Comparative study on the dynamic heat transfer characteristics of PCM-filled glass window and hollow glass window

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A B S T R A C T

In order to determine the effects of the phase change material filled glass window (PCMW) on building energy consumption in the hot summer and cold winter area of China, dynamic heat transfer process and heat transfer parameters of the PCMW and the hollow glass window (HW) exposed to different non-steady boundary conditions related to the climatic characteristic were investigated. The experiments and the numerical simulations in a representative sunny summer day were conducted, and the results were in good agreement. Then the validated numerical model was used to simulate the dynamic heat transfer processes of the two kinds of windows at more different weather conditions, the temperature and heat flux fluctuations on the interior surfaces were analyzed based on simulation results. It was concluded that in the representative sunny summer day, the peak temperature on the interior surface of the PCMW reduced by 10.2 °C, and the heat entered the building through the PCMW reduced by 39.5%, comparing with the HW. However, in the other representative days, the dynamic thermal performance of the PCMW was unsatisfactory as it cannot decrease the building energy consumption. The annual energy consumption of the air conditioning system and the heating system because of the heat transferred though the PCMW decreased 40.6% comparing with the HW applied.

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1. Introduction

The energy consumption in buildings accounted for 25.5% of the total energy consumption in China in 2004 [1]. In the hot summer and cold winter area of China, energy consumption of the building envelope accounted for 60–80% of the total energy consumption in buildings, and the energy consumption through the window accounted for 30% of the energy consumption of the building envelope [2]. It played an important role on the building energy conservation to improve the thermal performance of window.

A series of studies related to the energy conservation in transparent envelope were conducted. The vanadium dioxide thermochromic glass window [3] and the near-infrared electrochromic glass window [4] were studied. The thermochromic and electrochromic glass windows reduced the solar radiation heat gain by changing the solar radiation transmittance of the window; as a result energy consumption of the air conditioning system in summer decreased while the energy consumption of heating system in winter increased. The double-glazed window with fluid channel which could improve the heat recovery and reduce the heat losses were studied [5,6]. It had a complex structure and a high cost although it could save energy by 25–34% in different regions in China. In addition, the double-glazed windows with semi-conductor solar cells [7] and low-E film [8,9] were investigated. The high cost, the complex structure and the unsatisfactory annual energy saving effect needed to be improved although these windows could reduce the energy consumption to a certain extent. Building envelope filled with phase change material (PCM) can smooth the temperature fluctuations of the internal ambient as the external temperature changes, increase the heat capacity and the thermal inertia of the lightweight building walls, improve the thermal comfort of the indoor environment as PCM have a large energy storage density and an approximate stationary temperature when the phase change takes place. The double-glazed window filled with PCM was put forward by researchers. It was proposed originally for cold climate conditions and it was also applicable in warm region according to recent studies [10].

Series of studies about the PCM-filled glass window (PCMW) were conducted. Ismail and Henriquez [11,12] studied the overall coefficient of heat transfer (U), the solar heat gain coefficient (SHGC) and the shading coefficient (SC) of the PCMW by numerical and experimental investigation. The optical properties (the extinction, scattering and absorption coefficients) of the PCMW (RT27) were researched by Gowreesunker [13] by the T-history.
method and spectrophotometry principles. These researches focus on studying the thermal and optical properties of the PCMW but lack of the practical application investigation. The thermal performance of the PCMW (CaCl₂·6H₂O) on the condition of simulative heat source was researched by Luo [14]. More experimental investigation needed to conduct as the PCMW (CaCl₂·6H₂O) was applied in the simulative environment not in the actual environment, and it was not comprehensive that the interior surface temperature was taken as the single evaluation index to evaluate the thermal performance of the PCMW. The PCMW (paraffin, RT35) which was applied in a humid subtropical climate area was investigated by Goia [15–17]. The heat transferred through the PCMW was calculated and the thermal comfort of the indoor environment was evaluated, and found that the shading and heat insulation effects of the PCMW was significant in high solar radiation, the PMV value of the indoor environment with the PCMW applied was lower than the hollow glass window (HW) in summer in the humid subtropical climate area. However, the PCMW filled with different kinds of PCM and the PCMW applied in different climate conditions are necessary to be investigated.

