THERMAL PERFORMANCE EXPERIMENT AND NUMERICAL SIMULATION OF MICRO-PCM CEMENT MORTAR COMPOSITE WALL

by

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In order to reduce the heat transfer between indoor and outdoor environments and reduce the influence of outdoor ambient temperature fluctuation on the indoor environment, adding micro-PCM to the building envelope is one of the effective means. Micro-PCM can "intelligently" control temperature by absorbing or releasing heat during phase change to maintain temperature stability. In this paper, the phase change temperature-adjustable mortar was prepared by using micro-PCM with a phase change temperature of 25 ℃, and was painted on the surface of cement wallboard (300 × 100 mm) to form a phase change thermostatic mortar layer with a cross-section size of 300 × 20 mm. The solar radiation on the outer surface of the building envelope was simulated by an incandescent lamp. The influence of micro-PCM on the temperature control performance of cement wallboard was tested. The thermal performance of the PCM wallboard was simulated by COMSOL software. Results show that compared with ordinary cement wallboard, when the micro-PCM content is 40%, the maximum temperature of the inner wall can be reduced by 5.17 ℃, and the time to reach the maximum temperature is delayed by 145 minutes. The temperature fluctuation amplitude of the inner wall is reduced by 1.90 ℃, and the maximum instantaneous heat transfer is reduced by 22.202 W/m^2.

Key words*: phase change temperature-adjustable mortar, thermal performance building envelope heat transfer, inner wall surface temperature*

Introduction

With the rapid development of social and economic development, the consumption of energy in various industries is also increasing. At present, China's annual energy consumption has ranked second in the world. Reducing energy consumption and carbon emissions has become the goal of sustainable development for all countries in the world. The three major areas of energy consumption in China are construction, industry and transportation. Among them, the energy consumption of the construction industry accounts for about 1/3 of the total energy consumption of the whole society, the carbon dioxide emissions of the construction industry account for more than 1/4 of the total carbon emissions of the country, and the energy

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consumption in the building operation stage accounts for more than 70% of the building energy consumption. At present, the air conditioning system, which includes HVAC, is an important part of the energy consumption during the operation phase of a building. The frequency of use of these devices is closely related to the material, design and construction of the building envelope. The energy consumption of the HVAC system can be effectively reduced by improving the thermal insulation performance of the building envelope. However, at present, traditional building materials (concrete, brick, sand, *etc*.) and thermal insulation materials are sensible heat storage, and heat storage performance, energy saving and emission reduction effect is poor. Therefore, the research and development of new building energy-saving technology, improving the living environment conditions and reducing the energy consumption and carbon emissions in the building operation stage, have become the top priority of energy conservation work in the new era, which has important theoretical and practical significance for the realization of China's *double carbon* goal.

Using phase change energy storage technology to reduce building energy consumption is one of the hotspots of building energy conservation research. Phase change energy storage technology is a new and effective way of energy storage with good application prospects. Its principle is to store energy and improve energy utilization efficiency by using PCM, which have two outstanding advantages of large heat storage per unit body and almost constant temperature in the endothermic and exothermic process. The use of PCM as energy storage media in the building envelope can significantly increase the thermal inertia of the envelope, thus weakening the amplitude of the thermal cycle and preventing excessive abrupt changes in the internal temperature of the building. Figure 1 shows the schematic diagram of the principle of the phase change energy storage wall to adjust the indoor temperature. The PCM will undergo an alternating process of melting heat absorption and solidification heat release according to the change of the external environment temperature, which makes the phase change cement wallboard have the ability to maintain the indoor temperature stable within the comfortable temperature range of the human body. Therefore, PCM have a good application prospect in the field of building energy conservation.

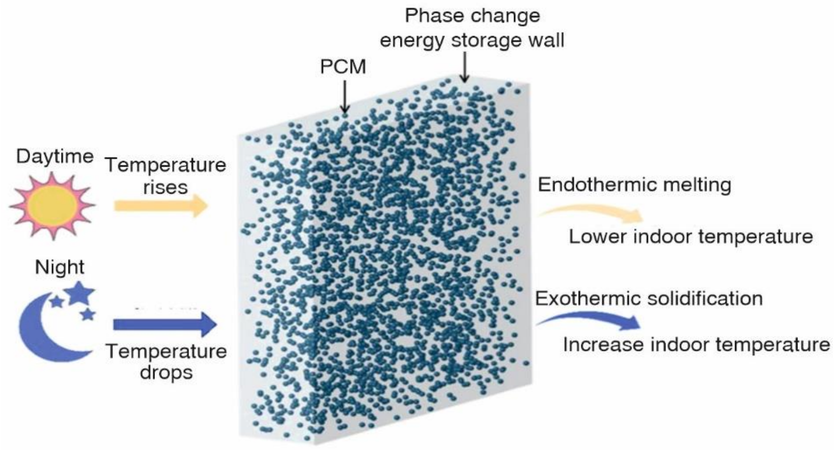

Figure 1. Schematic diagram of the cooling and heating cycle function of the PCM composite wall

