Influence of glazed roof containing phase change material on indoor thermal environment and energy consumption

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A R T I C L E   I N F O

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- PCM
- Glazed roof
- Energy consumption
- Thermal comfort

A B S T R A C T

Glazed roof has a convenient place to receive solar radiation, however its bad thermal mass affects the indoor thermal environment and energy consumption. In the present work, the effect of glazed roof filled with phase change material on its thermal mass was experimentally investigated and compared with conventional glazed roof. Experiments with different PCM melting temperatures, PCM layer thicknesses and glazed roof slopes were performed to analyze their effect on the energy consumption and dissatisfaction rate of indoor thermal environment. Also, a general economic analysis was performed to assess the viability of glazing units containing PCM. The results show that the energy consumption of glazed roof filled with PCM is significantly less than that of air, and up to 47.5% of energy saving can be achieved. Payback period can be reduced to 3.3 years by proper selection of PCM melting temperature. Increasing the melting temperature of PCM can effectively decrease the temperature of internal surface of glazed roof, but has a slight influence on the dissatisfaction rate of indoor thermal environment. Increasing the thickness of PCM layer decreases the peak temperature of internal surface of glazed roof and indoor chamber, the energy consumption and the dissatisfaction rate. The highest energy consumption and dissatisfaction rate are obtained at 20° of the inclination angle.

1. Introduction

Due to good daylighting and passive solar gain, glazed roof is extensively applied in modern buildings [1–6], such as airport terminals [7], greenhouses [8,9] and museums [10]. However, the thermal mass of glazed roof is poor due to high overall heat transfer coefficient and high solar energy transmittance, which has a big effect on the indoor energy consumption and thermal environment.

A lot of novel methods to improve the thermal mass of the glazed envelope are being promoted to reduce energy consumption of buildings. Phase change material (PCM) applied in the glazed envelope is one of the novel and efficient methods due to its excellent characteristics such as isothermal and high energy storage capacity in the process of phase change [11–28]. The aim of employing PCM in the glazed envelope is not only to absorb part of the solar irradiation for improving its thermal mass, but also to allow visible light get into the indoor environment for controlling solar energy transmittance.

There are numerous research works on the indoor thermal environment and energy consumption in building glazed envelope containing PCM, such as facades [29–34] and windows [35–44]. Kolacek et al. [35] investigated the indoor thermal environment and energy consumption of building glazed envelope equipped with PCM-filled window, and found that the PCM-filled window improves the thermal mass of the building and markedly reduces the indoor temperature. The authors also
indicated that the heat gain through window filled with PCM decreases by 66% in the summer cycle. Several works explored the thermal performance of glazed unit filled with PCM [40–44]. Liu et al. [40,41] reported that the PCM thickness and melting temperature have a great influence on thermal performance of double glazing units in the cold area of northeast China. Li et al. [42–44] studied the heat transfer performance of PCM-filled glass window (PCMW) in the subtropics of China. They found that the heat gain through the PCMW reduces by 18.3% in a typical sunny summer day, and the thermal performance of PCMW improves by decreasing the temperature difference between the liquid phase and solid phase.

The above stated researches clearly indicate that the thickness and melting temperature of PCM have a significant effect on the indoor thermal environment and energy consumption in building equipped with glazing envelope containing PCM. However, there are few experimental studies about glazed roof filled with PCM. In our previous researches, we investigated the thermal and optical performances of double glazed roof numerically and analyzed the effect of thickness and optical parameters on the interior heat and light transfer process. However, we did not study the effect of PCM on the indoor thermal environment and energy consumption in building equipped with glazing envelope containing PCM. Therefore, in the present experimental work, we aimed to investigate the influence of PCM glazing unit on the indoor thermal environment and energy consumption in the cold area of northeast China considering different PCM melting temperatures, PCM layer thicknesses and roof slopes. To evaluate the performance of PCM glazing, we conducted the experiments for the conventional double glazing filled with air in the interspace also, as a reference case.