According to the literature review, the PCM filled glass window was investigated simply reduce heat gain in summer or to store heat from sun radiation in winter. The performance of PCM filled glass window in a region with both hot summer and cold winter was rarely investigated. And the PCMW investigate in the PCMW is usually paraffin, while the thermal conductivity and energy storage density of it are both lower than that of the inorganic PCM (such as Glauber’s salt), therefore, it will be necessary to study the thermal performance of the PCMW filled with inorganic PCM in order to improve the thermal performance of the PCMW. In this paper, the dynamic thermal performances of the PCMW (Glauber’s salt, Na₂SO₄·10H₂O) and the HW in the representative weather conditions both in summer and winter in the hot summer and cold winter area of China have been studied by numerical simulation and experimental measurement. In addition, temperature time lag, temperature decrement factor and energy saving rate are defined to evaluate the thermal performance of the PCMW.

2. Numerical model

2.1. Heat transfer process of the PCMW and the HW

The heat transfer process of the PCMW and the HW is shown in Fig. 1. The solar radiation reaching the glass surface is divided into three parts. The first part is the radiation reflected by the glass surface, the second part is the radiation absorbed by double-glazed window, and the last part is the radiation transmitted through the PCMW and the HW. The heat transfer process with the combination of thermal radiation and convection takes place on the boundary of the exterior surface and the interior surface, respectively.

The following assumptions are made to establish the heat transfer model: (1) all the materials are considered to be thermally homogeneous and isotropic media as both the PCM and glass is homogeneous; (2) thermo-physical properties of the PCM are different for solid and liquid phases but are independent of temperature as temperature range in this investigation is narrow and the thermo-physical properties can be considered as constant; (3) the interior and exterior surfaces of the glass windows are considered as diffuse grey surface; (4) the convective process is neglected and the heat transfer depend on the conductive process in double-glazed window because the Grashof number (Gr) in the PCMW and the HW is less than 2860; (5) The heat transfer through the window is simplified to one-dimensional unsteady heat transfer process in double-glazed window because the height and width of the window are 10 times of the thickness.

![Fig. 1. Heat transfer process of the PCMW and the HW.](image-url)
2.2. Governing equations and boundary conditions

The heat transfer is calculated in three regions. They are the exterior glass layer, interior glass layer and the air or PCM layer in the middle. The governing equations for each region are when \( 0 < x < x_1 \) and \( x_2 < x < x_3 \),

\[
\rho_k c_p \frac{\partial T}{\partial t} = \lambda_g \frac{\partial^2 T}{\partial x^2}
\]

(1)

when \( x_1 < x < x_2 \) and the double-glazed window filled with air,

\[
\rho_g c_a \frac{\partial T}{\partial t} = \lambda_a \frac{\partial^2 T}{\partial x^2}
\]

(2)

when \( x_1 > x < x_2 \) and the double-glazed window filled with PCM,

\[
\rho_{PCM} \frac{\partial T}{\partial t} = \lambda_{PCM} \frac{\partial^2 T}{\partial x^2}
\]

(3)

where \( \rho_k, \rho_a \) and \( \rho_{PCM} \) are the density of glass, air and PCM, respectively, \( c_p \) and \( c_a \) are the specific heat capacity of glass and air, respectively, \( \lambda_g, \lambda_a \) and \( \lambda_{PCM} \) are the thermal conductivity of glass, air, and PCM, respectively, \( H \) is the specific enthalpy of PCM.

The specific enthalpy of PCM in Eq. (3) is calculated as follows.

\[
H = H_0 + \Delta H
\]

(4)

\[
H_0 = H_{ref} + \int_{t_{ref}}^{t} c_p dt
\]

(5)

\[
\beta = \frac{t - t_{solid}}{t_{liquid} - t_{solid}} (t_{solid} \leq t \leq t_{liquid})
\]

(6)

\[
\beta = 1 (t > t_{liquid})
\]

(7)

\[
\Delta H = \beta \times Q_l
\]

(8)

where \( \Delta H \) is the latent heat during the phase change process.