At present, researchers in various countries have carried out extensive research on phase change energy storage building materials. Early researchers directly added PCM to building materials, but it was found during the experiment that solid-liquid PCM would cause three problems that cannot be ignored: leakage, PCM interacts with building material matrix, and reduce heat transfer efficiency. In order to overcome the previous problems, the researchers developed a shaped PCM. The shape-stabilized PCM include shape-stabilized phase change aggregate, macro-encapsulation PCM and micro-encapsulation PCM. Among them, micro-encapsulation phase change materials (micro-PCM) are a new type of composite PCM, which are composed of solid-liquid PCM (core materials) coated by a stable polymer membrane (shell material). Using micro-PCM, researchers have developed different kinds of energy storage building materials. For example, Griffiths and Eames [1] added micro-PCM (phase change temperature is 18 °C) to the mortar and coated them on the ceiling as heat storage media to study their heat transfer performance. The results show that adding micro-PCM can effectively reduce the ceiling temperature. Cui *et al.* [2] prepared graphite-modified micro-PCM and combined it with cement mortar to develop a phase change temperature-controlled cement mortar board. Results show that when the micro-PCM content in cement mortar reaches 20 wt.%, the indoor temperature adjustment effect is obvious compared with ordinary cement mortar board. The maximum temperature difference can reach 3.6 °C, and the peak temperature delay time is increased by 3 minutes. Han *et al.* [3] mixed micro-PCM with ordinary paint at 1:1 and coated it on the wall surface, which could reduce the indoor temperature by 5~6 °C, greatly reduce the use time of air conditioning, and save 26% of power consumption. In summary, the introduction of micro-PCM into building materials can play a role in heat storage and thermal insulation, improving the thermal inertia of the building envelope, reducing indoor temperature fluctuations, and reducing building energy consumption. However, the introduction of foreign particles will change the micro-structure of building materials, thus affecting the mechanical properties of building materials. For example, Djamai *et al.* [4] conducted mechanical experiments on cement mortars containing 5 wt.%, 10 wt.%, and 15 wt.% micro-PCM. The results show that the strength of the composite is reduced by 70.5% by adding 20 wt.% micro-PCM. Yu *et al.* [5] combined micro-PCM with cement mortar to develop a thermal energy storage cement mortar. The results show that the 28*d* compressive strength and flexural strength of the cement mortar mixed with 20% micro-PCM are 36.5 MPa and 6.2 MPa, respectively, and the mechanical strength is slightly lower than that of ordinary cement mortar. Das *et al.* [6] substituted micro-PCM for fine aggregates in high-fluidity cement mortar to study the mechanical properties of phase change temperature-adjustable mortar. The results show that the compressive strength of cement mortar with 5 wt.% and 10 wt.% micro-PCM is reduced by 15% and 54%, respectively. In order to overcome the problem of mechanical strength decline of building materials caused by micro-PCM, micro-PCM mixed with cement mortar was applied to the building envelope, which not only avoided the strength loss of structural materials, but also improved the thermal performance of the envelope [7].

In addition, when domestic and foreign scholars study the role of micro-PCM in the field of construction, most of them consider the uniform distribution or neat arrangement of micro-PCM in the matrix to make phase change layer, but do not consider the irregular arrangement of micro-PCM in the matrix structure. In view of this, this study randomly distributed micro-PCM in cement mortar, studied the phase change temperature-adjustable cement mortar, and explored its thermal properties. The micro-PCM random distribution heat transfer model was constructed by using MATLAB random distribution program and COMSOL finite element software, and the heat storage performance of the PCM mortar wallboard was simulated and analyzed. By simulating and analyzing the temperature variation of the inner surface of the wall with time during the heat transfer process of the phase change temperature-adjustable mortar wallboard, the temperature fluctuation of the inner surface of the ordinary wallboard and the phase change temperature-adjustable mortar wallboard is compared during the heat transfer process. The relationship between the content of micro-PCM in the phase change temperature-adjustable mortar wallboard and the temperature amplitude, heat flux and temperature delay of the inner/outer wall surface of the wall is obtained.

Experiment

Raw material

In this paper, micro-PCM produced by Anhui Microdelivery Smart Microcapsule Sci & Tech Co. Ltd. is used as an additive to cement mortar to obtain a microencapsulated passive heat-regulating composite material coated on the wall. The microcapsule method utilizes film-forming substances. The PCM is wrapped in it to form a tiny core-shell structure. The core material is paraffin wax with latent heat storage energy, which can maintain a specific temperature during the phase change process. The PCM content in each capsule accounts for about 85-90% of the total weight. The micro-PCM wall is composed of a stable, inert polymer with a particle size between 5 and 1000. The phase change temperature is 26.44 °C, and the latent heat of phase change is 175.39 J/g, fig. 2. The appearance of micro-PCM is shown in fig. 3, with many wrinkles on the surface. This is caused by the volume change caused by the phase change of the PCM in micro-PCM.

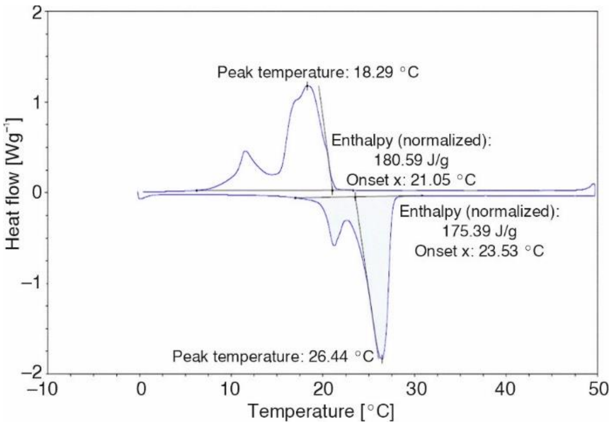

Figure 2. Micro-PCM DSC

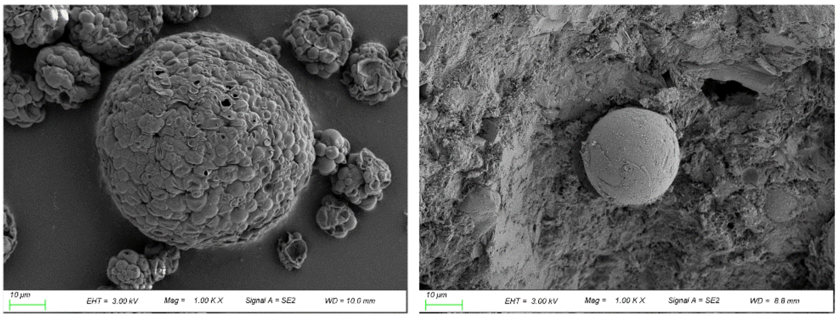

Figure 3. The SEM diagram of micro-PCM

Preparation of phase change building materials and experiment of heat storage characteristics

In order not to affect the mechanical properties of the wall, the phase change cement mortar (micro-PCM-CM) is coated on the outside of the wall in the form of plaster. The raw materials are P.O32.5 ordinary Portland cement, ISO standard sand, tap water, and micro-PCM.