2. Methodology

2.1. Experimental set

Fig. 1 shows the photograph of glazing unit integrated to the roof. The glazing unit is made of aluminum skeleton and glass with the dimension of 500 × 450 × 4mm (Height × Width × Thickness), which is used to contain the PCM (or air) in the experiments. Before pouring PCM into the cavity between panes, four sides of glazed unit are sealed by the sealant except for one hole with the size of 15 mm. After injecting the liquid PCM into the cavity, the small hole is finally sealed for three layers to ensure the sealing performance. Considering the volume expansion in the solidifying process of PCM, about 97% of the total volume of cavity is filled with PCM. Nine sets of glazing units were built to investigate the effects of PCM melting temperature (18, 26 and 32 °C), PCM layer thickness (6, 9 and 16 mm) and roof slope (10, 20 and 30°) on the indoor thermal environment and energy consumption of experimental chambers equipped with glazed roof unit.

The PCMs (paraffin wax) employed in the experiments were supplied from Shanghai Joule Wax Industry (Shanghai, China), which are named as PCMⅠ, PCMⅡ and PCMⅢ according to their melting temperatures of 18, 26 and 32 °C, respectively. Table 1 presents the thermophysical parameters of PCMs.

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity (W/m K)</th>
<th>Specific heat capacity (kJ/kg K)</th>
<th>Latent heat (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCMⅠ</td>
<td>Solid 885</td>
<td>0.2</td>
<td>2.32</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid 880</td>
<td>0.21</td>
<td>2.24</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>PCMⅡ</td>
<td>Solid 894</td>
<td>0.22</td>
<td>2.26</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid 890</td>
<td>0.23</td>
<td>2.22</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>PCMⅢ</td>
<td>Solid 899</td>
<td>0.29</td>
<td>2.24</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid 897</td>
<td>0.2</td>
<td>2.2</td>
<td>172</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 provides the sketch and photograph of experimental setup located in the Northeast Petroleum University of China. The experimental setup is composed of two main modules; experimental test chamber and data acquisition system. The experimental test chamber consists of four identical chambers with the dimension of 762 × 712 × 613 mm (Length × Width × Thickness, external dimension) and 500 × 450 × 460 mm (Length × Width × Thickness, internal dimension), which provides the experimental platform for modelling the room environment and energy consumption. The experimental test chambers are thermally insulated by using a heat insulating material (Expanded Polystyrene, i.e. EPS), and the glazing unit is installed on the top section of experimental test chamber. The data acquisition system provides the platform for measuring thermal environment and energy consumption of the chambers equipped with the glazed roof, including

![Fig. 1. PCM-filled glazed roof unit (left: liquid state; right: solid state).](image-url)
2.2. Performance parameters definition

In order to analyze the effect of glazed roof filled with PCM on the thermal environment and energy consumption of test chambers, four performance parameters based on the experimental data are quantified, which are heat flux through the glazed roof, energy consumption of the test chamber, dissatisfaction rate of the indoor thermal environment and energy saving rate.

2.2.1. The heat flux of glazed roof

The heat flux of internal surface of glazed unit is calculated by using the temperature and convective heat transfer coefficient. The reason is that convective heat transfer coefficient is small and nearly constant as heat transfer between the internal surface of glazed unit and indoor air occurs by natural convection. Thus, the heat flux through the glazed roof into indoor environment is given as

$$q_i = \alpha_i (T_1 - T_2)$$  \hspace{1cm} (1)

where $q_i$ is the heat flux, W/m$^2$. $T_1$ and $T_2$ are the interior surface temperature of glazed roof and the indoor temperature of test chamber, respectively, $\alpha_i$ is the convective heat transfer coefficient on the interior surface of glazed roof, 7.43 W/(m$^2$ K) [42].

2.2.2. Energy consumption of test chamber

Energy consumption of test chamber is the sum of supplied energy and removed energy to maintain the thermal comfort zone of test chamber. The thermal comfort zone of test chamber is defined based on the indoor temperature, which is in the range of 18–26 °C. The energy consumption of test chamber can be calculated as

$$Q_{SE} = \sum c_p \rho (18 - T_2) \text{ if } T_2 < 18 \degree C$$  \hspace{1cm} (2a)

$$Q_{RE} = \sum c_p \rho (T_2 - 26) \text{ if } T_2 > 26 \degree C$$  \hspace{1cm} (2b)

$$Q = Q_{SE} + Q_{RE}$$  \hspace{1cm} (2c)

where $Q$, $Q_{SE}$ and $Q_{RE}$ represent the energy consumption of test chamber, supplied energy and removed energy in one whole day, kJ/m$^3$ day, respectively. $c_p$ and $\rho$ are the specific heat and density of air, respectively.

