A new kind of phase change material (PCM) for energy-storing wallboard

Chao Chen, Haifeng Guo *, Yuning Liu, Hailin Yue, Chendong Wang

College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100022, China

Received 30 January 2007; received in revised form 8 July 2007; accepted 9 July 2007

Abstract

A new kind of phase change material (PCM) for energy-storing wallboard is introduced in this paper. By establishing the one-dimensional nonlinear mathematical model for heat conduction of the PCM energy-storing wallboard and according to the “effective heat capacity method”, simulation and calculation were made using the software MATLAB to analyze and solve the heat transfer problem of the PCM room. Meanwhile, the property can be found that the heat storing/releasing ability of the new PCM is significantly higher than that of ordinary materials by the experiment-based method. The result indicates that applying proper PCM to the inner surface of the north wall in the ordinary room can not only enhance the indoor thermal-comfort dramatically, but also increase the utilization rate of the solar radiation. So the heating energy consuming is decreased and the goal of saving energy has been achieved. If the parameters of the PCM is given as follows: the phase change temperature is set at 23 °C, the thickness is set at 30 mm, the phase change enthalpy is set at 60 kJ/kg, and the heating temperature is set at 20 °C, the energy-saving rate of heating season can get to 17% or higher. So the energy is effectively used and saved obviously.

Keywords: New PCM energy-storing wallboard; Heat transfer of PCM; Effective heat capacity method; Experiment; Energy conservation

1. Introduction

In many areas of north China, the solar energy resource is abundant in winter with the properties as long-time sunshine and intense solar radiation. Let us take Beijing as an example, the winter sunshine rate reaches as high as 76%; meanwhile, the solar elevation angle is small. So the intensity of solar radiation directly entering into the room is great. As shown in Fig. 1: the solar radiation directly radiating on the south wall or permeating the north window in winter is much higher than that in summer, and extremely higher than that on the east wall and the west wall. This property provides a great advantage for the application of reused sources in the building energy-saving aspect. However, the amount of the solar radiation is affected by many factors, such as the rotation and revolution of the earth, the weather and climate change and so on, which results in a large fluctuation of solar energy amount everyday. Thus how to effectively store the extra solar energy that enters the room in the daytime and release it at night when demanded, and achieve the goal of “time shifting” of solar energy to reduce the energy consumption in air conditioning and heating will become a crucial topic.

In order to make buildings have the ability of absorbing solar energy and achieving the goal of “time shifting”, it is not only necessary to ensure the building envelopes have a certain heat resistance, but also have a big heat capacity, by which we should enhance the heat storage capacity and the thermal inertia. Having this property, the PCM could absorb or release a large amount of phase transition latent heat under an isothermal condition. In recent years, scholars all over the world have conducted various investigations on PCMs. The researchers Feldman and co-workers [1–12] have made theoretical analysis and experimental research on the manufacture method, heat storing/releasing characteristic, stability, flammability and the security of the PCM in the Centre for Building Studies of Concordia University in Canada. And they have gained very outstanding result on this subject. Neeper [13] made some researches on the thermal performances of the PCM used in passive solar house which provides references for the choosing of better PCM and make better estimation on the energy conservation characteristic for the PCM. Tyagi and Buddhi [14] in Indian made a comprehensive review on different possible
modes for heating and cooling in buildings. Furthermore, they also made a detailed introduction on different ways of thermal storage for the system like PCM trombe wall, PCM wallboards, PCM shutters, PCM building blocks, air-based heating systems, floor heating, ceiling boards, etc. The research result indicated that applying the PCM in the heating and cooling systems has very great application potential. Moreover, it can decrease the energy consumption for the building dramatically.

Researches on PCMs and PCM wallboards in China are later than overseas. Zhang [15–17] in Tsinghua University has elaborated the classification and selecting, the thermal performances, the analysis method of heat transfer and the design method of heat storage equipment of the PCM since the 19th century. Based on the research, a new type of shape-stable PCM that is made of paraffin as a dispersed phase change material is developed and comparisons have been made about the heat storing/releasing characteristic, the uniformity and the stability of the material between different PCMs whose supporting material is HDPE and LDPE. F. Guohui [18,19] have developed a new kind of PCM wallboard through immersion method and carried out the PCM room experiment in the north climate of China.