The experiment mix ratio is based on the proportion requirements in the Design Regulations for Masonry Mortar Mix Ratio (JGJT 98-2010) and combined with previous relevant experience. The mix ratio design is shown in tab. 1. The mix was prepared under a constant water-cement ratio and the constant ratio of fine aggregate to cement (W/C = 0.6 and FA/C = 6.95), and 7.5% of medium sand was replaced by micro-PCM. To prevent the micro-PCM from breaking, the micro-PCM is added in the last step. The first step is to put the cement and water in the mixing bucket and start the mixer. The mixing procedure is as follows: Low speed 30 s → sand 30 s → high speed 30 s → stop 90 s → add micro-PCM and water reducing agent at high speed 60 seconds, and finally adjust the amount of high-efficiency water reducing agent (0~1.1% of cement content), so that cement mortar has ideal fluidity (consistency value 70 mm). It is easy to be coated on the surface of the wall specimen (300 mm × 300 mm × 100 mm), and the coating thickness of micro-PCM-CM is 20 mm. The preparation process of the specimen is shown in fig. 4. Finally, the prepared phase change energy storage wall (micro-CPM-W) was placed in a curing box with a temperature of (20 ±2) °C and humidity greater than 95% for maintenance. The next phase change energy storage experiment was carried out after 7 days of maintenance.

Table 1. Micro-PCM-CW ratio

Volume fraction	Mass fraction	Cement [kgm^{-3}]	Water [kgm^{-3}]	ISO standard sand [kgm^{-3}]	Phase change materials [kgm^{-3}]	High-efficiency water reducing agent (SP)	Consistency
0%	0%	230	138	1600	0	0~1.1%	70 mm
17.8%	7.5%	212.9	127.74	1480	120	0~1.1%	70 mm

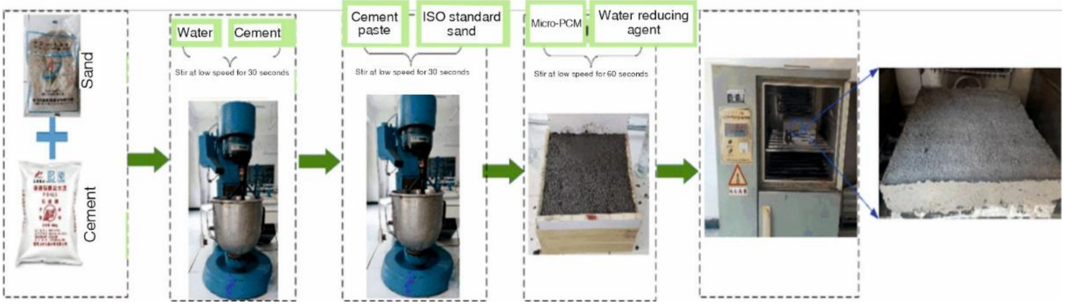

Figure 4. Preparation process of micro-PCM cement mortar

In numerical calculations, volume fractions are usually used. Mass fractions were converted to volume fractions in order to use the formula:

$$f_{\text{micro-PCM}} = \frac{w_{\text{micro-PCM}}}{\dfrac{\rho_{\text{micro-PCM}}}{\rho_{\text{cement}}} + w_{\text{micro-PCM}}\left(1-\dfrac{\rho_{\text{micro-PCM}}}{\rho_{\text{cement}}}\right)} \tag{1}$$

where $f_{\text{micro-PCM}}$ and $w_{\text{micro-PCM}}$ are the volume fraction and mass fraction of micro-PCM respectively, $\rho_{\text{micro-PCM}}$ and ρ_{cement} are the density of micro-PCM and the density of cement mortar, respectively, and $\rho_{\text{micro-PCM}}$ = 694 kg/m^3.

Heat storage performance experiment

In order to test the temperature control performance of micro-PCM-W, the size of the temperature control experiment chamber made by the research group is 1600 mm × 380 mm ×

380 mm. A 100 W incandescent lamp is fixed on the top of the experiment chamber as a heat source for radiant heat transfer. In order to reduce the heat exchange between the experiment chamber and the external environment, two 40 mm thick polyurethane foam insulation boards are pasted on the inner wall of the experiment chamber, and the surface of the insulation board is pasted with grid lines to strengthen the tin foil paper. The acquisition equipment was a Captec Entreprise HFM-8 heat flux acquisition instrument and an HS-30 heat flux density meter purchased by the research group. The heat flux sensing surface was 30 mm × 30 mm and the *T*-type thermocouple was built in. In order to accurately measure the upper and lower temperatures and surface heat flow of micro-PCM-W, HS-30 heat flow density meters are arranged on the upper and lower surfaces of micro-PCM-W. One HS-30 heat flow density meter is arranged on the upper surface, and two HS-30 heat flow density meters are arranged on the lower surface. On the lower surface, the average of the experiment results of the two measuring points is taken as the heat flow and temperature measurement values. The arrangement of measuring points is shown in fig. 5.