2.2.3. Dissatisfaction rate of indoor thermal environment

When the indoor temperature of living zone is out of thermal comfort range, the occupants feel uncomfortable. Therefore, the dissatisfaction rate (DR) parameter is introduced to analyze the impact of glazed roof on the indoor temperature of test chamber. The DR is defined as

$$DR = \frac{r}{24} \times 100\%$$  \hspace{1cm} (3)

where $r$ stands for the total time duration when the indoor temperature in the building is out of thermal comfort temperature range, h.

2.2.4. Energy saving rate

In order to determine the potential energy saving provided by the glazed roof containing PCM, the energy consumption is compared to that of referent glazing unit. The energy saving rate (ESR) is calculated as [45]

$$ESR = 1 - \frac{Q_{PCM(ULED)}}{Q_{Air}}$$  \hspace{1cm} (4)

where $Q_{PCM(ULED)}$ and $Q_{Air}$ represent the energy consumptions of test chamber equipped with glazed roof containing PCM and air, kJ/m$^3$ day, respectively.

2.2.5. Economic feasibility of glazing unit filled with PCM

A thermoeconomic analysis is performed to evaluate the viability of glazing units containing PCM. For that purpose, an economic model is built based on the life cycle cost analysis ($P_1 - P_2$ method) [46]. The total cost of glazing unit filled with PCM ($C_T$, CNY) is obtained by the sum of investment cost of PCM ($C_I$) and present worth of the cost of the required energy over the lifetime (Eq. (5)).

$$C_T = C_I + C_{PW}$$  \hspace{1cm} (5)

Here, $C_I$ stands for the annual heating and cooling energy costs to maintain the occupied zone in the thermal comfort range and PWF is the present worth factor which is used to convert the total energy cost over the lifetime to the present value. It is noted that the maintenance and operation cost of PCM is assumed to be zero and the installation and seal costs are not taken into account in the analysis since their costs are very small compared to the cost of PCM. The cost of PCM used in this work is 27,000 Chinese Yuan (CNY) per m$^3$. Thus the investment cost of PCM ($C_I$) can be given as a function of PCM layer thickness.

$$C_I = 6075L_{PCM}$$  \hspace{1cm} (6)

PWF is defined as follows,

$$PWF = \frac{1}{i} \left(1 - \frac{1 + g}{(1 + i)^N}\right) \text{ if } i \neq g$$  \hspace{1cm} (7)
where \( i \) is the interest rate (2%), \( g \) is the inflation rate (7.5%) and \( N \) is the lifetime (10 years).

The annual energy cost is estimated by,

\[
C_a = \frac{C_e DV Q_{PCM}}{\text{COP}}
\]

Here, \( C_e \) is the electricity cost (1 CNY/kWh, i.e. 0.278 CNY/MJ), \( D \) is the number of days in each year out of the thermal comfort zone (it is assumed to be 180 days considering the climatic conditions in Daqing city) which requires an air conditioning system to be operated to heat or cool the occupied zone. \( V \) is the volume of occupied zone and COP is the coefficient of performance of air conditioning system (2.5).

Regarding all the above mentioned specified values, the total cost over the lifetime of glazing unit containing PCM is calculated as

\[
C_T = 6075L_{PCM} + 2.07Q_{PCM}PWF
\]

Taking the conventional double glazing with air in the interspace as a referent glazing unit, life cycle saving (\( S \)) is defined as the difference between the saved energy cost over the lifetime and the investment cost

\[
S = 2.07PWF(Q_{air}-Q_{PCM})-6075L_{PCM}
\]

Payback period of the glazing unit filled with PCM is also estimated by setting the life cycle saving (Eq. (10)) to zero and solving for \( N \).

3. Results and discussion

In this section, the effects of PCM melting temperature, PCM layer thickness and glazed roof slope on the thermal environment and energy consumption of test chambers were analyzed. The experiments were conducted on 20th August, 25th August and 21st September 2016.

3.1. Effect of PCM melting temperature

Experiments were carried out for different PCM melting temperatures (namely, 18, 26 and 32 °C) and compared with the referent glazing unit i.e. glazing unit filled with air). In the experiments, the thickness between panes (i.e. PCM or air layer thicknesses in the glazed roof) is 9 mm, and the slope of glazed roof is 10° toward the west. Fig. 3 illustrates the measured data of solar radiation intensity and ambient temperature on 25th August 2016.

