Investigations on thermal and optical performances of a glazing roof with PCM layer
Changyu Liu *, Yangyang Wu, Dong Li*†, Tengfei Ma and Xiaoyan Liu
School of Architecture and Civil Engineering, Northeast Petroleum University, 99 Fazhan Street, Daqing, China

SUMMARY
The thermal and optical performances of a roof in a building containing phase change material (PCM) were investigated in this paper. The glazing roof model consists of two layers of glass and one layer of PCM. The purpose of filling the roof structure with PCM is to utilize the solar energy efficiently. The effectiveness of thermal and optical performances of the roof PCM system was determined by analyzing the heat flux and temperature at the indoor surface with different absorption coefficients and refractive index of PCM in solid and liquid states. The results show that the absorption coefficients and refractive index of solid and liquid PCMs have both effects on thermal performance in the roof PCM system. Of all the thermal performances, the effect on internal temperature, temperature lag, and total transmitted energy is smaller and the effect on solar transmittance and transmitted solar energy is bigger. The absorption coefficients have the opposite effect with the refractive index on interior temperature lag. Considering the indoor daylight, increasing the refractive index and absorption coefficient of liquid PCM is a better method to better the thermal performance of a roof PCM system. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS
phase change material (PCM); glazing roof; thermal and optical performances

Correspondence
* Dong Li, School of Architecture and Civil Engineering, Northeast Petroleum University, 99 Fazhan Street, Daqing, China.
† E-mail: lidong@nepu.edu.cn

Received 18 December 2016; Revised 30 March 2017; Accepted 24 April 2017

1. INTRODUCTION
The roof dedicates nearly 70% of the heat loss in the retaining structure as a result of advantageous position toward sunlight, which leads to bigger air conditioning and heating load [1–3]. In general, heat loss in a building can be obviously reduced by three conventional methods, including using thermal insulation materials and shading devices or decreasing a window’s size [4–6]. As to the glazing roof, filling it with semitransparent PCM (phase change material) is also a potential method, which can contribute a great power for energy use and reductions. PCM enclosed in a building roof can melt to absorb a portion of solar irradiation at day and freeze to release a portion of thermal energy indoor at night [7–9].

A crowd of numerical and experimental researches about filling the building roofs with PCM have been developed, accompanied by many obtained key conclusions about its heat transfer characteristics; the effect of its good energy saving has been also demonstrated [2,10–20]. Most of the present studies about roof containing PCM are merely utilized to the opaque structure, such as concrete roof and PVC roof; for example, Chung et al. [10] experimentally investigated transient heat transfer characteristic of various sorts of roofs in South Korea, in which the PCM roof system was built by doped PCM. Two weather conditions were simulated containing summer and winter. The results showed that PCM-doped titles have the ability to control urban heat islands while reducing heating penalty. Jayalath et al. [12] established a numerical model to assess the thermal property and heat comfort of roof containing PCM and made the validation by experimental data obtained from the other literatures. The result shows that the thermal property of a roof containing PCM and the roof containing PCM has a big effect on its heat insulation performance. Kong et al. [15] used the apparent heat capacity method in FLUENT 6.3 software to simulate the heat performance of roof filled with PCM panel and validate the model by the experimental data. However, for the roof made in semitransparent material like glass, the interior heat transfer has the fundamental differences with the opaque materials.

There are also a number of experimental and numerical works of heat energy transfer in conventional roof filling with semitransparent building envelopes that have been
developed [21–32]. Many of them paid attention to the effect of thermophysical parameters on the thermal performance, especially for the optical parameters. For example, Li et al. [21] experimentally researched the dynamic thermal performance of a triple-pane window containing PCM and found that the window has a bigger effect of heat insulation than the double-pane one in both sunny and rainy days. The recent researches show that optical parameters of solid and liquid PCM have a big effect on the optical performance of double glazing unit containing PCM [33]. Ismail et al. [23] studied the thermal and optical performances of double glazing window containing PCM and concluded that the reflectance and transmittance of window sharp declined in the infrared waveband and ultraviolet waveband of solar irradiance and the effect of thickness on transmitted energy in the waveband of visible light is big. Goia et al. [28] introduced a numerical model to study the heat and light transfer of a PCM layer and compared the optical and thermal performances of PCM with the ones of other materials.