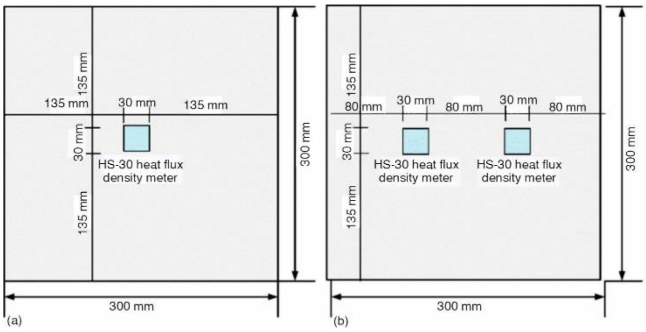

Figure 5. Experiment points of HS-30 heat flux density meter; (a) Cement upper surface measuring point and (b) cement subsurface measuring point

Before the experiment, the specimen was placed in a freezer with a refrigeration temperature of 8 °C for 24 hours to stabilize the initial temperature of micro-PCM-W at 8 °C. During the experiment, when the HS-30 heat flux density meter was installed at the experiment point, the measured temperature of micro-PCM-W was 10 °C, and the measured temperature was taken as the initial temperature for numerical calculation. In addition, the HFM-8 heat flux acquisition device was set to collect temperature and heat flow values every 1 minute. Launch HFM8-lab software in the computer was started, communication between Launch HFM8-lab software and HFM-8 heat flux acquisition equipment was established, and the acquisition equipment was set to synchronously store experiment data. Third, the incandescent lamp switch is turned on, so that the incandescent lamp continues to provide heat in a radiating manner, and at the same time, the device starts to collect values. The experiment time of the two phase-change cement boards is 624 minutes. The experiment process is shown in fig. 6.

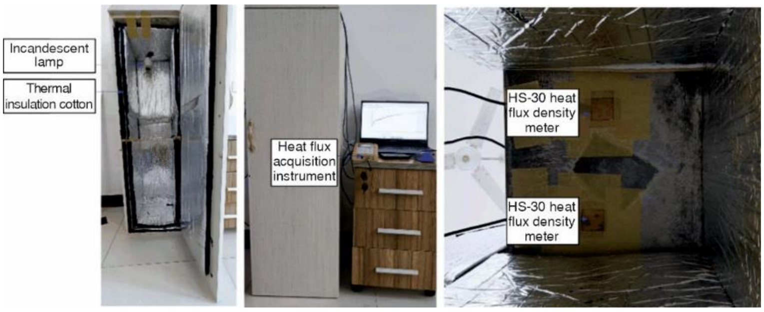

Figure 6. Micro-PCM-CMW heat storage experiment system

Simulation of phase change wall

Geometric model

In this paper, the random distribution model of PCM particles is established by using the RAND function in PFC software, fig. 7. The model is generated according to the following algorithm:

- Input the number of Micro-PCM, the radius of the phase change material particles and the size of the matrix material model.
- Use the RAND function to randomly generate the first Micro-PCM coordinate value.
- Use the RAND function to randomly generate the position of Micro-PCM, and determine whether the Micro-PCM will intersect with the already generated Micro-PCM. If it does not intersect, the Micro-PCM model will be generated, and vice versa.
- Repeat the above process until the specified number of Micro-PCM is generated.

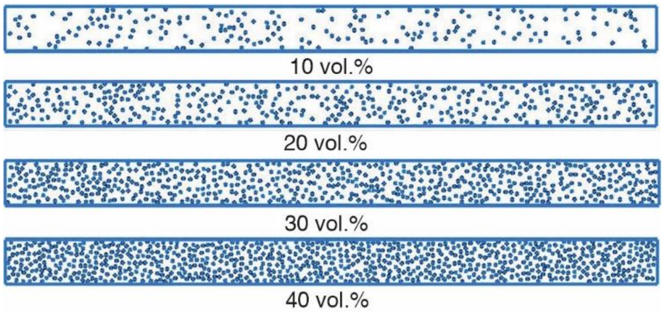

Figure 7. Flow chart of random distribution model of micro-PCM particles in cement mortar

Physical model

As shown in fig. 8, the thickness and height of the study micro-PCM-W are 100 mm and 300 mm, and the thickness of micro-PCM cement mortar is 20 mm. The thermophysical parameters of the concrete wall [8] are: $\rho_w = 1800$ kg/m^3, $k_w = 0.81$ W/m/K, $C_{p,w} = 1.05$ J/kgK, and the thermophysical parameters of the micro-PCM are: $\rho_{\text{micro-PCM}} = 880$ kg/m^3, $k_{\text{micro-PCM}} = 0.232$ W/m/K, $L_{\text{micro-PCM}} = 175.39$ J/g, $C_{p,\text{micro-PCM}} = 3.22$ J/kgK, $T_m = 26.44$ °C. It is assumed that the phase change takes place in a small temperature range $[T_s, T_l]$, and $T_s = T_m - \Delta T_m/2$, $T_l = T_m + \Delta T_m/2$, $\Delta T_m = 1$ K. The left side of micro-PCM-W is the indoor environment; the right side is the outdoor environment, and the upper/lower surface is insulated.

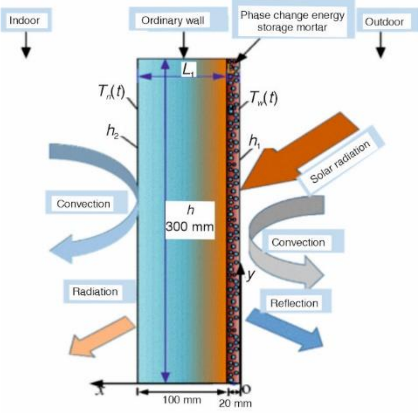

Figure 8. Micro-PCM-W model (Micro-PCM, 7.5 vol.%)

Mathematical model

In order to simplify the calculation, the following assumptions are made for the problem under study [9]:

- Micro-PCM is randomly distributed in cement mortar, ignoring the change of volume during phase change.
- Wall, cement mortar and micro-PCM are isotropic and constant-property.
- Due to the small particle size of micro-PCM, the influence of natural convection is ignored.
- The thickness of the wall is much less than the width and height, the temperature only changes along the thickness direction, and the heat transfer process is a 1-D heat transfer process.

Governing equation

In this paper, the equivalent heat capacity method is used to theoretically model the phase change process of melting and solidification. The governing equation is:

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T \tag{2}$$

where ρ is the density, C_p – the specific heat capacity, T – the temperature, and k – the coefficient of heat conduction.