The boundary condition at \( x = 0 \) m is

\[
\lambda_g \frac{\partial T}{\partial x} = a_1 (t_{s,1,T} - t_{s,0,T})
\]

(9)

The boundary condition at \( x = 0.024 \) m is

\[
\lambda_a \frac{\partial T}{\partial x} = a_0 (t_{s,a,T} - t_{s,0,T}) + \gamma I
\]

(10)

where \( \lambda_g, \lambda_a \) are the thermal conductivity of glass, \( a_1 \) and \( a_0 \) are the composite heat transfer coefficient of the interior and exterior surfaces of the PCMW and the HW, respectively (in summer \( a_1 = 7.75 \text{ W m}^{-2} \text{ °C}^{-1} \) and \( a_0 = 7.43 \text{ W m}^{-2} \text{ °C}^{-1} \); in winter \( a_1 = 6.61 \text{ W m}^{-2} \text{ °C}^{-1} \) and \( a_0 = 7.66 \text{ W m}^{-2} \text{ °C}^{-1} \). \( t_{s,1,T} \) and \( t_{s,0,T} \) are the temperature on the interior and exterior surfaces of the PCMW and the HW, respectively. \( t_{s,a,T} \) and \( t_{s,0,T} \) are air temperature of the indoor and outdoor, respectively. \( \gamma \) is the solar absorptance of the PCMW and the HW (when it is the HW, \( \gamma = 0.19 \); when it is the PCMW, \( \gamma = 0.37 \)). \( I \) is the solar radiation in vertical plane.

The governing equations and boundary conditions are discretized by finite difference method. Central differences are applied in space step while a fully implicit finite difference scheme is applied in time step. The space step size is 0.0005 m and the time step size is 30 s, while the convergence criterion is less than 10⁻⁶. The discrete equations are solved by the Tridiagonal Matrix Algorithm (TDMA) principle.

The thermal performances of the PCMW and the HW with the same size and thickness of the interlayer are analyzed comparatively in this paper. Temperature time lag and temperature decrement factor are used to evaluate the dynamic thermal performance of the windows, and the energy saving rate is used to evaluate the thermal insulation performance of the windows.

Temperature time lag is the phase difference of the temperature waves on the interior surfaces of the PCMW and the HW, which is calculated by Eq. (12), and temperature decrement factor is the ratio of the temperature waves on the interior surfaces of the amplitude of the PCMW and the HW, which can be calculated by Eq. (13). The schematic of the temperature time lag and temperature decrement factor is shown in Fig. 2. If the temperature time lag is high and the temperature decrement factor is low, it means that the impact of the outdoor thermal environment on the indoor thermal environment is small and the thermal performance of building envelope is satisfactory.

\[
\Psi_{PCM} = \frac{t_{PCM,\max} - t_{air,\max}}{t_{air,\max} - t_{air,\min}}
\]

(12)

\[
f_{PCM} = \frac{t_{PCM,\max} - t_{PCM,\min}}{t_{air,\max} - t_{air,\min}}
\]

(13)

where \( \Psi_{PCM} \) is the temperature time lag of the PCMW comparing with the HW, \( f_{PCM} \) and \( f_{air} \) are the time of the interior surface maximum temperature of the PCMW and the HW in the temperature waves, respectively, \( f_{PCM} \) is the temperature decrement factor of the PCMW comparing with the HW, \( t_{PCMW,\max} \) and \( t_{PCMW,\min} \) are the maximum and minimum temperature on the interior surface of the PCMW in the temperature waves, respectively, and \( t_{air,\max} \) and \( t_{air,\min} \) are the maximum and minimum temperature on the interior surface of the HW in the temperature waves, respectively.

The energy saving rate is defined as the ratio between the difference of the heat transferred into the building through the HW/PCM and the heat transferred into the building through the HW, as shown in the following equation:

\[
\eta = \frac{Q_{l,air} - Q_{l,PCM}}{Q_{l,air}}
\]

(14)

where \( Q_{l,PCM} \) and \( Q_{l,air} \) are the heat transferred through the PCMW and the HW, respectively. \( \eta \) is the energy saving rate of the PCMW comparing with the HW (when \( \eta > 0 \), the energy consumption of air conditioning system or heating system with the PCMW is reduced; when \( \eta < 0 \), the energy consumption of air conditioning system or
heating system with the PCMW applied is increased; when $\eta = 0$, the energy consumptions of air conditioning system or heating system with the PCMW comparing with the HW are tantamount.

