Numerical analysis on thermal performance of a PCM-filled double glazing roof

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Abstract:

Phase change material (PCM) applied in the glazing roof can decrease building energy consumption and improve thermal comfort by enhancing its thermal energy storage capacity. In the present work, thermal performance of a PCM-filled double glazing roof with different thickness of phase change material was numerically investigated on two groups of extinction coefficients of solid and liquid PCM, and the effect of the semi-transparent property of the glazing roof and zenith angle on the thermal performance was also studied. The results show that the semi-transparent property and zenith angle have a big effect on the thermal performance, including temperature time lag, total transmitted energy and transmitted solar energy. With PCM thickness increasing, the temperature time lag increases. However PCM thickness effect on total transmitted energy and transmitted solar energy is different in different time, which has a big effect on total transmitted energy mainly at 0:00-14:30 and 20:00-24:00, and has a violent effect on transmitted solar energy and solar transmittance mainly at 5:00-11:00. When the extinction coefficients of PCM increase, PCM thickness effect on

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thermal performance parameters turns bigger except for the temperature time lag.

Keywords: Phase change material (PCM), double glazing roof, thermal performance

Nomenclature

A	solar absorptance, -	n	refractive index
c	specific heat, J/(kg K)	Q_L	latent heat, J/kg
F	view factor, -	q	heat flux, W/m ²
h	specific enthalpy of PCM, J/kg; convective heat transfer coefficient, W/(m ² K)	T^*	solar transmittance, -
I	radiative heat flux, W/m ²	T ,	temperature, K
k	thermal conductivity W/(mK)	L	thickness, m

Greek letters

Subscript

α	absorption coefficient, m ⁻¹	a	air
β	liquid fraction,-	con	convective
ρ	density, kg/m ³	g, p	glass and PCM
τ	time, s	in, out	inner surface and exterior surface
ϕ	radiative source term, W/m ²	rad	radiative
ε	surface emissivity of glass,-	sol	solar radiation
σ	Stefan–Boltzmann constant,-	l, s	liquid and solid PCM
θ	angle between the glazing roof and the sky,-	ref	reference
θ_s	Zenith angle, -	ave	average
φ	temperature time lag, -	max	maximum
ξ	relative value, -		

1. Introduction

Nowadays, energy and environment as two keys in the development of human beings are turning more and more important. The energy production from coal and fossil fuel is the preponderant factors for CO₂ emission into the atmosphere, which is widely believed contributing to global warming [1, 2]. Building consumes about 40% of total fossil energy per each year in China in the last five years [3, 4], and this number is still increasing with the developing demand for the life style and the living standards. During recent years, developing the novel technology to promote energy efficiency and conservation in buildings has been one of the major issues of governments and societies, whose aim is reducing the energy consumption without affecting the thermal comfort in the wide range of weather conditions [5, 6].

In the buildings, the thermal loss of roofs in the building envelope is the main source, which is contributing approximately 70% of the total heat loss due to directly solar radiation and better location in the heat transfer between the exterior and the interior spaces of the building [7-9]. Especially, the heat loss of the glazing roof in the large gymnasium and other similar large buildings is even beyond 70% of total amount, which owes to the semi-transparent property of the glass. In addition, when transparent materials are applied in the roof, the indoors temperature is often beyond 40°C due to its poor heat insulation and direct solar irradiation [10,11]. An effective method to enhance thermal performance of glazing roofs is to increase its thermal storage capacity, which improves energy use and energy demand reductions, and enhances occupant comfort. The latent heat thermal energy storage employing PCM is particularly an effective technique due to its high energy storage density and

isothermal operating characteristics. A variety of experimental and numerical researches about thermal energy storage solutions with the integration of PCM into conventional building construction have been studied [12-26].

Some researchers experimentally analyzed the effect of PCM on the thermal performance of the building [6, 12], and made contrast experiment groups to investigate the effect of PCM on the temperature, heat flux, solar transmittance of the roof. For instance, Kos'ny et al. [12] investigated thermal performance of the full-scale experimental PV-PCM roof/attic system using building integrated PV laminates and dynamic roof deck technologies in the mixed climatic conditions of Tennessee (USA), compared with a conventional asphalt shingle roof, and found that about 30% heating and 50% cooling load reductions are possible comparing to a control asphalt shingle roof. However, the above stated experimental studies paid much attention to the traditional roof filled with PCM, and most traditional roof is opaque. There were numerical models to study the PCM applied in buildings, which includes 1D (one-dimensional) heat transfer model [13-22], 2D (two-dimensional) heat transfer model [23,24], and 3D (three-dimensional) heat transfer model[25,26]. Most of the models contained the radiation and convective heat transfer of the roof with the indoor and outdoor surroundings [13-20, 23-26]. However, most models are only applied to the opaque roof, such as concrete roof and PVC roof.

There are also some experimentally study about the effect of PCM on other envelope structure [27-31], such as the window [28] and wall [31]. Furthermore, some semi-transparent models were also built to analyze the effect of PCM on the thermal

performance of double glazing window [32, 33]. However, because of their different positions of the building between window and roof, the heat loss and heat gain coefficient of solar radiation is distinct, which results that the researches about window can not directly applied in the design of the double glazing roof.