In order to ensure the stability of the calculation, the phase change is assumed to occur in a very small temperature interval [T_s, T_l], and the temperature interval $\Delta T_m = T_l - T_s = 1$ K, $T_s = T_m - \Delta T_m/2$, $T_l = T_m + \Delta T_m/2$. When $T < T_s$ is a solid phase, $T < T_l$ is a liquid phase, and $T_s < T < T_l$ is a mixed phase. Then the relationship between each phase and the liquid fraction is:

$$f = \begin{cases} 0 & T < T_\mathrm{s} \\ \dfrac{T - T_s}{T_l - T_s} & T_\mathrm{s} \le T < T_l \\ 1 & T > T_l \end{cases} \tag{3}$$

where T_s is the upper limit of the solid phase temperature, T_l – the lower limit of liquid phase temperature, and the subscripts *s* and *l* represent the solid and liquid phases, respectively.

According to the definition of liquid phase volume fraction, the equivalent heat capacity C_p is given:

$$C_p = \frac{1}{\rho}\left[(1-f)\rho_s C_{p,s} + f\rho_l C_{p,l} + L_m D(T)\right] \tag{4}$$

where $C_{p,s}$ is the specific heat capacity of solid-phase micro-PCM, $C_{p,l}$ – the specific heat capacity of liquid-phase micro-PCM, $D(T)$ – the standard Gaussian function in the phase change interval ΔT_m, and the integral of this function in the phase change interval is 1.

Definite condition

In this experiment, only the temperature change is considered, so the boundary conditions of the mathematical heat transfer model of the outer building envelope are proposed:

$$q = q_0,\ x = 0 \tag{5}$$

where q_0 is the experiment value of the upper surface of the specimen with a micro-PCM volume content of 0%.

The supplementary initial conditions are:

$$T_2 = T_1 = T_0 < T_m \quad t = 0 \tag{6}$$

Finite element model of phase change wall

The COMSOL, a large general finite element software, was used to establish the finite element model, fig. 9. In the finite element simulation of heat conduction, very fine triangular mesh is used to obtain a mesh-independent convergent solution. In the simulation, the calculation time step is set to 1 second, and the PARDISO direct solver in COMSOL is used to solve the highly non-linear multi-physics coupling problem.

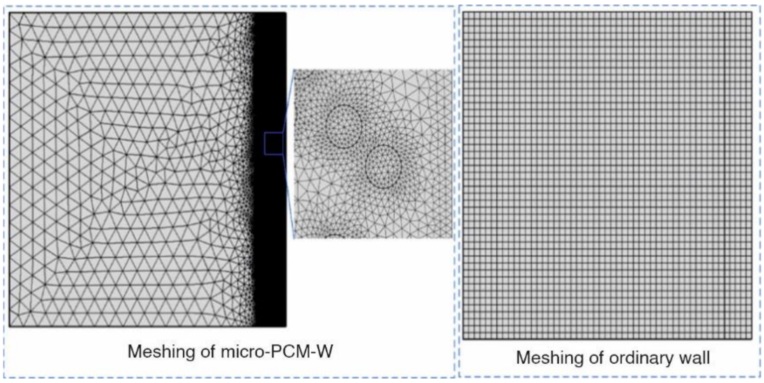

Figure 9. Meshing of micro-PCM-W and ordinary wall finite element models (PCM, 10 vol.%)

Results and discussion

Model verification

In this study, relative mean error (RME) analysis method was used to verify the results, and the relative error between the numerical simulation calculation value and the experiment value was used to characterize the difference between the results of the two research methods.

The RME is the maximum relative error, which is defined in the literature [8, 10] as:

$$RME = \text{Maximum}\left[\left(\frac{x_{\text{sim}} - x_{\text{exm}}}{x_{\text{exm}}}\right)\times 100\%\right] \tag{7}$$

Relative average error (RAE) is the average value of relative error, and the calculation as:

$$RAE = \text{Average}\left[\left(\frac{x_{\text{sim}} - x_{\text{exm}}}{x_{\text{exm}}}\right)\times 100\%\right] \tag{8}$$

where x_{sim} is the calculation result of numerical simulation and x_{exm} is the experiment value.

The heat storage experiment environment of the phase change energy storage wall is taken as the boundary condition to simulate the calculation of the phase change energy storage wall, and the experiment results are compared with the simulation results to verify the consistency of the experiment results and the numerical simulation results.

According to the comparison between the numerical simulation results and the experiment results in fig. 10, it can be seen that the curve change trend of the numerical simulation results and the experiment results are consistent. When the temperature rises to the melting temperature of the PCM, the numerical calculation results are faster than the experiment results. The maximum error rate of the internal surface temperature of the micro-PCM phase change energy storage wall is 2.24% and the average error is 1.89%. The maximum error rate and the average error rate did not exceed 3%, indicating that the calculation model established in the numerical simulation and the selected material parameters were consistent with the experiment results, and the numerical results were consistent with the experiment results.