The heat flux on the interior surfaces of the PCMW and the HW is calculated by the following equation:

$$q_i = \alpha_i (t_{g,i} - t_{a,i}) + \sigma \times I$$  \hspace{1cm} (15)

where $q_i$ is the interior surface heat flux of the PCMW or the HW, $\alpha_i$ is the interior surface composite heat transfer coefficient of the PCMW or the HW, $t_{g,i}$ is the temperature on the interior surface of the PCMW or the HW, $t_{a,i}$ is the temperature of the indoor air, $I$ is the solar radiation in vertical plane, $\sigma$ is the solar transmittance of the PCMW or the HW ($\sigma$ of the HW is 0.76, while $\sigma$ of the PCMW is 0.56). The heat transferred through the PCMW and the HW is calculated by the following equation:

$$Q_i = \int q_i \times d\tau = \int \alpha_i (t_{g,i} - t_{a,i}) \times d\tau + \int \sigma \times I \times d\tau$$ \hspace{1cm} (16)

where $Q_i$ is the specific cumulative heat transferred through the PCMW or the HW, the other symbols is the same as Eq. (15).

3. Experimental study

The experimental system was built. The temperatures on the interior surfaces of the PCMW and the HW were obtained by direct measurement, while the heat transferred through the PCMW and the HW was calculated by Eq. (17).

3.1. Experimental setup

The experimental setup consists of three parts. The first part is two completely same thermal guarded chambers which are made of polyurethane sandwich insulation panel, and there is a testing chamber in each guarded chamber, as shown in Fig. 3. The second part is the air conditioning system and electrical heating system to keep the guarded chamber and the testing chamber at the same
temperature, as shown in Fig. 4. The third part is the temperature, flow, power, solar radiation intensity measuring devices and data acquisition instrument.

The heat transferred into or out of the building through the PCMW and the HW was obtained from the energy conservation of the testing chamber. In Fig. 4, fan coil unit with an electric heater was set in each guarded chamber and testing chamber; the cold water and hot water flow in the fan coil unit were provided by an air source heat pump unit; the electric heater in fan coil unit provided heat for each guarded chamber and testing chamber. The guarded chamber and testing chamber were set at the same temperature by adjusting the heating power of electric heater according to the air temperature in guarded chamber and testing chamber. There will be no heat transferred through the polyurethane sandwich insulation panel between the guarded chamber and testing chamber when the guarded chamber and testing chamber were set at the same temperature, so the heat transferred only through the PCMW or the HW between the testing chamber and the external environment. Therefore, the heat transferred through the PCMW and the HW can be calculated by energy conservation equation of the testing chamber as shown in Eq. (17). The power of the fan in fan coil unit in testing chamber which converted to the heat in testing chamber and the power of the electric heater in testing chamber were directly measured by digital power meter. The cooling capacity provided by the fan coil unit was calculated by the measured inlet and outlet water temperature and the flow rate of the water in the fan coil unit. The heat transferred through the PCMW and the HW was calculated by the following equation:

\[ Q_i = Q_C - Q_H - Q_F = c_w \times \rho_w \times G_w \times (t_{w,i} - t_{w,o}) - (Q_H + Q_F) \]  \hspace{1cm} (17)

where \( Q_i \) is the heat transferred through the PCMW and the HW, (when \( Q_i > 0 \), the heat transferred through the PCMW and the HW from the outside into the testing room; when \( Q_i < 0 \), the heat transferred through the PCMW and the HW from the testing room to outside; when \( Q_i = 0 \), the heat transferred through the PCMW and the HW are zero), \( Q_H \) is the power of the electric heater in testing chamber, \( Q_F \) is the power of the fan in the fan coil unit in testing chamber, \( Q_C \) is the cooling capacity provided by the fan coil unit in testing chamber, \( c_w \) is the specific heat capacity of the circulating water in the fan coil unit in testing chamber, \( \rho_w \) is the density of the circulating water in the fan coil unit in testing chamber, \( G_w \) is the volume flow rate of the circulating water in the fan coil unit in testing chamber, \( t_{w,o} \) and \( t_{w,i} \) are the outlet and inlet water temperature of the fan coil unit in testing chamber, respectively.