In recent years, our research group [20,21] has been engaged in the theoretical and experimental study on the PCM technology. And a new kind of phase change material (PCM) has been developed according to the meteorological characteristic of China and construction characteristic of the building in China. It can be mixed with ordinary constructive materials and directly applied to the inner surface of the ordinary wall to get a new type of PCM energy-storing wallboard. This paper makes a discussion on the phase change heat transfer of the building envelope with the new PCM energy-storing wallboard. Through establishment of phase change heat transfer model of the room [22], simulations and calculations according to the heat storing/releasing characteristics of the PCM are made by effective heat capacity method [20] and the software MATLAB. The effects of the PCM energy-storing wallboard on the heating energy consumption of the room and the energy conservation rate are studied according to phase change temperature, the phase change enthalpy and the thickness of the PCM energy-storing wallboard. Furthermore, by the experimental method, the validity of this new type material has also been approved.

2. Heat transfer analysis of the PCM energy-storing wallboard

2.1. Estimate parameters of thermal performance

In general, the main parameters by which estimate the thermal performance of the building envelope consist of the thermal resistance $R$, the heat storage coefficient $S$ and the index of thermal inertia $D$. The thermal resistance is mainly used to estimate the heat preservation performance of the wall, while the latter two are mainly used to estimate the heat storage capacity of the wall.

(1) Thermal resistance $R$: The reciprocal of the heat transfer coefficient [23]; which denotes the total resistance that when the heat flow transfer from one side of the wall to the other side, and expresses the resistance ability of the wall to the heat flow. The bigger the thermal resistance is, the smaller the heat flow density that we can get from the other side of the wall will be. $R$ is the most important parameter in estimating the heat preservation performance of the wall.

\[
\begin{align*}
\text{Nomenclature} & \\
c & \text{specific heat of each material (kJ/(kg K))} \\
c_a & \text{specific heat of the air (kJ/(kg K))} \\
C & \text{heat capacity of each material (kJ/K)} \\
G_{\text{tv}} & \text{value of the room ventilation (m}^3/\text{s)} \\
H & \text{latent heat of the PCM (kJ/kg)} \\
l & \text{liquid state} \\
Q_c & \text{total heating load of the ordinary room in a whole heating time (kW)} \\
Q_l & \text{heat transfer by the air penetrate or ventilation (W)} \\
Q_{\text{pcm}} & \text{total heating load of the PCM room in a whole heating time (kW)} \\
Q_{\text{sc}} & \text{heat convection of the illumination, the personnel and the equipment (W)} \\
Q_{\text{wk}} & \text{heat convection of the inner surface of the room envelope with the air (W)} \\
s & \text{solid state} \\
t & \text{temperature (°C)} \\
t_f & \text{phase change temperature (°C)} \\
t_{\text{in}} & \text{indoor air temperature (°C)} \\
t_{\text{out}} & \text{outdoor air temperature (°C)} \\
\Delta t & \text{phase change temperature difference (°C)} \\
V_R & \text{volume of the room (m}^3) \\
\text{Greek symbols} & \\
a & \text{thermal diffusivity (m}^2/\text{s)} \\
\eta & \text{heating season efficiency of energy saving (°C)} \\
\lambda & \text{thermal conductivity of each material (W/}(\text{m K})) \\
\rho & \text{density of each material (kg/m}^3) \\
\rho_a & \text{density of the air (kg/m}^3) \\
\tau & \text{time (s)} \\
\chi & \text{phase change interface (m)}
\end{align*}
\]
(2) Heat storage coefficient $S$: Denotes the sensitivity of the materials to the heat flow wave. Under the same condition of the heat flow wave, the bigger the materials’ heat storage coefficient is, the smaller the temperature of the wall surface will be. Meanwhile the better the thermal stability of the wall will be. As a basic property of the materials, the value of $S$ depends on the thermal conductivity and bulk heat capacity of materials (the product of specific heat and density). At the same time, it will also be influenced by the seasonal heat flow wave. When the cycle of heat flow wave is 24 h, $S$ can be calculated using the following equation [23]:

$$S = \sqrt{\frac{2\pi c_p \rho}{T}}$$  \hspace{1cm} (1)

When using the multiple-wall, the total heat storage coefficient of the wall is obtained by the regeneration of the material’s heat storage coefficient of each layer.

