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

Dong Li[a], Yangyang Wu[a], Guojun Zhang[a], Müslüm Arıcı[b,*], Changyu Liu[a,*], Fuqiang Wang[c]

[a] School of Architecture and Civil Engineering, Northeast Petroleum University, Fazhan Lu Street, Daqing 163318, China
[b] Engineering Faculty, Mechanical Engineering Department, Kocaeli University, Umuttepe Campus, 41380 Kocaeli, Turkey
[c] School of Automobile Engineering, Harbin Institute of Technology at Weihai, 2, West Wenhua Road, Weihai 264209, China

HIGHLIGHTS

- Influence of glazed roof containing PCM was investigated.
- Utilizing PCM has a great potential to reduce energy consumption.
- Up to 47.5% of energy saving through glazed roof can be achieved.
- Indoor thermal environment improves.
- Roof slope with 10° is recommended for the studied climatic zone.

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ABSTRACT

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 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

* Corresponding authors.
E-mail addresses: muslumarici@gmail.com (M. Arıcı), lidonglvyan@126.com (C. Liu).

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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.

Table 1
Thermophysical parameters of PCMs.

Material	Melting temperature (°C)	Density (kg/m^3)		Thermal conductivity (W/m K)	Specific heat capacity (kJ/kg K)	Latent heat (kJ/kg)
PCM I	18	Solid	885	0.2	2.32	185
		Liquid	880	0.21	2.24	
PCM II	26	Solid	894	0.22	2.26	174
		Liquid	890	0.23	2.22	
PCM III	32	Solid	899	0.29	2.24	172
		Liquid	897	0.2	2.2	

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.

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).