The main parameters of the measuring instruments are shown in Table 1. The error analysis of the experiment was analyzed. The relative accuracy of the electromagnetic flow meter is 0.5%, while the accuracy of the inlet and outlet water temperature of the fan coil unit in testing chamber is 0.05 °C, and the temperature difference between the inlet and outlet water temperature of the fan coil unit in testing chamber is about 5 °C. So the relative error of the cooling capacity \( Q_C \) is 2.5% by calculating. The relative accuracy of the digital power meter is 0.1%, while the power of the fan in the fan coil unit in testing chamber is about 30 W; the power of the electric heater in the fan coil unit in testing chamber is about 200 W; the cooling capacity provided by the fan coil unit in testing chamber is about 400 W. The relative error of the heat transferred through the PCMW and the HW is 5.9% by calculating according to Eq. (18). The error analysis indicates that the results of this experimental system are satisfactory.

\[
\left( \frac{\Delta Q_i}{Q_i} \right) = \left( \frac{Q_C}{Q_C - (Q_H + Q_F)} \right) \times \left| \frac{\Delta Q_C}{Q_C} \right| - \frac{Q_H + Q_F}{(Q_C - (Q_H + Q_F))} \times \frac{\Delta (Q_H + Q_F)}{(Q_H + Q_F)} \]  \hspace{1cm} (18)

3.2. Comparative analysis of the experimental and simulation results

To validate the numerical model of the dynamic heat transfer process in the PCMW and the HW, the PCMW (Glauber's salt) is selected for the experimental measurement and numerical simulation under the same conditions. The PCMW (Glauber's salt) is shown in Fig. 5, which is made of clear glass and Glauber's salt (PCM). The thickness of the glass is 0.005 m, and the thickness of the PCM layer is 0.014 m. The measurement of the PCMW and the HW had been conducted from April 12, 2013, 9:00 a.m. to April 13, 2013, 9:00 p.m. The outdoor air temperature and solar radiation intensity during the experiment are shown in Fig. 6, and the relative humidity and the outdoor wind velocity during the experiment are shown in Fig. 7. The numerical simulation has been conducted under the same conditions at the same time. The thermo-physical properties of the related materials are shown in Table 2. The temperatures on the interior surfaces are obtained by the experimental measurement and numerical simulation, as shown in Fig. 8. The results indicate that the peak temperature on the interior surface of the PCMW (Glauber's salt) is 5 °C lower than that of the HW, while the temperature on the interior surface of the PCMW (Glauber's salt) is about 2–3 °C higher than
Table 1
Main parameters of the experimental measuring instruments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument</th>
<th>Instrument model</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (interior surface)</td>
<td>Thermocouple</td>
<td>Omega/T</td>
<td>~200–350 °C</td>
<td>0.4 °C</td>
</tr>
<tr>
<td>Temperature (water)</td>
<td>Platinum resistance thermometer</td>
<td>PT100</td>
<td>~200–400 °C</td>
<td>0.05 °C</td>
</tr>
<tr>
<td>Temperature (outdoor air)</td>
<td>Meteorological station</td>
<td>Davis/06162C</td>
<td>~40–65 °C</td>
<td>0.5 °C</td>
</tr>
<tr>
<td>Flow</td>
<td>Electromagnetic flow meter</td>
<td>Zhonghuan Ti/LDTH-10B</td>
<td>0–2.8 m³ h⁻¹</td>
<td>0.5%</td>
</tr>
<tr>
<td>Power</td>
<td>Digital power meter</td>
<td>Yokogawa/WT230</td>
<td>0–12 kW</td>
<td>0.1%</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Solar spectral radiometer</td>
<td>Jinzhou Sunshine/TQB-4-5</td>
<td>0–1400 W m⁻²</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 2
Thermo-physical properties of the related materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg m⁻³)</th>
<th>Specific heat capacity (kJ kg⁻¹ °C)</th>
<th>Latent heat (kJ kg⁻¹)</th>
<th>Thermal conductivity (W m⁻¹ °C)</th>
<th>Melting temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glauber’s salt (Na₂SO₄·10H₂O)</td>
<td>1458 (solid)</td>
<td>1.76 (solid)</td>
<td>241</td>
<td>0.554 (solid)</td>
<td>30–32</td>
</tr>
<tr>
<td></td>
<td>1485 (liquid)</td>
<td>3.30 (liquid)</td>
<td></td>
<td>0.45 (liquid)</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>1.1644</td>
<td>1.0064</td>
<td></td>
<td>0.0264</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>2500</td>
<td>0.79</td>
<td></td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
Results of the relative difference between experimental results and simulation results.