(3) Index of thermal inertia $D$: When a periodical heat flow wave was applied to the wall surface, the temperature wave will transfer forward the interior of the wall configuration; meanwhile get attenuation gradually until reach the opposite of the wall. $D$ is a main parameter in estimating the attenuation degree of the temperature wave on the opposite of the wall. It expresses the resisting ability of the building envelope according to the periodical temperature wave.

For a single material, $D$ is the product of $R$ and $S$ [23]:

$$D = RS$$  \hspace{1cm} (2)

For the multiple-wall with several layers of materials, $D$ is the sum of each $D$ according to different materials:

$$\sum D = D_1 + D_2 + \cdots + D_n$$  \hspace{1cm} (3)

Obviously, the bigger $D$ is, the stronger the heat storage ability of materials will be.

Table 1 shows comparison of the heat performance parameters between the ordinary building materials and the new phase change material developed by our research group. Comparison results indicate that when the thickness is the same, the thermal resistance $R$ of the new phase change material is twice bigger than that of ordinary building materials (the gypsum and the cement); the heat storage coefficient $S$ is 2.3 times bigger than that of the gypsum, and 1.9 times bigger than that of the cement; the index of thermal inertia $D$ is 4.3 times bigger than that of the gypsum, and 4.5 bigger than that of the cement. Thus, the heat storing/releasing ability and the heat preservation performance of the new phase change material are both better than that of ordinary building materials.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity (W/(m K))</th>
<th>Specific heat (effective specific heat) (kJ/(kg K))</th>
<th>Thermal resistance $R$ ((m² K)/W)</th>
<th>Heat storage coefficient $S$ (W/(m² K))</th>
<th>Index of thermal inertia $D$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The gypsum</td>
<td>20</td>
<td>1500</td>
<td>0.76</td>
<td>1.05</td>
<td>0.026</td>
<td>9.33</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>The cement</td>
<td>20</td>
<td>1800</td>
<td>0.93</td>
<td>1.05</td>
<td>0.022</td>
<td>11.31</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>The new PCM</td>
<td>20</td>
<td>800</td>
<td>0.40</td>
<td>20a</td>
<td>0.05</td>
<td>21.57</td>
<td>1.08</td>
</tr>
</tbody>
</table>

* The effective specific heat of the new PCM is the equivalent specific heat determined by the effective heat capacity method.

2.3. Heat transfer control equation of the PCM energy-storing wallboard

Whether the ordinary wallboard or the PCM energy-storing wallboard are building envelopes comprised by multi-storey materials and its inner heat transfer phenomena is complex. In order to build the heat transfer control equation of the PCM energy-storing wallboard (shown in Fig. 2), we delaminated the PCM energy-storing wallboard as two kind of layers, i.e. the ordinary building material layer and the PCM layer, and considered separately.

2.3.1. Heat transfer control equation of the ordinary building material layer

If the surface structure of the wallboard is symmetrical, and the thickness is much less than the surface size (length and width), the instability heat transfer in the wallboard is considered as one-dimensional process. The conductive differential coefficient equation of ordinary wallboard is shown as follows [22]:

$$\rho c_p \frac{\partial T(x, \tau)}{\partial \tau} = \lambda \frac{\partial^2 T(x, \tau)}{\partial x^2}$$  \hspace{1cm} (4)

Fourier laws parse equation is

$$q(x, \tau) = -\lambda \frac{\partial T(x, \tau)}{\partial x}$$  \hspace{1cm} (5)
2.3.2. Heat transfer control equation of PCM layer

Contrasting with ordinary building materials, the PCM has three states: solid state, liquid state and solid–liquid coexistence state, therefore it has three heat transfer control equations in the whole solving region. In order to write the control equation, following assumptions have been made:

1. Thermal properties (such as \( \lambda \), \( c \) and \( \rho \)) in the solid–liquid coexistence state are considered as constant.
2. Free convection in the liquid state is neglected.
3. Supercooling when freezing is neglected.

