was prepared by vacuum adsorption. The specific preparation steps are as follows: (1) According to the optimum adsorption ratio of EVMT (EVMT: PCM = 40%: 60%), EVMT and PCM were added to the drum, and then the circulating water vacuum pump was pumped to a vacuum of 0.05 MPa and maintained. (2) Turned on the electric heater to heat the water at the bottom of the drum to boiling; (3) Adjusted the frequency of the motor to make the drum rotate at a constant speed of 60 rad/min; (4) After 2 hours, opened the vacuum valve and stopped heating, so that the PCMPs were cooled to normal temperature under normal pressure; (5) Turned off the motor and discharge.

The PCMPs and styrene-acrylic emulsion (85%:15%) were simultaneously added to the mixer, and then put the mixture evenly spread in the prepared mold. A constant pressure of 5 MPa was given. After the press molding, the mold was disassembled and left to dry naturally. The CPCP was finished.

### 2.2. Measurement and analysis of DSC

For the inside PCM(PCM2), a binary eutectic mixture of fatty acids and fatty alcohols is also selected as the indoor PCM. The tetradecanol (TD, purity \( \geq 98\% \), melting point 43.05 °C) and lauric acid (LA, purity \( \geq 99\% \), melting point 54.74 °C) were selected. The mass ratio is TD: LA = 48.23: 51.77. Figure 1(a) shows the DSC curves for PCM1 which has high melting point (31.24 °C) and can be used for the outside layer of VRCPCM. Figure 1(a) shows the DSC curves for PCM2 which has relatively low melting point (24.12°C) and is suitable for using inside layer of VRCPCM.

### 2.3. Composition of ventilation roof with composite phase change material (VRCPCM)

The structure sketch of the VRCPCM is shown in Figure 2.
3. Scheme and strategy

3.1 Overview of experimental system

The CPCP is selected as the PCM1 layer of VRCPCM experimental hut. PCM2 is poured into a square iron box, and a seamless steel pipe with a diameter of 10 mm is welded every 100 mm in the width direction of the iron box. The two ends of the steel pipe are connected with the water divider and the water collector which are connected with the programmed cryostat which controls active cooling.

When the solar radiation is strong in the daytime, the topside PCM1 melts and absorbs most of the heat passively, so that the heat is stored outdoors. The phase change temperature of the PCM2 in the iron box located in the indoor side is close to the comfort temperature of human. It reduces the fluctuation range of indoor temperature and maintains the thermal comfort of human body. At the same time, cold water pipes in iron boxes are used for active cooling in order to charge the PCM2. The air layer in the middle can increase the heat transfer resistance of the whole roof. The combination of the above three parts can increase the insulation effect of the roof and cool the indoor environment.

The comparison hut has the same structure as the experimental hut. The difference is that the comparison hut uses two 3cm extruded polystyrene boards instead of the outdoor side CPCP and the square iron box filled with PCM on the indoor side.

3.2 Experimental strategy

This study was divided into the following two strategies:

(1) Ventilation layer regularly opened
During the experimental test, the doors and windows of the experimental hut and the comparison hut were closed. The ventilation floor was closed from 8:00 to 18:00 and opened from 18:00 to 8:00 the next morning. In the case of high temperature during the day, the outdoor PCM absorbed heat and stored it passively. At night, the ventilation layer opened to cool the outdoor PCM to release heat and store cold energy.

(2) Ventilation layer regularly opened and combined timing cooling
During the experimental test, the doors and windows of the experimental hut and the comparison hut were closed. The cold water(20°C) was supplied from 8:00 to 18:00 during the day for active cooling. At the same time, the air layer was closed. The indoor temperature was lowered while the indoor PCM was stored for a part of the cooling capacity. The cooling was stopped at 18:00 to 8:00 the next morning and the ventilation layer was turned on. The indoor PCM released the cooling capacity, and the ventilation layer took away the heat stored in the outdoor PCM to continue to maintain the indoor temperature.

3.3 Experimental point arrangement

The thermocouples were arranged in the same position in the experimental hut and the comparison hut. Figure 3 shows the layout of the experimental points.

![Figure 3. Experimental point distribution](image)

4. Results and discussion

(1) Ventilation layer regularly opened
At this stage, the ventilation layer was regularly opened for cold storage. The test began at 00:00 on
As shown in Table 1, the indoor peak temperature comparisons of the experimental hut and the comparison hut. It can be seen from the table that the average peak temperature in the experimental hut and the comparison hut is reduced by 23.81°C and 17.21°C respectively compared with the average value of the three-day peak temperature of the outdoor air integrated temperature. And the experimental hut is reduced 6.69°C compared with the comparison hut. For the comparison hut, the ventilation layer is opened at night to accelerate the room heat dissipation, so the peak temperature is lowered during the daytime. For the experimental hut, on the one hand, the opening of ventilation layer accelerated indoor heat dissipation and lowered temperature. On the other hand, when the temperature decreases at night, the heat released passively as indoor side PCM solidify. So the PCM can lower the indoor temperature.