<table>
<thead>
<tr>
<th>The type of window</th>
<th>Relative difference (maximum) (%)</th>
<th>Relative difference (minimum) (%)</th>
<th>Relative difference (average) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HW</td>
<td>8.56</td>
<td>0.17</td>
<td>2.73</td>
</tr>
<tr>
<td>PCMW</td>
<td>8.35</td>
<td>0</td>
<td>0.66</td>
</tr>
</tbody>
</table>

4. Thermal performance analysis based on the validated numerical model

The dynamic thermal performance of the PCMW (Glauber’s salt) and the HW in the hot summer and cold winter area of China has been simulated based on the validated numerical model. The meteorological data of four representative days (rainy summer day, sunny summer day, sunny winter day and rainy winter day) of Nanjing, one of the typical representative cities of the hot summer and cold winter area of China, are shown in Figs. 9 and 10. The meteorological data of the four representative days is selected because they represent the common range of the outdoor air temperature, solar radiation, outdoor relative humidity and outdoor wind velocity both in summer and in winter. The temperature and heat flux on the interior surfaces of the PCMW and the HW, which are the numerical simulation results, are shown in Figs. 11–14. The temperature time lag and decrement factor were calculated according to Eqs. (12) and (13). The heat transferred through the PCMW and the HW was calculated according to Eq. (16), and the energy saving rate was calculated by Eq. (14). The results of the temperature

Fig. 5. Picture of the PCMW filled with Glauber’s salt (Na₂SO₄·10H₂O).

Fig. 6. Outdoor air temperature and the solar radiation intensity during the experiment.
time lag, temperature decrement factor and energy saving rate are shown in Table 4.

Fig. 11 shows that the temperature and heat flux fluctuations on the interior surfaces of the PCMW and the HW. The temperature and heat flux on the interior surfaces changed periodically with the increase and decrease of the outdoor air temperature and solar radiation. The amplitude of the temperature fluctuation on the interior surface of the PCMW is significantly lower than that of the HW. The interior surface temperature of the PCMW is about 9°C lower than the HW from 8 h (8:00 a.m.) to 16 h (4:00 p.m.), and it is about 4°C higher than the HW from 19 h (7:00 p.m.) to 26 h (2:00 a.m.).

(a) Temperature and the solar radiation of two representative days in summer

(b) Outdoor relative humidity and outdoor wind velocity of two representative days in summer

Fig. 9. Meteorological data of the representative sunny and rainy summer days in Nanjing. (a) Temperature and the solar radiation of two representative days in summer. (b) Outdoor relative humidity and outdoor wind velocity of two representative days in summer.
The results in Table 4 indicate that the temperature time lag and the temperature decrement factor of the PCMW are 3 h and 0.387 in the sunny days of summer. In addition, the peak temperature on the interior surface of the PCMW is 10.2 °C lower than the HW. The heat transferred through the PCMW reduces 39.5% compared with the HW. The reason for the variation in temperature and heat flux is that the PCM melted when the solar radiation is great. The temperature fluctuation on the interior surface of the PCMW is mitigated because the latent heat of the PCM is high and the temperature changed slightly when the phase change took place. The heat gain of the PCMW significantly reduced because PCM absorbed the solar radiation. The peak temperature on the interior surface of the PCMW is reduced, and the heat transferred is declined as a result. Therefore, the use of the PCMW can reduce the energy consumption of air conditioning system in the representative sunny summer day.