The recent researches show that optical parameters of solid and liquid PCMs have a big effect on the heat mass of glazing units containing PCM [21–32]. But almost all the recent studies of glazing units with PCM are about glass windows and glass facades. Considering bigger heat loss of glazing roof, it may be a dominant factor on the thermal performance, for its key effect on the solar absorptance. Although the previous work with the other model used to study the effect of thickness on the heat and light transfer of a glazing roof containing PCM was shown in Ref. [34], the detailed analysis of the optical performance of a roof containing PCM needs to be explained. In the present work, the heat and light transfer of a glazing roof containing PCM with different absorption coefficient and refractive index of PCM in solid and liquid states were numerically studied, which can provide theoretical reference for its design.

2. PHYSICAL AND MATHEMATICAL MODELS

2.1. Geometric description

Figure 1 shows a roof made in double glazing unit containing PCM, which comes from a gym built in Daqing City, China. As shown in Figure 1, when solar energy is reaching the roof surface, it is partly absorbed by the double glazing roof; the other is transmitted and reflected. The boundary conditions at the exterior and the interior surface include the effect of thermal radiation and convection. In the semitransparent media PCM and glass, solar energy undergoes reflections for many times between the interior and exterior surfaces.

2.2. Governing equations and boundary conditions

Some hypotheses are listed as follows for mathematical model:

1. The light and heat transfer in roof containing PCM is considered as a one-dimensional unsteady model.
2. The internal convection of liquid PCM is ignored.
3. All interfaces are considered as mirror faces.
4. The PCM is considered to be an absorbing medium.
5. The roof is considered as level.

As shown in Figure 2, the heat transfer in a glazing roof containing PCM is divided into three parts: the external glass layer, the PCM layer, and the internal glass layer. The unsteady energy equation is calculated as

$$\rho \frac{\partial H}{\partial \tau} = k \frac{\partial^2 T}{\partial x^2} + \phi$$

where $\tau$ is time (s); $T$ is temperature (K); $\rho$ and $k$ are density (kg/m$^3$) and thermal conductivity (W/m K), respectively;
In Eqn (1), the specific enthalpy is calculated by the equations in the succeeding texts, where Eqn (2a) is applied to glass region; the others are applied to the PCM region.

\[ H = c_{p,g} T_g \]  

\[ H = T_{ref} c_{p,p} dT + \gamma Q_l \]  

\[ \gamma = 0, \ T < T_s \]  

\[ \gamma = \frac{T - T_s}{T_1 - T_s}, \ T_s \leq T \leq T_1 \]  

\[ \gamma = 1, \ T > T_1 \]  

where \( T_{ref} \) is the reference temperature (K), \( c_{p,g} \) and \( c_{p,p} \) are specific heat of PCM layer and glass layer (J/kg K), \( T_g \) is the temperature of glass, \( Q_l \) is the absorbed and released latent heat of PCM (J/kg), \( \gamma \) is liquid fraction of PCM, and \( T_s \) and \( T_l \) are the temperatures of initial and final stages in the phase transformation of PCM (K), respectively.

The energy equations were discretized by finite volume method. Bouguer law was used to calculate the source term. The source term is mainly composed of solar radiant energy absorbed by media in control volume. In the calculation process, the source term was calculated by the difference of short-wave radiation intensity that enters and leaves the control volume for many times, due to the reflectance of many interfaces between all media containing glass and PCM.

For the control volume \( i \), the radiation source term is calculated by

\[ \Phi_i = \sum_{j=1}^{n} \left( I_{i_1-i_j} + I_{i_1+i_j} - (I_{i_1-i_j} + I_{i_1+i_j}) s^2 / \Delta x_i \right) \]  

where \( I_{i_1-i_j} \) variables express short-wave radiation intensity that enter/leave the control volume \( i \) during the condition that the sunlight passes through the glazing unit for \( j \) times.

For example, in Figure 2, when the volume of glass 1 is equally divided into \( n_1 \) parts, the source term of the internal node 1 in glass 1 near outdoor is calculated by

\[ n_1^2 \cos \theta_i \]

Figure 2. Distribution of glazing roof containing phase change material. [Colour figure can be viewed at wileyonlinelibrary.com]
\[-k \frac{\partial T}{\partial x} = q_{rad} + h_{out}(T_{out} - T_{a, out}) \quad (5)\]

where $q_{rad}$ is the radiation heat transfer quantity between outdoor environment and the external surface of glass (W/m²), $T_{out}$ and $T_{a, out}$ are the external temperature of outer surface and ambient temperature (K), respectively. $h_{out}$ is the convective heat transfer coefficient of external surface.

The radiation heat transfer quantity between the outside environment and roof $q_{rad}$ is given by

\[q_{rad} = q_{rad, air} + q_{rad, sky}\quad (6)\]

where $q_{rad, air}$ and $q_{rad, sky}$ are the radiation heat exchange of external glass directed against the air and sky (W/m²), respectively.