Thus, the conductive differential coefficient equation of the phase change problem is shown as follows [20]:

\[
\frac{\partial t_s}{\partial x} = \alpha_s \nabla^2 t_s \quad \text{solid state}
\]

(6)

\[
\frac{\partial t_l}{\partial x} = \alpha_l \nabla^2 t_l \quad \text{liquid state}
\]

(7)

\[
\lambda_s \left( \frac{\partial t_s}{\partial t} \right) - \lambda_l \left( \frac{\partial t_l}{\partial t} \right) = H \rho \frac{\partial x}{\partial x} \quad \text{solid–liquid coexistence state}
\]

(8)

2.4. Solution of the PCM heat transfer problem

In fact, it is difficult to solve Eqs. (6)–(8). In order to simplify the calculation, a unified control equation in the whole region (including solid state, liquid state and solid–liquid coexistence state) is established, for example, in virtue of the “enthalpy model” and the “effective heat capacity model”, which are both based on the finite difference method [20]:

\[
\text{enthalpy model} : \quad \frac{\partial H}{\partial x} = \lambda \nabla^2 t
\]

(9)

\[
\text{effective heat capacity model} : \quad C \frac{\partial t}{\partial x} = \lambda \nabla^2 t
\]

(10)

Enthalpy model introduces the concept of enthalpy, and adopts enthalpy and temperature both as the solving parameters. The characteristic of this method is, though the temperature curve in the phase change interface is discontinuous, the enthalpy curve is continuous. Thus it need not to track the phase change interface when determining the enthalpy distribution, which makes it possible to establish a unified equation in the solid state, liquid state and solid–liquid coexistence state. After the distributions of enthalpy and temperature have been known, the location of phase change interface can be determined.

Effective heat capacity model introduces the concept of effective or equivalent heat capacity, and considers the phase change latent heat as a great heat in sensible form in the whole phase transition temperature interval. In virtue of the effective heat capacity model, the heat transfer problem of the PCM, which is described by three equations (i.e. solid state, liquid state and solid–liquid coexistence state), can be transformed into “single-phase” non-linear conduction problem in the whole calculation region. The location of phase change interface can be determined when the temperature distribution is gained.

According to the analysis, the effective heat capacity method is more suitable for this study. The effective heat capacity model (shown in Eq. (10)) is a three-dimensional control equation. Considering the heat transfer characteristic of phase change problem, some basic assumptions are made as follows: (1) the heat transfer can only be along the direction of the thickness of the wall and is considered as a one-dimensional non-linear conduction process; (2) the new shape-stable PCM is considered as having an equivalent and effective specific heat in the phase change region, whereas it should be considered as constant in the solid state and liquid state; the density is constant; no or small volume change during phase transitions; (3) free convection when melting and supercooling when freezing of the new shape-stable PCM are neglected. Thus, the one-dimensional non-linear conductive differential coefficient equation of the new PCM energy-storing wallboard in the whole calculation region can be conformably written by

\[
\rho c \frac{\partial t(x, t)}{\partial x} = \lambda \frac{\partial^2 t(x, t)}{\partial x^2}
\]

(11)