Fig. 4 shows the temperature and heat flux of internal surface of glazed roof, and indoor temperature of test chamber. As can be seen from Fig. 4a, the temperature trends of internal surface of glazed roof filled with PCM are different from each other and also obviously different from that of the referent glazing unit. It is also observed that the peak temperature of internal surfaces of glazed roof filled with PCM decreases significantly and delays to the later time in the day compared with that of air. The decrease magnitude of peak temperature is 11.4, 10.3 and 16.3 °C, and the time delay of peak temperature is 39, 22 and 39 min, for PCM melting temperature of 18, 26 and 32 °C, respectively.

The reason for this phenomenon is that increasing the melting temperature of PCM, more solar energy is stored in the PCM layer, which results in a decrease in the peak temperature and an increase in the time lag. Therefore, the glazed roof filled with PCM effectively improves the indoor thermal environment. However, proper selection of PCM melting temperature is important for the indoor thermal environment.
A similar observation can be found in Fig. 4b, which demonstrates the variation of indoor temperature of test chamber. Compared to the reference glazing unit, the indoor peak temperature decreases 7.6, 7.2 and 15.1 °C, and the time lag increases 25, 44 and 64 min for the PCM melting temperature of 18, 26 and 32 °C, respectively. The results indicate that with the increase of melting temperature, the indoor peak temperature decreases considerably and the time lag increases. The energy cost savings range from about 5 CNY to 67 CNY by incorporating about 1.8 kg of PCM in the glazing unit. By the proper selection of PCM melting temperature, payback period can be decreased from 6.2 (PCM I) to 3.3 years (PCM III).

Fig. 5 illustrates the energy consumption of test chamber and the dissatisfaction rate (DR) of indoor thermal environment. The energy consumption of four kinds of test chamber are substantially different from each other, and the highest energy consumption is observed for air. By incorporating PCM into the glazed unit, the energy consumption of test chamber decreases remarkably. As PCM melting temperature increases, energy consumption decreases. The energy consumption of test chamber for PCM with melting temperature of 18 °C is 12.52 MJ/m² d reduces to 11.27 and to 8.57 MJ/m² d for melting temperatures of 26 and 32 °C, respectively. Referring to Fig. 5, the dissatisfaction rate of indoor thermal environment also decreases by utilizing PCM. The minimum dissatisfaction rate of indoor thermal environment, 42.57%, is attained for PCM II (melting temperature of 26 °C). In other words, about 13.8 h of the day when the experiments were executed falls in the range of thermal comfort temperature zone.

Energy saving rate (ESR) of glazed roof filled with PCM is evaluated by Eq. (4) for different PCM melting temperatures. About 23.3%, 31.0% and 47.5% of energy saving from the glazed unit can be obtained by utilizing PCM for melting temperature of 18, 26 and 32 °C, respectively. Consequently, it can be concluded from the perspective of energy efficiency that the higher the melting temperature, the higher energy saving. Table 2 presents the results of thermoeconomic analysis. As seen in the table, the life cycle total cost and payback period decreases and net energy saving increases considerably as melting temperature increases. The energy cost savings range from about 5 CYN to 67 CYN by incorporating about 1.8 kg of PCM in the glazed unit. By the proper selection of PCM melting temperature, payback period can be decreased from 6.2 (PCM I) to 3.3 years (PCM III).

### Table 2

<table>
<thead>
<tr>
<th>PCM</th>
<th>Investment cost (CNY)</th>
<th>Annual energy cost (CNY)</th>
<th>Total cost (CNY)</th>
<th>Net saving (CNY)</th>
<th>Payback period (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>54.68</td>
<td>25.92</td>
<td>251.04</td>
<td>5.08</td>
<td>6.2</td>
</tr>
<tr>
<td>II</td>
<td>54.68</td>
<td>23.33</td>
<td>231.43</td>
<td>24.69</td>
<td>4.8</td>
</tr>
<tr>
<td>III</td>
<td>54.68</td>
<td>17.74</td>
<td>189.09</td>
<td>67.03</td>
<td>3.3</td>
</tr>
</tbody>
</table>

3.2. **Effect of PCM layer thickness**

In this section, the influences of different PCM layer thicknesses (6, 9 and 16 mm) on the monitoring parameters are presented. Experiments were performed for PCM melting temperature of 26 °C and glazed roof slope of 10° toward the west. Fig. 6 shows the measured data of solar radiation intensity and ambient temperature on 20th August 2016.