The radiative heat flux $q_{rad, sky}$ and $q_{rad, air}$ are respectively calculated by

\[q_{rad, sky} = \varepsilon \sigma F_{sky} \beta (T_{out}^4 - T_{sky}^4) \quad (7a)\]

\[q_{rad, air} = \varepsilon \sigma F_{sky} (1 - \beta) (T_{out}^4 - T_{a, out}^4) \quad (7b)\]

where $\beta$ is a factor that expresses the ratio of the heat exchange between the external glass and sky, $T_{sky}$ is the temperature of sky (K), $\varepsilon$ is the emissivity of glass, $\sigma$ is Stefan–Boltzmann constant, $F_{sky}$ is the view factor between sky and the glazing roof. The parameters $F_{sky}$, $\beta$, and $T_{sky}$ are all established by [26]

\[F_{sky} = \frac{1 + \cos \theta}{2} \quad (8a)\]

\[\beta = \sqrt{\frac{1 + \cos \theta}{2}} \quad (8b)\]

\[T_{sky} = 0.05527 \beta a_{out}^{1.5} \quad (8c)\]

where $\theta$ is the angle between sky and roof, for horizontal glazing roof, $\theta = 0^\circ$.

For the inner surface of internal glass, the boundary condition ($x = x_{g}$) is given as

\[-k \frac{\partial T}{\partial x} = h_{in}(T_{in} - T_{a, in}) + \varepsilon \sigma (T_{in}^4 - T_{a, in}^4) \quad (9)\]

where $T_{in}$ and $T_{a, in}$ are the temperatures of internal glass and indoor airflow (K) and $h_{in}$ expresses the convection heat transfer coefficient of internal glass (W/m² K).

The two parameters in the succeeding texts are applied to the heat transfer process of the roof. The first one is the temperature lag, which is the peak air temperature difference of the external and internal environments in the roof. The other two are the average relative value and the max relative value, which are convenient to weigh the effect level on the thermal performance of the roof [24].

\[\varphi_g = r_g, max - r_g, min \quad (10a)\]

\[\varphi_{ave} = \frac{1}{k} \sum_{i=1}^{k} \frac{a_i^2 - a_i^1}{a_i^1} \quad (10b)\]

\[\varphi_{max} = \max_{1 \leq i \leq k} \left\{ \frac{a_i^2 - a_i^1}{a_i^1} \right\} \quad (10c)\]

where $\varphi_g$ is the temperature peak value difference of roof and outdoor airflow, $r_g, max$ is the internal maximum temperature time of the roof, $r_g, min$ is the maximum outdoor temperature time, $\varphi_{ave}$ and $\varphi_{max}$ are the max relative value and the average relative value. $i$ expresses the node number. $a_i^1$ and $a_i^2$ are the compared parameter value and the standard value.

### 2.3. Method of solution and validation in numerical procedure

The numerical model is validated by the experimental results. The measurements were conducted in a small-scale test facility consisting of glass roof and rooms at Northeast Petroleum University in Daqing City. As shown in Figure 3, the internal dimension of the test facility was 762 mm × 712 mm × 613 mm (height × width × depth) and the glazing roof used in the experiments was composed by two glass panes with PCM. The thicknesses of the glass and PCM are 4 mm and 16 mm ($b_1 = b_3 = 4$ mm, $b_2 = 16$ mm).

Indoor and outdoor temperatures were measured by using thermocouple type K, and the solar radiation was measured by using Jinzhou Sunshine/TBQ-4-5 solar spectral radiometer. The experimental data are measured with the experimental setup in sunny early winter days on 20–21 October 2016. The solar radiation is depicted in Figure 4a, and the outdoor and indoor temperatures with the double glazing roof containing PCM are shown in Figure 4b. The physical properties of all materials can be obtained from Ref. [33].

In the calculation process, the model was simplified into a one-dimensional one, considering the shape of glazing roof. As shown in Figure 5a and b, the curves of the two results for interior temperature and transmitted solar energy both keep the same. On the basis of the experimental result, the average relative values of the simulation result for temperature and transmitted solar energy are 6.8% and 9.6%, respectively. Compared with the temperature average relative value, the one of transmitted solar energy is bigger. The main reason is that the accuracy of solar spectral radiometer is smaller than the one of thermocouples. The results illustrate that the model built in this paper can simulate the heat and light transfer in double glazing roof containing PCM.
Investigations on thermal and optical performances of a glazing roof

Liu C. et al.