Actually, the effective heat capacity model does not increase other new parameters, and can convert the phase change latent heat into the parameter equivalent specific heat \( c \) in the phase transition temperature interval. The pending parameters, such as the equivalent heat capacity \( C \) and the thermal conductivity \( \lambda \) are considered as the function of the nodal temperature, which transforms the phase change problem into the conductive problem of variable thermal properties. When the specific heat in solid state and liquid state are considered to be constant, equivalent heat capacity \( C \) and thermal conductivity \( \lambda \) are shown as

\[
C = \begin{cases} 
C_s(t) & t < t_f - \Delta t \\
\frac{C_s + C_l}{2} & t_f - \Delta t \leq t_f + \Delta t \\
C_l(t) & t > t_f + \Delta t 
\end{cases}
\]

(12)

\[
\lambda = \begin{cases} 
\lambda_s(t) & t < t_f - \Delta t \\
\lambda_s + \frac{\lambda_s - \lambda_l}{2\Delta T}[t - (t_f - \Delta t)] & t_f - \Delta t \leq t_f + \Delta t \\
\lambda_l(t) & t > t_f + \Delta t 
\end{cases}
\]

(13)
Therefore, Eqs. (4) and (5) are both suited to the new PCM energy-storing wallboard and the ordinary wallboard, but only for the new PCM energy-storing wallboard, $\rho$ is the density of the PCM, $\lambda$ and $c$ are calculated by the effective heat capacity method (shown in Eqs. (12) and (13)), which significantly reduces the calculation difficulty.

3. Energy conservation estimation of PCM room

Apply the PCM layer to the inner building envelop, i.e. the inner partition wall and floor of ordinary building room, comprising the PCM room, and discuss the influence of the PCM energy-storing wallboard on the room’s heat stability and energy consumption.

3.1. Computation object

Take the unit room in the middle floor in Beijing as the research object. In the computation, the south wall is the outer building envelope, however, the floor, the ceiling and other walls are all inner building envelopes. Main heat performance parameters of building materials in the unit room are shown in Table 2.

The unit room is considered as two conditions when calculating: ordinary room without PCM energy-storing wallboard and PCM room with PCM energy-storing wallboard. When the unit room stands for the ordinary room, the inner material layers of the partition wall and floor are cement layers, and the thickness of outer material layers is constant. When the unit room stands for the PCM room, the inner material layers of the partition wall and floor are new PCM layers, and outer material layers are the same as ordinary room. The south window of unit room adopts the single frame double-decked vacuum glass, whose heat transfer coefficient $U$ is 2.7 W/(m² K), and the total area of south window is 9 m².

3.2. Establishment of heat balance equation

In order to completely describe the heat transfer process of a building room, the whole room’s dynamic heat balance equation must be established, as well as the mathematical model of the heat transfer process of all building envelopes. As for the PCM room, values of heat conduction and heat convection of the new PCM energy-storing wallboard have already been included in the results of the effective heat capacity method, and the other values are the same as ordinary room, not going to be repeated here.

The transient state heat transfer process should satisfy three heat balance equations as follows [22]:

(a) Heat balance equation of outer surface of the wall:
\[
\text{the heat conduction} + \text{the heat convection with the air} + \text{the solar radiation} + \text{the sky radiation} + \text{the earth radiation} = 0
\] (14)

(b) Heat balance equation of inner surface of the wall:
\[
\text{the heat conduction} + \text{the heat convection with the air} + \text{radiant heat} = 0
\] (15)

(c) Heat balance equation of the air in the room space:
\[
c_a \rho_a V \frac{d T_a}{d t} = \sum_{k=1}^{N} Q_{wk} + Q_{sc} + Q_L
\] (16)

Here
\[
Q_L = c_a \rho_a G_L (t_{out} - t_{in})
\] (17)

Finally, the differential equations (shown in Eqs. (14)–(17)) of ordinary room and PCM room mentioned above are united and solved by the finite difference method and in virtue of the third-class boundary conditions, which does not increase the unknown parameters. The control equations are separated into differential equations in both space and time aspects, dispersed and solved by the Gauss-Seidel type iterative method. At the same time, the intermediate differential format in the space and the hidden difference format (backward Euler format) in the time are adopted, the unit length is 1 cm, and the time step is 1 min. Take initial conditions as a starting point, and carry

