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Influence of PCM design parameters on thermal and optical performance of multi-layer glazed roof

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HIGHLIGHTS

- Influences of air layer convection process and PCM design parameters were investigated.
- Due to air convection, temperature D-value experiences multiple peaks and troughs in one day.
- PCM thickness of 12–20 mm and melting temperature of 16–18 °C were recommended.

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ABSTRACT

Phase change material (PCM) applied in the multi-layer glazed roof can decrease energy consumption of building and increase thermal comfort by improving its thermal energy storage capacity. In present work, a numerical model was developed to provide a tool to determine thermal and optical performance of a multi-layer glazed roof filled with phase change material for developing engineering analyses. The model was validated by the experimental results measured in a multi-layer glazed roof test facility. The influences of air convection and PCM design parameters on thermal and optical performance of the multi-layer glazed roof filled with PCM were also investigated by the model. The results show that a good agreement was obtained between experimental data and simulations. The influence of air convection on the thermal and optical performance of multi-layer glazed roof is weak for different PCM melting temperatures and thicknesses, except for its effect on the interior temperature. Considering that the maximum and minimum interior temperatures are key parameters to analyze the thermal performance of multi-layer glazed roof, the air convection process should be considered. The influences of PCM thickness and melting temperature on optical performance are big. The PCM thickness has also serious influences on the thermal performance, which include interior temperature, temperature time lag, temperature difference of the interior surface and the upper surface of air layer, and total transmitted energy. With the PCM thickness increasing, the variation of temperature difference of the interior surface and the upper surface of air layer in one day experiences multiple peaks and troughs. Considering influence of PCM design parameters on both thermal and optical performance of glazed roof, thickness of 12–20 mm and melting temperature of 16–18 °C was recommended.

1. Introduction

Multi-layer glazed envelope is widely used in modern buildings due to its higher light transmittance and better view [1–3], which includes glazed walls, glazed windows and glazed roofs. However, the thermal performance of multi-layer glazed envelope is much poorer than any other parts of building, which plays a key role in the building energy demand in general [4,5], especially for the glazed roof due to facing directly to solar radiation and better location in the heat transfer process between the external and the internal surroundings of the building, compared with other enclosure structures. For example, when the glazed area accounts for a large proportion in the building envelopes including glazed windows and roof, the heat loss is much bigger than the common buildings, and it may nearly occupy 30% of the energy consumption capacity [6,7].

New methods for improving the thermal performance of the multi-layer glazed envelope are being promoted to reduce energy consumption of buildings [8]. Phase change material (PCM) applied in the multi-layer glazed envelope is a new method to achieve this objective [9–12], whose aim is not only to absorb part of the solar irradiation for heat storage, but also to let visible light get into the indoor environment for daylighting [13–15]. The PCM filled in the multi-layer glazed envelope

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Nomenclature

$c_{P,g}$, $c_{P,p}$ specific heat of glass and PCM, J/(kg K)
F_{sky} view factor between sky and the glazing roof, –
H, h_{out}, h_{in} specific enthalpy of PCM, J/kg; convection heat transfer coefficient between the external surface and outer airflow, inner surface and internal airflow, W/(m^2 K)
I_0 solar radiation intensity, W/(m^2 sr)
k_g, k_p, $k_{p,l}$, $k_{p,s}$ thermal conductivity of glass and PCM, liquid PCM near to liquid–solid interface, thermal conductivity of solid PCM next to liquid–solid interface, W/(m K)
$k_{g,t}$ effective thermal conductivity of glass, W/(m K)
H specific enthalpy of PCM, J/kg
Gr_δ Grashof number, –
Pr Prandtl number, –
Nu Nusselt number, –
k absorption coefficient of media, m^{-1}
h_{in}, h_{out} convective heat transfer coefficients between the interior surface and indoor airflow, convective heat transfer coefficient between the exterior surface and outdoor airflow, W/(m^2 K)