Figure 3. Picture of the small-scale test facility. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 4. Solar radiation and temperatures in the experiment (a: heat flux and zenith angle; b: temperature). [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 5. Numerical and experimental results of the roof containing PCM (a: temperature; b: transmitted solar energy). [Colour figure can be viewed at wileyonlinelibrary.com]
3. RESULTS AND DISCUSSION

In the simulation process, the boundary conditions were obtained from the experimental data in Daqing City, which is shown in Figure 6. The $h_{out}$ and $h_{in}$ are 7.75 W/m² K and 7.43 W/m² K \cite{24}, respectively. The air flow temperature indoor is 26 °C. The physical properties of the materials were obtained from Refs \cite{33,34}, which are shown in Table I. In computational domain, the initial temperature is 23 °C. The simulation results were obtained under the condition of periodic steady state, which needs 2 to 4 days.

3.1. Effects of PCM refractive index

Five kinds of refractive index of PCM in two states were selected to investigate its effect on heat and light transfer of roof containing PCM, which included that $n_g$ and $n_l$ are 1.5 and 1.3, 2 and 1.3, 3 and 1.3, 3 and 2, and 3 and 2.5, respectively. The former three data analyze the effect of PCM refractive index in solid state, where the refractive index of liquid PCM is the same; the last three data analyze the effect of PCM refractive index in liquid state. The absorption coefficients of PCM in solid and liquid states are 30 and 5 m⁻¹, respectively.

Figure 7 illustrates the thermal results of the internal surface on glazing roof with different PCM refractive index in solid and liquid states. In Figure 7a, the temperature curves of the five conditions keep almost the same, which illustrates that the effect of PCM refractive index in solid and liquid states on the internal surface.
temperature is small. When \( n_l = 1.3 \), compared with the result of \( n_g = 1.5 \), the average relative value and the max average value of the ones of \( n_g = 2 \) and \( n_g = 3 \) are 0.2% and 2.5% and 1.1% and 11.5%, respectively. When \( n_g = 3 \), based on the result of \( n_l = 1.3 \), the average relative value and the max average value of the ones of \( n_l = 2 \) and \( n_l = 2.5 \) are 0.2% and 2.19% and 0.6% and 2.3%, respectively. Compared with the effect of PCM refractive index in liquid state, the one of PCM refractive index in solid state is bigger. Similar result is also found about the total transmitted energy in Figure 7b. Moreover, the temperature lags \( \phi_g \) of five conditions are 5, 8, 18, 16, and 16 min, which illustrates that with PCM refractive index in solid state increasing, the temperature lag \( \phi_g \) increases. On the contrary, with PCM refractive index in liquid state increasing, the temperature lag \( \phi_g \) decreases. In Figure 8a and b, as the refractive index of solid and liquid PCM increases, transmitted solar energy and solar transmittance decrease. Besides, when \( n_l = 1.3 \), compared with the results of \( n_g = 1.5 \) and \( n_g = 2 \), the one of \( n_g = 3 \) has obviously smaller transmitted solar energy and solar transmittance at between 4:00 and 11:00, which illustrates that when \( n_g > 2 \), increasing the PCM refractive index in solid state has a big effect on the indoor lighting. The main reason is that when \( n_g > 2 \), solar reflectance of the outer surface of roof is bigger at between 4:00 and 11:00, which is shown in Figure 8c. The results indicate that it is a better method for increasing the PCM refractive index in liquid state to improve the thermal performance of glazing roof containing PCM.

### 3.2. Effects of PCM absorption coefficients

Five kinds of absorption coefficients of PCM in two states were selected to investigate its effect on thermal and light transfer of roof containing PCM, which included that \( k_g \) and \( k_l \) are 50 and 30, 100 and 30, 200 and 30, 200 and 50, and 200 and 100 m\(^2\)/C\(\cdot\)l, respectively.