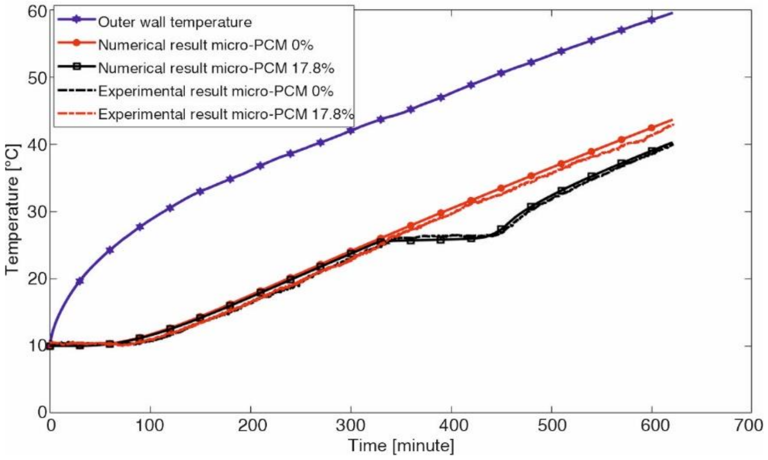

Figure 10. The numerical simulation results are compared with the experimental results

Analysis of dynamic thermal insulation performance of phase change energy storage wall under transient meteorological conditions

Based on the typical meteorological data of hot summer and cold winter areas (Zhengzhou, Henan Province), the dynamic thermal insulation of the phase change wall was analyzed. The temperature and solar radiation intensity from July 25-27, the hottest month in Zhengzhou, were selected as the boundary conditions, and the comprehensive outdoor air temperature expression was obtained by fitting the west-facing wall as an example:

$$t_{25}(\tau) = 33.0 + 8.0\sin[\pi(\tau - 8.28)/9.96] + 273.15 \tag{9}$$

$$t_{26}(\tau) = 34.5 + 9.2\sin[\pi(\tau - 8.12)/11.7] + 273.15 \tag{10}$$

$$t_{27}(\tau) = 35.0 + 9.0\sin[\pi(\tau - 9.32)/11.6] + 273.15 \tag{11}$$

In order to facilitate analysis, for micro-PCM mortar coated on the outer surface of the wall, the fixed solution conditions set in this paper are as:

Initial conditions

$$T(x,0) = T_0, \qquad x \in [0,120], \tau = 0 \tag{12}$$

Outdoor side boundary conditions:

$$-\lambda_b \frac{\partial T}{\partial x}|_{x=0} = h_{\text{in}}(T_b - T_{\text{in}}) \tag{13}$$

Indoor side boundary conditions

$$-\lambda_b \frac{\partial T}{\partial x}\Big|_{x=120} = h_{\text{out}}(T_b - T_{\text{out}}) \tag{14}$$

Insulation on the upper side of the wall

$$-\lambda_b \frac{\partial T}{\partial y}\Big|_{y=0} = 0 \tag{15}$$

Insulation on the lower side of the wall

$$-\lambda_b \frac{\partial T}{\partial y}\Big|_{y=300} = 0 \tag{16}$$

where h_{in} is the convective heat transfer coefficient of the indoor side, h_{out} – the convective heat transfer coefficient on the outdoor side, τ – the time, T_b – the wall surface temperature, T_{in} – the indoor side temperature, T_{out} – the outdoor temperature, λ_b – the thermal conductivity of the wall, T – the temperature, and T_0 – the initial wall temperature.

Based on the previous physical and mathematical models, COMSOL software is used to simulate and calculate the heat transfer process of the ordinary wall and the micro-PCM-W wall. The temperature cloud diagram at 8 h-65 h is shown in fig. 11. From fig. 11, it is clear that at the same outdoor temperature boundary conditions, the heat transfer process of the ordinary wall is faster than that of the micro-CPM-W. Moreover, the high temperature region in the outer area of the wall is blocked by the micro-CPM-W, indicating that the PCM improves the thermal inertia of the wall.

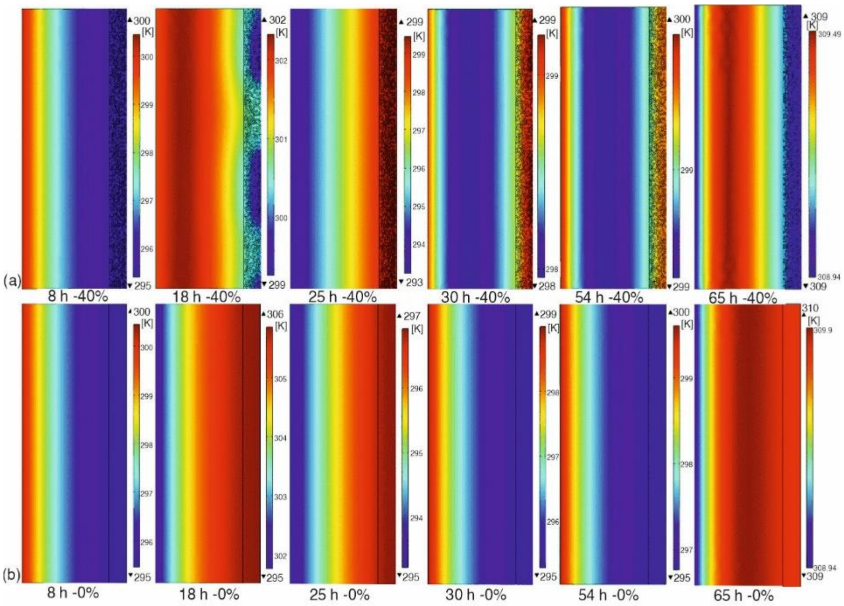

Figure 11. Cloud diagram of the calculated temperature of micro-PMM-W (a) and ordinary wall (b) (micro-PCM, 10 vol.%)

According to the step-by-step heat transfer eqs. (9)-(11) of the phase change process of the micro-PCM-W wall, the transient distribution curves of temperature and liquid fraction inside the micro-PCM-W wall can be obtained under outdoor transient meteorological conditions, as shown in fig. 11. As can be seen from the changes in the liquid fraction curve and the inner temperature curve of micro-PCM-W in fig. 11, when the outer surface of an ordinary wall is coated with a certain thickness of micro-PCM-CM layer, its inner surface temperature decreases compared with that of an ordinary wall. The specific analysis are:

- 0 - 10 h: It indicates that the outer surface temperature of micro-PCM is lower than the phase change temperature, and the PCM is solid. The heat transfer process of the phase change energy storage wall is the same as that of the ordinary wall, but the temperature is lower.
- 10 h - 19 h: It indicates that the outer surface temperature of micro-PCM is higher than the phase change temperature, and the PCM begins to change from solid to liquid, while continuously absorbing heat in the form of latent heat. The temperature at the solid-liquid interface remains unchanged at the phase change temperature.
- 19 h – 21 h: It indicates that after the solid-liquid phase change, the PCM is in a liquid state and continues to heat transfer under the action of external temperature. The heat transfer process is the same as that of ordinary walls, but the temperature is lower than that of ordinary walls.
- 21 h – 31 h: It indicates that the outer surface temperature of micro-PCM begins to be lower than the phase change temperature, and the PCM begins to change from liquid to solid, while continuously releasing heat in the form of latent heat. The temperature at the solid-liquid interface remains unchanged at the phase change temperature.
- 31 h – 38 h: It indicates that the outer surface temperature of micro-PCM is higher than the phase change temperature. Some solid PCM begin to melt, while continuously absorbing heat in the form of latent heat. The temperature at the solid-liquid interface remains unchanged at the phase change temperature.

Effect of micro-PCM content on dynamic thermal insulation performance of micro-PCM-W

The inner wall temperature determines the indoor thermal environment. The relationship between the inner wall temperature and the outdoor air ambient temperature is shown in fig. 12. As can be seen from fig. 13, the outdoor ambient temperature takes 24 hours as a cycle, and there are three cycle fluctuations within 72 hours. The temperature of the inner wall of the nine types of walls also has three fluctuation cycles. Because of the thermal inertia of the walls, the temperature fluctuation of the inner wall of the nine types of walls delays the change of the external environment temperature. However, the delay of the micro-PCM-W is higher than that of the ordinary wall, and the higher the micro-PCM content is, the higher the delay is. For example, in the first temperature fluctuation period, the ordinary wall reached the highest temperature of 32.975 °C at about 16.96 hours, while the phase-change energy storage wall with 40% micro-PCM volume content reached the highest temperature of 27.809 °C at 19.39 hours. The lag time is 145 minutes, and the temperature reduction amount is 5.166 °C. The maximum temperature, time, lag time and temperature reduction amount of the nine types of walls are summarized in tab. 2. As can be seen from tab. 2, the temperature peak lag time and temperature reduction amount of the micro-PCM-CMW wall are better than those of the ordinary wall, and the higher the micro-PCM content, the greater the temperature peak lag time and temperature reduction amount of the wall.

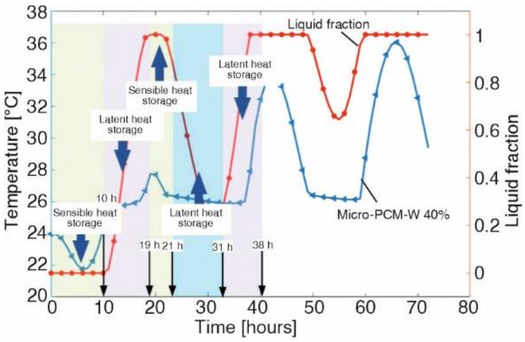

Figure 12. Temperature change inside the micro-PCM-W and liquid fraction change inside the micro-PCM-W (Micro-PCM, vol-40%)

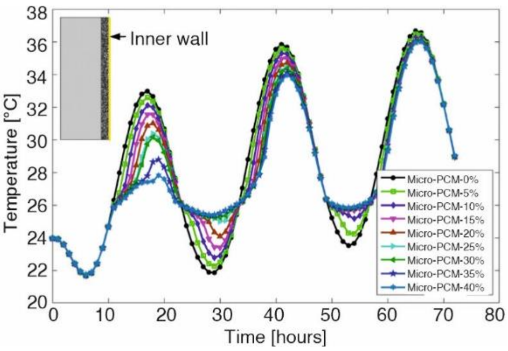

Figure 13. The inner wall temperature change of micro-PCM-W under different micro-PCM content

Table 2. Temperature peak, lag time, and temperature reduction amount under different volume contents of micro-PCM

	Volume content [%]	Temperature peak [°C]	High temperature time point [minute]	Lag time [minute]	Temperature reduction amount [°C]
First cycle	Ordinary wall	32.975	1018	–	–
	5	32.579	1028	10	0.396
	10	32.114	1048	30	0.861
	15	31.609	1057	39	1.366
	20	31.014	1074	56	1.961
	25	30.374	1091	73	2.601
	30	30.149	1097	79	2.826
	35	28.813	1132	114	4.162
	40	27.809	1163	145	5.166

Table 3. Peak and trough differences, and temperature reduction amount of micro-PCM with different volume contents

	Volume content [%]	Highest temperature [°C]	Lowest temperature [°C]	Peak and trough differences	Temperature reduction amount [°C]
Second cycle	Ordinary wall	35.837	23.510	12.327	–
	5	35.589	24.194	11.395	0.248
	10	35.316	25.183	10.133	0.521
	15	35.029	25.812	9.217	0.808
	20	34.719	25.934	8.785	1.118
	25	34.449	26.004	8.445	1.388
	30	34.359	26.020	8.339	1.478
	35	34.096	26.088	8.008	1.741
	40	33.936	26.118	7.818	1.901

In the second cycle, the temperature fluctuation range of the inner wall surface of the ordinary wall is 12.327 °C. When the content of micro-PCM is 5~40%, the temperature fluctuation range of the inner wall surface is 7.818~11.395 °C, which is lower than that of the ordinary wall 0.248~1.910 °C , tab. 3. The higher the content of micro-PCM, the smaller the temperature fluctuation on the indoor side of micro-PCM-W, namely, the phase change energy storage wall will provide a stable indoor thermal environment.