The temperature and heat flux fluctuations on the interior surfaces of the two compared windows in the rainy summer day are plotted in Fig. 12. The interior surface temperature of the PCMW is about 0.5 °C lower than the HW from 14 h (2:00 p.m.) to 16 h (4:00 p.m.), and it is about 1–2 °C higher than the HW from 8 h (8:00 a.m.) to 12 h (12:00) and from 18 h (6:00 p.m.) to 21 h (9:00 p.m.). The results in Table 4 indicate that the temperature time lag and decrement factor of the PCMW are 1 h and 0.863 in the rainy days of summer. In addition, the peak temperature on the interior surface of the PCMW is 0.6 °C lower than that of the HW. The heat transferred into the building through the PCMW increases

Table 4
Temperature time lag and temperature decrement factor and the energy saving rate of the PCMW comparing with the HW in different weather conditions.

<table>
<thead>
<tr>
<th>Weather conditions</th>
<th>$t_{\text{PCM, max}}$ (h)</th>
<th>$t_{\text{HW, max}}$ (h)</th>
<th>$\psi_{\text{PCM}}$ (h)</th>
<th>PCMW Temperature</th>
<th>HW Temperature</th>
<th>$f_{\text{PCM}}$</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunny summer day</td>
<td>16</td>
<td>13</td>
<td>3</td>
<td>32.1</td>
<td>25.6</td>
<td>0.387</td>
<td>39.5</td>
</tr>
<tr>
<td>Rainy summer day</td>
<td>16</td>
<td>13</td>
<td>3</td>
<td>30.0</td>
<td>25.6</td>
<td>0.481</td>
<td>−43.5</td>
</tr>
<tr>
<td>Sunny winter day</td>
<td>14</td>
<td>12.5</td>
<td>1.5</td>
<td>13.1</td>
<td>5.5</td>
<td>0.863</td>
<td>−78.9</td>
</tr>
<tr>
<td>Rainy winter day</td>
<td>17</td>
<td>14.5</td>
<td>2.5</td>
<td>10.9</td>
<td>5.6</td>
<td>0.108</td>
<td>−5.8</td>
</tr>
</tbody>
</table>
more than that of the HW. Therefore, the heat transferred through the PCMW is increased, and the use of the PCMW increases the air-conditioning energy consumption in the representative rainy summer day.

Fig. 13 shows that the temperature and heat flux fluctuations on the interior surfaces of the PCMW and the HW in the sunny winter day. The interior surface temperature of the PCMW is about 2–9°C lower than the HW from 7 h (7:00 a.m.) to 15 h (3:00 p.m.), and it is about 1–2°C higher than the HW from 18 h (6:00 p.m.) to 26 h (2:00 a.m.). The peak temperature on the interior surface of the PCMW is 9°C lower than that of the HW. The results in Table 4 indicate that the temperature time lag and decrement factor of the PCMW are 1.5 h and 0.481 in the sunny winter day. The heat transferred into the building through the PCMW decreases 78.9%. The reason for the variation in temperature and heat flux is that there is no phase change in the PCM because the surface temperature of the PCMW is significantly lower than the phase change temperature of Glauber's salt in the sunny winter day. The PCM absorbs solar radiation and blocks solar radiation into the building. The heat transferred out of the building by heat conduction through the PCMW is more than the HW since the thermal conductivity of the PCM is significantly greater than the air's. Therefore, the heat transferred into the building through the PCMW is decreased, and the use of the PCMW increases the heating energy consumption in the representative sunny winter day.