Figure 9 illustrates the thermal results of the internal surface on the glazing roof with different PCM absorption coefficients in solid and liquid states. In Figure 9a, the former three data analyze the impact of PCM absorption coefficient in solid state, where the PCM refractive index in liquid state is the same; the last three data analyze the effect of PCM absorption coefficient in liquid state. On the whole, with the increasing of PCM absorption coefficients in solid and liquid states, the internal temperature increases. When \( k_l = 30 \) m\(^2\)/C\(\cdot\)l, based on the result of \( k_g = 50 \) m\(^2\)/C\(\cdot\)l, the average relative values of the ones of \( k_g = 100 \) m\(^2\)/C\(\cdot\)l and \( k_g = 200 \) m\(^2\)/C\(\cdot\)l are 0.65% and 0.88%, respectively. When \( k_g = 200 \) m\(^2\)/C\(\cdot\)l, based on the result of \( k_l = 30 \) m\(^2\)/C\(\cdot\)l, the average relative values of the ones of \( k_l = 50 \) m\(^2\)/C\(\cdot\)l and \( k_l = 100 \) m\(^2\)/C\(\cdot\)l are 1.2% and 2.7%, respectively. Compared with the effect of PCM absorption coefficient in solid state, the one of PCM refractive index in liquid state is bigger. The temperature lags \( \phi_g \) of five conditions are 5, −4, −8, −6, and −4 min, respectively. With the PCM absorption coefficient in solid state increasing, the temperature lag \( \phi_g \) decreases; with the PCM absorption coefficient in liquid state increasing, the temperature lag \( \phi_g \) increases, which shows that the absorption coefficients have the opposite effect.
with the refractive index on the interior temperature lag of the roof. In Figure 9b, the effect of PCM absorption coefficients in solid and liquid states on total transmitted energy has been divided into two parts by 10:00. Before 10:00, the effect of PCM absorption coefficient in solid state is bigger; after 10:00, the effect of PCM absorption coefficient in solid state is bigger. The same condition is also applied to transmitted solar energy and solar transmittance, which is shown in Figure 10a and b. The main reason is that when the sun is getting up in the morning, PCM with bigger absorption coefficient will absorb more solar energy to be easier to melt and release latent heat, which leads to its better thermal performance. And when after 10:00, latent heat of PCM has already released completely, PCM has turned into liquid, and the bigger absorption coefficient can improve its thermal performance. However, in Figure 10c, when the absorption coefficient of solid PCM is bigger than 100 m^2/C, solar transmittance is smaller than 0.02 before 10:00, which has direct impact on indoor daylight. So, increasing PCM absorption coefficient in liquid state is a better method to improve the optical and thermal performances of double glazing roof containing PCM.

4. CONCLUSIONS

In this study, the effect of absorption coefficient and refractive index of PCM in solid and liquid states on the heat and optical process of a glazing roof containing PCM was investigated numerically. The following conclusions can be gained:

1. The absorption coefficients and refractive index of PCM in solid and liquid states have both effect on the heat and light performance of a glazing roof containing PCM. Of all the thermal performance, the effect on internal temperature, temperature lag, and total transmitted energy is smaller and the effect on solar transmittance and transmitted solar energy is bigger.
2. The absorption coefficients have the opposite effect with the refractive index on the interior temperature lag of the roof for the comparison of the effect of liquid and solid PCMs. With the PCM absorption coefficient in solid state increasing, the temperature lag decreases; but with the PCM absorption coefficient in liquid state increasing, the temperature lag increases.

3. The effect of PCM absorption coefficients in solid and liquid states on total transmitted energy has divided into two parts by 10:00. Before 10:00, the effect of PCM absorption coefficient in solid state is bigger; after 10:00, the effect of PCM absorption coefficient in solid state is bigger.

4. Considering the indoor daylight, increasing refractive index and absorption coefficient of PCM in liquid state is a better method to improve the thermal performance of a glazing roof containing PCM. However, when the PCM refractive index in solid is bigger than 2, and the PCM absorption coefficient in solid state is bigger than 100 m⁻¹, solar transmittance is smaller than 0.05.

Greek letters

\( \gamma, \beta \) = a factor that express the ratio of the heat exchange between the external glass and sky

\( \rho_{g}, \rho_{p} \) = density of glass and PCM, kg/m³

\( \rho_{i} - j \) = the mirror interface reflectance of media \( i \) and \( j \)

\( \tau \) = time, s

\( \phi \) = radiative source term, W/m²

\( \varepsilon \) = surface emissivity of glass

\( \sigma \) = Stefan–Boltzmann constant

\( \theta \) = angle between the glazing roof and the sky

\( \theta_{s}, \phi_{s} \) = Zenith angle of incidence and reflectance

ACKNOWLEDGEMENTS

The financial support is provided by the Guided Innovation Foundation of Northeast Petroleum University through grant no. 2016YDL-01, the National Science Foundation of China (NSFC) through grant no. 51306031, and the Guided Science and Technology Plan of Daqing through grant no. zd-2016-128.

REFERENCES


7. Lu SL, Chen YF, Liu SB, Kong XF. Experimental research on a novel energy efficiency roof coupled