<table>
<thead>
<tr>
<th>Component</th>
<th>Constituent material</th>
<th>Thickness (mm)</th>
<th>Thermal conductivity (W/(m K))</th>
<th>Heat capacity (kJ/(kg K))</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer wallboard (from outer layer to inner layer)</td>
<td>1. Cement layer</td>
<td>25</td>
<td>0.93</td>
<td>1.05</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td>2. Heat preservation</td>
<td>40</td>
<td>0.07</td>
<td>1.19</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>3. Concrete grout</td>
<td>200</td>
<td>1.74</td>
<td>1.05</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>4. Cement layer</td>
<td>20</td>
<td>0.93</td>
<td>1.05</td>
<td>1800</td>
</tr>
<tr>
<td>Inner wallboard (from outer layer to inner layer)</td>
<td>1. Cement layer</td>
<td>–</td>
<td>0.93</td>
<td>1.05</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td>2. Pottery concrete</td>
<td>180</td>
<td>0.465</td>
<td>0.837</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>3. New PCM layer</td>
<td>–</td>
<td>0.4</td>
<td>0.43</td>
<td>800</td>
</tr>
<tr>
<td>Floor and ceiling (from outer layer to inner layer)</td>
<td>1. Cement layer</td>
<td>–</td>
<td>0.93</td>
<td>1.05</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td>2. Concrete</td>
<td>80</td>
<td>1.628</td>
<td>0.837</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>3. New PCM layer</td>
<td>–</td>
<td>0.4</td>
<td>0.4</td>
<td>800</td>
</tr>
</tbody>
</table>
through calculating with time. When the temperature distribution of the inner nodes of walls in both ordinary room and PCM room are determined separately, the heat transfer of building envelopes and rooms can be gained.

3.3. Computation condition

(1) The computation object is located in Beijing; the Medpha software developed by Tsinghua University is used to compute the climate parameters; the computation time is the heating time of Beijing: 1/21–1/24, altogether 4 days.
(2) The designed indoor heating temperature is 20 °C in winter. Heating when the indoor air temperature is lower than 20 °C. Stop heating when it is higher than 20 °C.
(3) Assume the air change rate of the unit room with the outdoor air is 0.5, and with the north neighboring room is also 0.5.
(4) Assume the indoor air temperatures of neighboring rooms are also 20 °C, and the phase change temperature difference $\Delta t = \pm 1 °C$.

3.4. The energy-saving rate of heating season

Basing on the numerical simulations above, the Matlab software compiles this program; the heat storing/releasing characteristics and the energy conservation property of ordinary room and PCM room are compared. Influences of the phase change temperature, the phase change enthalpy, the specific heat, the density, and the thermal conductivity of the PCM energy-storing wallboard on winter heating energy consumption of building rooms are analyzed. At the same time, the concept of “energy-saving rate of heating season” $\eta$ is introduced in order to estimate the energy conservation effect of the new PCM energy-storing wallboard. The solution of energy-saving rate of heating season $\eta$ is shown as follows:

$$\eta = \frac{Q_c - Q_{pcm}}{Q_c}$$

4. Heat storing/releasing experiment of the new PCM

The new PCM layer is applied to the inner surface of the ordinary wallboard in the theoretical computation, shown in Fig. 2.

In order to contrast the heat storing/releasing characteristic of ordinary wall materials with the new shape-stable PCM, experiments have been carried on. Three columniform samples (shown in Fig. 3) for testing – each with a diameter of 40 mm and 150 mm long – are synchronously put into a container kept at constant temperature (shown in Fig. 4), carrying through the heat storing experiment; when temperature of the three samples reaches the designed temperature of the isothermal container, they are taken out and cooled in the outdoor cryogenic environment, carrying through the heat-releasing experiment.

In the experiment, 1# sample is gypsum material of 100%, 2# sample is the mixture of gypsum material and new shape-stable PCM, with 40% of new shape-stable PCM loading, and 3# sample is the new shape-stable PCM of 100%. The thermoelements are separately embedded into the center of the three samples, and connected with the data acquisition instrument. Then the samples are put into the isothermal container. Carry on the heat storing/releasing experiments test instantly and record the experimental data. Under the heat-storing process, the designed temperature of the container is heated up to nearly 28 °C; and under the heat-releasing process, the temperature of the outdoor cryogenic environment is about 10 °C.