Fig. 7 shows the variation of temperature and heat flux of internal surface of glazed roof, and indoor temperature of test chamber for different PCM layer thicknesses. The results show that, referring to Fig. 7a, PCM layer thickness has a little influence on the indoor surface temperature of glazed roof filled with PCM. As PCM layer thickness increases, the peak temperature decreases due to the increased solar energy storage capacity and minimum temperature formed for the given day, consequently the temperature amplitude decreases. For instance, increasing PCM layer thickness from 6 to 16 mm, the peak temperature on the internal surface decreases from 54.5 to 51.4 °C. PCM layer thickness has a marginal effect on the time when the peak temperature is achieved. For instance, the peak temperatures are measured at 14.47, 14.43 and 14.53 h for 6, 9 and 16 mm of PCM layer thickness, respectively.

The variation of indoor temperature of test chamber for different PCM layer thicknesses is presented in Fig. 7b. Referring to the figure, the effect of PCM layer thickness on the indoor temperature is more profound during the diurnal period due to activated solar energy, where the indoor temperature of test chamber decreases with the increase in PCM layer thickness. As a quantitative example, increasing PCM layer from 6 to 16 mm, the peak indoor temperature of test chamber decreases by 7.7 °C. On the other hand, as PCM layer thickness is increased, the peak temperature is achieved at slightly earlier times in the day. To be more precise, the indoor peak temperature is measured at 14.4, 14.3 and 14.1 h for 6, 9 and 16 mm of PCM layer thickness, respectively.

The variation of heat flux of internal surface of glazed roof filled with PCM is plotted in Fig. 7c for different PCM layer thickness. As seen from the figure, the heat flux trend is smooth during the nocturnal period (specifically before 10 h and after 18 h) while it fluctuates.
remarkably during the diurnal period, particularly for the PCM layer of 6 mm due to lower thermal inertia. Accordingly, it can be concluded that the PCM layer thickness has an influence on the heat flux of internal surface of glazed roof filled with PCM and the smaller PCM layer thickness, the higher fluctuation amplitude of heat flux.

The calculated energy consumption of test chamber and the dissatisfaction rate (DR) of indoor thermal environment of glazed roof filled with PCM for different PCM layer thicknesses on 20th August 2016 are shown in Fig. 8. The results indicate that the PCM layer thickness has a large influence on the energy consumption of test chamber. As the PCM layer thickness increases, the energy consumption of test chamber tends to weaken. For instance, increasing PCM thickness from 6 to 9 mm, the energy consumption of test chamber decreases from 15.7 to 12 MJ/m$^3$·d. However, the decrease rate reduces with the further increase in PCM layer thickness (10.8 MJ/m$^3$·d for 16 mm of PCM layer). Besides, it is seen from Fig. 8 that the dissatisfaction rate of indoor thermal environment is above 50% for 6 mm of PCM thickness. Increasing PCM layer to 9 mm, the dissatisfaction rate decreases. Further increase in PCM layer thickness has an insignificant effect on the DR. In other words, although the investment cost increases linearly with the PCM layer thickness, the decrease in energy consumption and dissatisfaction rate is not that much. Therefore, the PCM layer thickness should be optimized considering both energy consumption and dissatisfaction rate.

3.3. Effect of roof slope

Experiments for 10°, 20° and 30° inclination angles (all toward the west) of glazed roof were carried out to study the impact of slope on the indoor thermal environment and energy consumption under the actual environmental conditions. Experiments were done for PCM layer thickness of 9 mm and melting temperature of 18 °C. Fig. 9 shows the measured data of solar radiation intensity and ambient temperature on 21st September 2016.