The temperature and heat flux fluctuations of the interior surfaces of the PCMW and the HW in the rainy winter day are plotted in Fig. 14. The interior surface temperature of the PCMW is about 1°C lower than the HW from 5 h (5:00 a.m.) to 16 h (4:00 p.m.), and it is about 0.5°C higher than the HW from 19 h (7:00 p.m.) to 26 h (2:00 a.m.). The peak temperature on the interior surface of the PCMW is 0.8°C lower than the HW. The results in Table 4 indicate that the temperature time lag and decrement factor of the PCMW are 2.5 h and 1.082 in the rainy winter day. The temperature decrement factor of the PCMW is more than 1 indicates that the amplitude of the temperature fluctuation on the interior surface of the PCMW is greater than the HW. The heat transferred out of the building through the PCMW increases 5.8%. The reason for the variation in temperature and heat flux is that there is no phase change in the PCM because the temperature of the interior surface of the PCMW is significantly lower than the phase change temperature of Glauber's salt in the rainy winter day. The mitigating the temperature fluctuation effect of PCM is small and the solar heat gains of the PCMW and the HW in the rainy winter day are significantly less than that in the sunny winter day. Heat transferred from inside to outside through the PCMW and the HW because
The indoor air temperature of the building with heating system is higher than the outdoor air temperature in rainy winter day. The heat transferred out of the building by heat conduction through the PCMW is more than the HW since the thermal conductivity of the PCM is significantly greater than the air’s. Therefore, the heat transferred out of the building through the PCMW is increased, and the use of the PCMW increases the heating energy consumption in the representative rainy winter day.

The heat transferred through two different kinds of windows (the HW and the PCMW) in the whole summer and in the whole winter were calculated based on the validated numerical model and the meteorological data of the typical meteorological year. It was known according to the calculated results that the heat transferred through the HW from outdoor to indoor in the whole summer was 1480 MJ, and the heat transferred through the PCMW from outdoor to indoor in the whole summer was 904 MJ; the heat transferred through the HW from outdoor to indoor in the whole winter from outdoor to indoor was 104 MJ, and the heat transferred through the PCMW from indoor to outdoor in the whole winter was 86.4 MJ. As a consequence, the annual energy consumption of the air conditioning system and the heating system because of the heat transferred through the HW was 1380 MJ, while that of the PCMW was 817 MJ. The annual energy consumption of the air conditioning system and the heating system because of the heat transferred through the window of the building with the PCMW applied decreased 40.6% compared with the building with the HW applied. So it has great energy saving potential that applying the PCMW filled with Glauber’s salt in the hot summer and cold winter area of China.

5. Conclusions

The numerical model for calculating the dynamic heat transfer process in the PCMW and the HW is established and the experimental system for measuring the heat transfer characteristics of the PCMW and the HW is built in this paper. The PCMW (Glauber’s salt, the phase change temperature is 30–32 °C) is selected to be tested in the experiment for the validation of the numerical model. The validated numerical model is used to simulate the dynamic heat transfer process of the PCMW and the HW in the representative sunny and rainy days both in summer and in winter in the hot summer and cold winter area of China. The conclusions are as follows.

The comparison between the simulation and experimental temperature results on the interior surfaces indicates that the maximum relative difference is lower than 8.6% and the average relative difference is lower than 2.8%. The results of the experiment and simulation are in good agreement, which shows that the numerical model is accurate in the weather condition during the experiment. Based on the obtained results, which were obtained by simulation on the condition of the four representative days’ meteorological data both in summer and in winter, it was concluded that in the representative sunny summer day, the temperature time lag and decrement factor of the PCMW (Glauber’s salt) are 3 h and 0.387, respectively. The peak temperature on the interior surface of the PCMW is 10.2 °C lower than that of the HW, and the heat transferred into the building through the PCMW reduces 39.5% comparing with the HW. It can improve the thermal comfort of the indoor environment and reduce the energy consumption of the air conditioning system by using the PCMW in the representative sunny summer day. However, in the representative rainy summer day, the representative sunny winter day and the representative rainy winter day, the dynamic thermal performance of the PCMW is unsatisfactory as it cannot decrease the energy consumption. Therefore, it needs to make appropriate adjustments in PCM and the structure of PCMW to improve the thermal performance under different weather conditions. As a whole, the annual energy consumption of the air conditioning system and the heating system because of the heat transferred though the window of the building with the PCMW applied decreased 40.6% compared with the building with the HW applied.

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References