Table 1. Comparison of peak temperature between experimental hut and comparison hut.

| Date     | 3.9.2018 | 4.9.2018 | 5.9.2018 | Average |
|----------|----------|----------|----------|---------|
| $T_{air-out}$ (°C) | 53.61    | 54.36    | 57.64    | 55.20   |
| $T_C$ (°C)             | 35.60    | 37.78    | 40.87    | 38.08   |
| $T_E$ (°C)             | 29.51    | 30.69    | 33.97    | 31.39   |
| $T_{air-out} - T_C$ (°C) | 18.01   | 16.58    | 16.77    | 17.21   |
| $T_{air-out} - T_E$ (°C) | 24.10   | 23.67    | 23.67    | 23.81   |
| $T_C - T_E$ (°C)       | 6.09     | 7.09     | 6.90     | 6.69    |

Table 2 compares the time of indoor peak temperature and delay time between the experimental hut and the comparison hut. It can be seen from the table that the average peak temperature delay time of the experimental hut and the comparison hut is 220 min and 180 min respectively compared with the outdoor temperature. The peak temperature delay time of the experimental hut is 40 min compared with the comparison hut. When the air layer opens at night, the comparison hut can release heat faster and reduce the indoor temperature, while the experimental hut can reduce the indoor temperature and allow the PCM to store more cooling capacity. However, the delay time is not large, indicating that merely increasing the roof thermal inertia does not significantly increase the delay time.

Table 2. Time comparison of peak temperature between experimental hut and control hut.

| Date     | 3.9.2018 | 4.9.2018 | 5.9.2018 | Average |
|----------|----------|----------|----------|---------|
| $\tau_{air-out}$ | 11:50    | 12:00    | 11:40    | /       |
| $\tau_C$  | 15:10    | 14:40    | 14:40    | /       |
| $\tau_E$  | 15:50    | 15:30    | 15:10    | /       |
| $\tau_C - \tau_{air-out}$ (min) | 200      | 160      | 180      | 180     |
| $\tau_E - \tau_{air-out}$ (min) | 240      | 210      | 210      | 220     |
| $\tau_E - \tau_C$ (min)         | 40       | 50       | 30       | 40      |

(2) Ventilation layer regularly opened and combined timing cooling

At this stage, the ventilation layer regularly opened and combined timing cooling. The test began at 00:00 on September 7, 2018, and ended at 00:00 on September 10.

Figure 4 shows the comparison of the temperature of each floor of the roof. The average peak temperatures of $T_{out}$, $T_{mid}$, $T_{top}$, $T_{bottom}$, $T_{in}$, $T_{in}$ are 37.33°C, 35.60°C, 29.54°C, 23.36°C, 25.00°C, 28.66°C respectively, where $T_{out}$ is the highest and $T_{bottom}$ is the smallest. This shows that when the temperature wave is transmitted to the lower surface of the air layer, its peak temperature has been reduced to a minimum. Due to active cooling, the temperature of the $T_{bottom}$ can be maintained below the freezing point and absorb heat from the roof. Similarly, under the condition...
of active cooling, $T_{r_{in}}$ is maintained at a lower temperature. However, the CPCP layer, structural layer and air layer can insulate the influence of the outdoor environment, so $T_{a_{bottom}}$ is smaller than $T_{r_{in}}$. Besides, affected by the indoor temperature, $T_{r_{in}}$ absorbs heat and rises temperature. At night, the ventilation layer is opened, and all layers of the roof can be lowered to a lower temperature, that make the low-temperature PCM on the indoor side solidified and stored cold.

![Figure 4. Temperature comparison of each floor of the ventilation roof](image)

5. Conclusion
In this study, the practicability of the VRCPCM was verified by the comparative test of two huts. The results show that the use of outside PCM can significantly reduce the peak temperature of roof exterior surface. It can melt to absorb heat in high temperature environment during the day, and release heat to low temperature environment at night, so as to maintain a higher temperature on the exterior surface. In the case of zero energy consumption (when the ventilation layer regularly opened), the indoor air peak temperature can be effectively reduced. And the time of peak temperature of the experimental hut is delayed despite it is not delayed so long showed that other effective measures should be taken to delay the time of peak temperature. When the ventilation layer regularly opened and combined timing cooling, indoor side PCM as an indirect cold source could effectively absorb the heat in indoor air and reduce the fluctuation range of indoor air temperature. In the case of active cooling, the indoor PCM absorbs the heat of indoor air during the day and stores it in latent heat, and releases it into the indoor at night to reduce the indoor temperature fluctuation range and improve the indoor environment thermal comfort. In addition, by comparing the two strategies, we can see that the VRCPCM roof has shown good performance without auxiliary cold source. Of course, adding active cooling can improve indoor thermal comfort better, which needs further research. This work therefore provides justifications for the application of VRCPCM.

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