Fig. 10 illustrates the temperature and heat flux of internal surface of glazed roof, and indoor temperature of test chamber for different roof slopes. It is seen from Fig. 10a that with the increase of glazed roof
slope, the magnitude of surface temperature increases, and the temperature reaches a peak value at later time in the day since the glazing unit is exposed to higher solar radiation. For instance, the peak temperature of internal surface reaches to 41.2 °C at 13.9 h, 44.3 °C at 14.25 h and 46.5 °C at 14.72 h for the glazed roof slope of 10°, 20° and 30°, respectively. The remarkable effect of roof slope on the indoor temperature of test chamber can be seen from Fig. 10b. Similar to the surface temperature, as the inclination angle increases, the indoor temperature rises and moves away from the thermal comfort zone. The peak temperatures are measured to be 41.8, 48.1 and 49.5 °C for the glazed roof slope of 10°, 20° and 30°, respectively. Fig. 10c shows the variation of heat flux of internal surface of glazed roof filled with PCM for different inclination angles. Referring to the time between 11:00 and 18:00 in the figure, the heat flux increases sharply due to the rise of solar radiation and outdoor temperature (see Fig. 9), and then decreases gradually. As inclination angle increases, the fluctuation in heat flux is more profound since more solar radiation reaches the glazed unit. The effect of inclination on the heat flux diminishes at later time of night as all the PCM in the glazing unit solidifies.

Fig. 11 shows the energy consumption of test chamber and the dissatisfaction rate of indoor thermal environment for different inclination angles of glazed roof. Since the comfort temperature range is defined in the range of 18 °C and 26 °C, two conditions need to be considered; (i) the supplied energy when the internal temperature of test chamber is less than 18 °C and (ii) the removed energy when the internal temperature of test chamber is higher than 26 °C. As clearly seen from the figure, the amount of removed energy from the test chamber is much higher than that of supplied energy regardless of the inclination angle. The results obviously indicate that the surplus energy (i.e. removed energy from the chamber) can be stored and can later be utilized for heating purposes if necessary. Considering both the supplied and removed energy, roof slope of 20° requires the highest energy, 8.17 MJ/m² d in total, which is followed by roof slope of 10° (5.2 MJ/m² d) and roof slope of 30° (7.4 MJ/m² d). The dissatisfaction rate rises up to 70% for the roof with inclination angle of 20° whereas it is 64.51% and 65.9% for inclination angles of 10° and 30°, respectively. It can be claimed that by increasing the slope of glazing unit, the dissatisfaction rate of indoor thermal environment and energy consumption does not always rise and an optimal slope may exist.

4. Conclusions

In this study, an experimental work was carried out to explore the influence of melting temperature of phase change material, layer thickness and slope of roof on the thermal performance of glazed roof filled with PCM and indoor thermal comfort under the actual environmental conditions. Besides, general economic aspect of the glazing unit containing PCM is examined by a cost analysis. The following findings are drawn from the experimental results and discussions:

1. Incorporating PCM in the glazing unit instead of air reduces significantly the energy consumption and dissatisfaction rate of indoor thermal environment of glazed roof. By employing PCM with 32 °C of melting temperature, the peak temperature decreases about 16.3 °C, time lag increases to about 40 min and energy consumption...
reduces by 47.5%.

(2) As the PCM layer thickness increases, the indoor peak temperature decreases considerably, however the peak temperature time lag changes marginally. With the increase of PCM layer thickness, the energy consumption and the dissatisfaction rate of indoor thermal environment gradually weaken. Increasing the PCM layer thickness from 6 mm to 9 mm, the dissatisfaction rate decreases and the energy consumption reduces by 23%. Further increase in the PCM layer thickness (16 mm) has an insignificant effect on the dissatification rate and weakened effect on the energy consumption.

(3) Increasing the slope of glazed roof results in enhancement of peak temperatures. Indoor peak temperature of the glazed roof at 30° of inclination angle is 7.7 °C higher than that of the roof at 10°. The roof slope has a great influence on the energy consumption and dissatisfaction rate of indoor thermal environment. The highest energy consumption considering both the supplied energy from outside and removed energy from the test chamber, and highest dissatisfaction rate (70%) are obtained for the inclination angle of 20°. PCM layer thickness and PCM melting temperature should be optimized in order to improve thermal resistance of glazing unit and indoor thermal environment.

(4) Payback period of PCM glazing unit ranges from 3.3 to 6.2 years. By the proper selection of PCM melting temperature, payback period can be decreased.

The proposed concept of the glazed roof containing PCM is particularly easy to implement on the large venues, such as the gymnasium, whose roof is made of glass and can be implemented as a retrofit solution with energy consumption based on the goals of peak load reduction and the time length of storage.

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