Greek letters

γ, β liquid fraction, a factor that express the ratio of the heat exchange between the external glass and sky, –
ρ_g, ρ_p density of glass and PCM, kg/m^3
ρ_{i-j} the mirror interface reflectance of media i and j, –
τ time, s
ϕ radiative source term, W/m^2
ε surface emissivity of glass, –
σ Stefan–Boltzmann constant, W/(m^2 K^4)
θ angle between the glazed roof and the sky, –
φ zenith angle of incidence and reflectance, –
φ_g temperature time difference of the multi-layer glazed roof between the inner surface and the outdoor air, s
φ_{ave} average relative value, –
δ thickness of air layer, m
α_i^1, α_i^2 compared parameter value and the standard value, –
n_g, n_{p1}, n_{p2} refractive index of glass, phase1 and 2 of PCM, –
Q_L latent heat of PCM, J/kg
q_{rad}, $q_{rad,air}$, $q_{rad,sky}$ radiative heat exchange between external surface of outer glass with the outdoor environment, with the air, W/m^2
T_{out}, $T_{a,out}$, T_{sky}, T_{in}, $T_{a,in}$ temperature of the external surface of outer glass, ambient, sky temperature, inner surface of internal glass, indoors air, K
T Temperature, K
T_{ref} reference temperature of PCM, K
T_l, T_s temperature that solid PCM starts to melt, temperature that solid PCM completely changes into liquid state, K
b thickness, m
h_a convection heat transfer of the air interlayer, W/m^2 K
$I\,(x,\mu)$ radiative intensity of the sunlight at position x, the direction is θ, $\mu = \cos\theta$, W/(m^2 sr)
$I_{i+1\to i,j}$ short-wave radiation intensity that enter/leave the control volume i during the condition that the sunlight pass through the glazed unit for j times, W/(m^2 sr)

Subscript

a air, –
con convective
g, p glass and PCM, –
in, out inner surface and exterior surface, –
rad radiative, –
sol solar radiation intensity, –
l, s liquid and solid PCM, –

can improve solar energy utilization, which is an interesting and attracting technology in the field of applied energy. Therefore, numerous experimental and numerical works of heat storage solutions for the multi-layer glazed envelope containing PCM have been developed, especially for double glazed unit, which has been attracted much more attention as an effective method for reducing building energy consumption.

Gracia et al. [16–20] paid much attention to the fundamental research on thermal performance of ventilated facade containing PCM. For example, Gracia et al. [16,17] experimentally investigated the thermal performance of a ventilated double facade containing PCM in the Mediterranean climate, and concluded that PCM can significantly improve the thermal performance of buildings. And the authors indicated that the use of ventilated facade containing PCM reduces by 7.7% of the environmental impact of the whole building in a lifetime of 50 years [18]. Gracia et al. also [19,20] developed numerical methods to simulate the thermal performance of ventilated facade with PCM next to its air cavity, based on that the heat exchange between phase change material and the air layer is at isothermal conditions. Li et al. [21] and Goia et al. [22] also carried out experiment and simulation studies to investigate the thermal performance of multi-layer glazed unit. For example, Li et al. [21] utilized experimental methods to analyze the thermal performance of multi-layer glazed unit filled with PCM and air layers, and they found that the thermal performance of multi-layer glazed unit is better than the one of double glazed unit, owing to the insulation effect of air layer.

The previous studies show that optical performance of PCM has a big effect on the thermal performance of glazed units, and the characterization of the optical properties of PCM considerably affects the thermal performance of glazed units [23–27]. Goia et al. [23,24] utilized a commercial spectrophotometer and a dedicated optical test bed to measure the optical properties of glazed samples containing PCM with different PCM thicknesses, and found that the relevant difference in spectral feature can be seen for its different PCM states. Goia et al. [25,26] developed a full-scale prototype of a glazed system containing PCM, and analyzed its energy performance. And they found that the experimental results have highlighted a good ability of the PCM glazed unit to store thermal energy and to delay the total heat flux peak values. Gowreesunker et al. [27] utilized spectrophotometry principles and T-history method to investigate the thermal and optical performance of a glazed unit containing PCM, and they found that the PCM transmittance spectra are unstable during rapid phase change process, while the visible transmittance values of 90% and 40% are obtained for the liquid and solid phase states under stable conditions, respectively.

However, most of the researches about thermal and optical performance of glazed envelope focused on the glazed walls and windows, there are few studies about glazed roof [28,29]. In the design of the multi-layer glazed roof, the conclusions of the windows and walls may also supply theoretical reference, but the parameters cannot be directly used for multi-layer glazed roof. In our previous researches, the thermal and optical performance of double glazed roof were investigated, and the effects of thickness and optical parameters on its interior heat and light transfer process were analyzed by utilizing a numerical model, which considered the multiple reflectance of sunlight between the glass surfaces and the moving interface of PCM in solid and liquid states [28,29].

Compared with the model to simulate thermal and optical performance of double glazed roof filled with PCM, the one of multi-layer