The inner temperature of the first layer of material in the micro-PCM-W wall is shown in fig. 14. During the three-cycle heating process, when the measured inner temperature of the first layer of material reaches about 26 °C, the temperature rise rate of the micro-PCM-W begins to be lower than that of the ordinary wall, and the higher the micro-PCM content, the lower the heating rate. This is because when the outdoor air transfers heat to the inner side of the wall and the wall heats up to about 26 °C, the PCM begins to phase change and the heat is stored in the form of latent heat, which reduces the heat transferred to the inner area of the wall. In the first cycle, the inner temperature of the micro-PCM-W with a volume content of 40% decreased by 5.565 °C compared with the ordinary wall, indicating that the latent heat storage effect of micro-PCM did indeed reduce the temperature rise in the inner area of the wall. In the cooling process of the three cycles, the initial temperature of the ordinary wall is higher than that of the micro-PCM-W. However, its cooling rate is also high, which is because the heat stored by micro-PCM in the form of latent heat is released to the external environment in the form of an internal heat source during cooling.

The transient heat transfer from nine types of walls to the inner side is shown in fig. 15. During the three temperature fluctuation cycles, the micro-PCM-W stores part of the energy in the form of latent heat during the phase change process, which reduces the heat transfer to the room. During the first cycle of temperature fluctuations, the maximum transient heat transfer of phase change mortar walls with 5% to 40% micro-PCM content is reduced by 8.067 W/m^2, 12.006 W/m^2, 13.726 W/m^2, 16.913 W/m^2, 19.270 W/m^2, 19.793 W/m^2, 20.901 W/m^2, and 22.202 W/m^2 compared with ordinary walls, respectively, 202 W/m^2, indicating that the phase change energy storage mortar wall transfers less heat to the room.

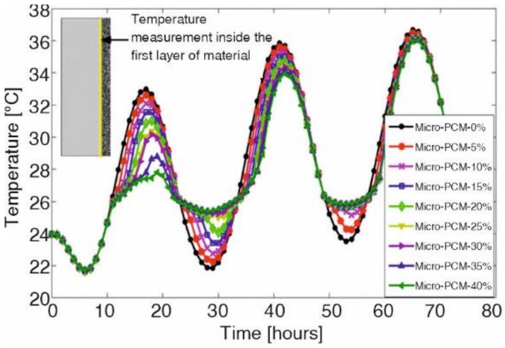

Figure 14. Temperature changes in the inner side of the PCM mortar layer under different micro-PCM contents

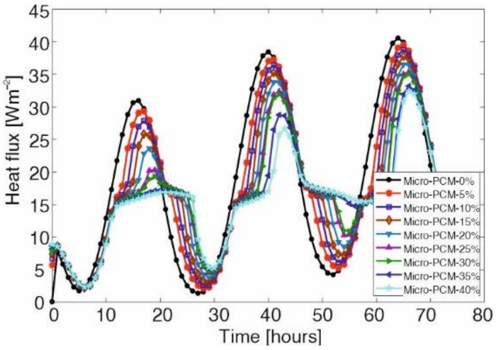

Figure 15. Change diagram of heat flux on the inside of Micro-PCM-CMW wall with different Micro-PCM content

In summary, from the temperature distribution in the inner side of the wall, the temperature in the inner side of the first layer of materials and the heat load transferred to the room, the temperature control performance of the micro-PCM-W is better than that of the ordinary wall.

Conclusions

- The mixed coating of micro-PCM and cement mortar on the building envelope can control the temperature inside the wall near the phase change temperature range for a long period.
- In the process of changes in the external environment, the latent heat storage/energy release of the PCM in micro-PCM changes periodically, and the temperature at the solid-liquid

interface remains unchanged at the phase change temperature, thus delaying or even reducing the indoor temperature peak.

- After the addition of micro-PCM, the heat storage and temperature control performance of the cement mortar composite wall is significantly improved, for example, the temperature peak of the inner wall of 40 vol.% micro-PCM-CMW is reduced by 5.166 °C, and the indoor temperature peak is delayed by 145 minutes.
- The temperature peak fluctuation of the ordinary wall is 12.327 °C, while the integration of micro-PCM in the plaster layer of the wall can effectively reduce the indoor temperature fluctuation, in which the minimum temperature peak fluctuation is 7.818 °C, PCM greatly reduce indoor temperature fluctuations and improve indoor thermal comfort.
- The micro-PCM-CMW wall stores part of the energy in the form of latent heat during the phase change process, reducing the heat transfer to the room. The maximum transient heat transfer is 22.202 W/m^2 lower than that of ordinary walls. The higher the micro-PCM content, the greater the thermal inertia of the wall, which can effectively improve the thermal stability of the wall.
- The rapid world economic growth has led to an increase in the energy consumption. The fossil fuels dominate the world energy market, with a share of about 81%. However, the fossil fuels are running out and present high costs. On the other hand, its use is related with the emission of harmful gases into the environment.

Thus, the energy efficient use and the possibility of the use of renewable sources of energy are becoming increasingly important. The energy efficiency of buildings is now one of the main objectives of regional, national and international energy policy. Buildings are one of the leading sectors in energy consumption in developed countries. In the EU the buildings represent 40% of energy consumption and CO^2 emissions to the atmosphere. The solutions based into the use of renewable energy contribute to the increase the energy efficiency, to decrease the use of fossil fuel reserves and to reduce the pollutant emissions into the atmosphere. The utilization of RES, like solar energy, is becoming a crucial measure promoting energy efficiency and sustainability of buildings. In addition, the use of RES is a key factor to reduce the energy dependence of the buildings.

Solar energy is one of the main RES because it provides a high amount of energy (estimated 5×10^{24} J per year). However, the geographical location and climatic conditions may limit the use of solar energy. On the other part, the utilization of PCM is a sustainable way to increase energy efficiency by storing thermal energy.

Therefore, the heat storage possible with PCM is a strategy for the development of construction projects with high energy performance. The PCM have the ability to reduce the temperature variation, due to their capability in absorbing and releasing energy to the environment. The PCM operating principle consists in change their status, according to the environment temperature. The PCM absorb and store energy, suffering a change from a solid state to a liquid state, while temperature increases.

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