5. Results of computation and experiment

5.1. Analysis of computational results

5.1.1. Effect of phase change enthalpy and thickness of the PCM to $\eta$

Fig. 5 shows the effect of phase change enthalpy and thickness of the new PCM layer to the energy-saving rate of heating season $\eta$, with the phase change temperature being set at 24 °C. The thickness of the partition walls and floor of the PCM room is constant, replacing the cement layer in the indoor airside with the new PCM layer. From Fig. 5 we know that, $\eta$ increases continuously with the continuous increase of the phase change enthalpy. The effect of thickness to $\eta$ has the same

![Fig. 3. Samples.](image1)

![Fig. 4. Schematic diagram of experiment equipments.](image2)
trend. However, the enthalpy’s effect is bigger than the thickness.

Comprehensive study shows that the energy-saving rate of heating season $\eta$ can get to 10% or higher during a whole winter when the optimal thickness is set at 30 mm and the phase change enthalpy of the PCM is set at 60 kJ/kg.

5.1.2. Effect of phase change temperature and enthalpy of the PCM to $\eta$

Fig. 6 shows the effect of the phase change temperature (22 °C, 23 °C and 24 °C, respectively) and the phase change enthalpy on the energy-saving rate of heating season $\eta$, when the thickness of the new PCM layer is set at 30 mm, and the heating indoor air temperature is set at 20 °C. As shown in Fig. 6, when the phase change temperature is 22 °C, the energy-saving rate of heating season $\eta$ is lowest, less than 4 %. This is mainly because that the difference between the room heating temperature and the phase change temperature is small, only 2 °C, which results in the energy stored by the new PCM energy-storing wallboard is much less. When the phase change temperature is 24 °C, the energy-saving rate of heating season $\eta$ increases slightly, however, the maximum is only 12%. This is mainly because that the phase change temperature is higher, bringing to the interval of the time that the actual room temperature achieves the phase change temperature is shorter, and the energy stored in the PCM wallboard is smaller, resulting in the energy-saving rate of heating season $\eta$ is lower. When the phase change temperature is 23 °C, the energy-saving rate of heating season $\eta$ is highest, and the maximum can reach as high as 17% or higher. At the same time, there is also a different phenomena: when the phase change enthalpy is less than 40 kJ/kg, the energy-saving rate of heating season $\eta$ enhances obviously with the phase change enthalpy’s continuously increasing. However, when the phase change enthalpy is higher than 40 kJ/kg, the energy-saving rate of heating season $\eta$ becomes stable, and the influence of the phase change enthalpy on the energy-saving rate of heating season $\eta$ becomes small.

Synthetical study shows that, the phase change temperature and the phase change enthalpy are main influential factors to the energy-saving rate of heating season $\eta$ in the PCM room, and the thickness’ influence is relatively small. The phase change temperature should be reasonably chosen based on the indoor air heating temperature.

5.1.3. Effect of the new PCM energy-storing wallboard to the indoor air temperature

In the simulation, the indoor air temperature is set at 20 °C, the phase change temperature is set at 23 °C, the phase change enthalpy is set at 60 kJ/kg, and the thickness is set at 30 mm. Add this kind of new PCM energy-storing wallboard to the inner surface of the ordinary room, composing the PCM room. Calculation results of the indoor air temperature are shown in Fig. 7. From Fig. 7 we know that, due to the high solar radiation in the daytime, the actual indoor air temperature of the ordinary room without the new PCM energy-storing wallboard tends to be higher, up to 25.5 °C (1/24), which has caused a certain degree of energy waste. However, the peak indoor air temperature of the PCM room in the daytime reduces significantly, the maximum is only 24 °C, reduced 1 °C. This is mainly because that the new PCM energy-storing wallboard, owing to the PCMs characteristic of absorbing or releasing large amount of latent heat isothermally, can store heat (main is the solar radiation) while the surface temperature of the new PCM energy-storing wallboard is higher than the phase change temperature of the PCM in the daytime, thus cutting the peak temperature of the room, and release heat while the surface temperature of the new PCM energy-storing wallboard falls beyond the phase change temperature of the PCM at night, thus heating the indoor air temperature. Thanks to the application of the new PCM energy-storing wallboard, it
not only avoid a strong solar radiation during the daytime, and reduce the indoor air temperature, but also improve the thermal comfort of the room, consequently reduce the winter heating load, and achieve the purpose of energy conservation of air conditioning.

5.2. Analysis of experimental results

The heat storing/releasing experiment results of the new PCM with ordinary building materials are shown in Fig. 8. From Fig. 8(a) we know that, 1# sample is gypsum material of 100%, so its heat-storing time is shortest, and it only takes 20 min when the center temperature of 1# reaches about 28°C, resulting that the heat-storing ability of 1# is smallest among the three samples. The heat storage ability of 2# (mixture of the PCM and the gypsum) is much stronger than 1#, and it takes 140 min when the center temperature of 2# reaches about 28°C. But the temperature “flattening” on the temperature history is small, so its heat-storing ability is limited. The heat-storing ability of 3# (the new shape-stable PCM of 100%) is strongest among the three samples because it presents a big temperature “flattening” on the temperature history, and it takes 200 min when the center temperature of 3# reaches about 28°C. The heat-releasing process also has the similar rule shown in Fig. 8(b). Thus it can be concluded that the new shape-stable PCM has preferable heat storing/releasing characteristic and certain economic advantage than ordinary building materials.

6. Conclusion

This paper makes an introduction of the new PCM energy-storing wallboard developed by our research group. According to the experimental study of the heat storing/releasing property of materials and the numerical analysis of the PCM room, some important conclusions can be obtained as follows:

(1) In the heat storing/releasing experiment of the new PCM and ordinary building materials, it took 20 min, 140 min and 200 min, respectively for the central temperature of the three samples (1#, 2# and 3#) reaching the temperature of the isothermal container (about 28°C) approximately. The result indicates that the new PCM has better heat storing/releasing ability than ordinary building materials. Moreover, the higher percentage of the PCM is, the stronger the heat storing/releasing ability of the new material will be.

(2) The energy-saving rate of heating season \( \eta \) increases continuously following the increasing of the phase change enthalpy and the thickness, in which the enthalpy has a bigger effect to \( \eta \) than the thickness. Comprehensive study shows that the energy-saving rate of heating season \( \eta \) can get to 10% or higher during a whole winter when the optimal thickness is set at 30 mm and the phase change enthalpy of the PCM is set at 60 kJ/kg.

(3) The phase change temperature should be reasonably chosen according to the indoor air heating temperature. When setting the phase change temperature at 23°C, the thickness at 30 mm, the phase change enthalpy at 60 kJ/kg and the heating temperature at 20°C, the maximum of \( \eta \) can reach as high as 17% or higher.

(4) Because the solar radiation is high in the daytime, the actual indoor air temperature of the ordinary room without the new PCM energy-storing wallboard tends to be as high as 25.5°C (1/24) when the heating temperature in the room is set at 20°C, which has caused a certain degree of energy waste. However, because of the energy-storing effect of the PCM, the indoor air temperature of the PCM room is decreased around 1°C (about 24°C) than the ordinary room.

Because the experimental conditions are limited, the measuring errors are big and some other uncertain factors, the heat storing/releasing experiment of materials is rough, which needs to be gradually improved, but the experimental results have proved that the new PCM has strong heat storing/releasing ability and certain heat preservation performance. Meanwhile, due to the limitations of self-programming, some interference factors have been neglected or predigested in the simulation. The choosing and applying conditions of the new PCM and more in-depth theoretical research and experimental study should be conducted on continuously.

Acknowledgement

The authors appreciate the financial support provided by the NSFC (50678006).
References