In the present work, the thermal performance of a PCM-filled double glazing roof with different thickness of PCM in the cold area of Northeast China was investigated numerically. The above discussed researches are composed of double glazing units filled with PCM, opaque roofs filled with PCM and single glazing roofs. In addition, the variety of zenith angle in one day plays an important role in the heat gain coefficient of solar radiation, and analyzing its effect on the thermal performance of the roof is essential. Section 2 describes the physical and mathematical model for calculating the light and heat transfer process in the roof and the model validation. Section 3 presents the effect of thickness of PCM on heat and light transfer process of the roof, which is based on analyzing the effect of semi-transparent property and zenith angle. Section 4 shows the results of the thermal performance of roof for five thicknesses with two different extinction coefficients of solid and liquid PCM.

2. Physical and mathematical models

In this section, a transient model to investigate the thermal performance of a PCM-filled double glazing roof was developed, combined with a method of solution and validation of numerical procedure.

2.1 Geometric description

Fig.1 shows a gymnasium located in Daqing city (a Northeast city in China),

whose roof is an arch structure circular made of double glazing with PCM. As shown in Fig.1, solar irradiance reaching the glazing unit surface is partly transmitted and partly reflected, and the remaining portion is absorbed by the two glass and the PCM. The heat transfer process with the combination of thermal radiation and convection takes place on the boundary of the exterior and the interior surface, respectively. The absorbed heat will be transmitted inward and/or outward, by the processes of conduction, convection and radiation exchange. For a transparent layer, the effective transmittance as well as the front and back reflectance are quantified as the consequence of multiple reflections between the front and back surfaces, plus the effects of absorption through the layer.

Fig.1. Double glazing roof filled with PCM

2.2 Governing equations and boundary conditions

Assumptions for the mathematical model have been listed as follows:

- (1) The heat transfer through the glazing unit is simplified to one-dimensional

unsteady heat transfer process.

(2) The convection within the PCM layer (when in liquid state) is neglected.

(3) The radiative exchange between the two glass surfaces facing the cavity filled with PCM is neglected too. And PCM both when in liquid state and in solid state is highly non-transparent to the long-wave radiation.

(4) The glass and PCM are considered to be thermally homogeneous and isotropic media, and the thermal properties of the materials are temperature independent.

(5) The scattering effect of PCM is omitted.

(6) The radius of the arch structure circular is omitted.

For the double glazing roof, the heat transfer includes three regions as shown in Fig.2, which are the outer glass layer, internal glass layer and PCM layer in the middle.

A one-dimensional unsteady energy equation for glass regions is given as Eq. (1)

$$\rho_g C_{p,g} \frac{\partial T}{\partial \tau} = k_g \frac{\partial^2 T}{\partial x^2} + \phi \quad (1)$$

Where, τ is time(s). T is temperature (K). ρ_g , k_g and $c_{p,g}$ are density(kg/m³), thermal conductivity (W/m K) and specific heat (J/kg K) of glass, respectively. ϕ is radiative source term (W/m³).

Fig.2. Layout of double glazing roof filled with PCM

The one-dimensional unsteady energy equation for PCM regions is given as

$$\rho_p \frac{\partial h}{\partial \tau} = k_p \frac{\partial^2 T}{\partial x^2} + \phi \quad (2)$$

Where, h is the specific enthalpy of PCM (J/kg). ρ_p and k_p are density(kg/m³), thermal conductivity (W/m K) of PCM, respectively.

The specific enthalpy of PCM in Eq. (2) is calculated by

$$h = \int_{T_{ref}}^T c_{p,p} dT + \beta Q_L \quad (3a)$$

$$\beta = 0, T < T_s \quad (3b)$$

$$\beta = \frac{T - T_s}{T_l - T_s}, T_s \leq T \leq T_l \quad (3c)$$

$$\beta = 1, T > T_l \quad (3d)$$

Where, T_{ref} is the reference temperature (K). $c_{p,p}$ is specific heat (J/kg K) of PCM. Q_L is the latent heat of PCM in the whole phase change process (J/kg). β is the local

liquid fraction in calculation region. T_s and T_1 is the temperature that the phase of PCM starts to change from solid to liquid (K), and the temperature that the phase of PCM completely changes into liquid (K), respectively.

The radiative source term for each layer is given as following.

When the calculation node is in the glass 1 as shown in Fig.2,

$$\phi = \frac{A_{g1} I_{sol} \cos \theta}{L_{g1}} \quad (4a)$$

when the calculation node is in the phase 1 of PCM layer as shown in Fig.2,

$$\phi = \frac{T_{g1}^* A_{p1} I_{sol} \cos \theta}{L_{p1}} \quad (4b)$$

when the calculation node is in the phase 2 of PCM layer as shown in Fig.2,

$$\phi = \frac{T_{g1}^* T_{p1}^* A_{p2} I_{sol} \cos \theta}{L_{p2}} \quad (4c)$$

when the calculation node is in the glass 2 as shown in Fig.2,

$$\phi = \frac{T_{g1}^* T_{p1}^* T_{p2}^* A_{g2} I_{sol} \cos \theta}{L_{g2}} \quad (4d)$$

Where, I_{sol} is solar radiation (W/m^2). T_{g1}^* , T_{p1}^* and T_{p2}^* is solar transmittance of glass 1 layer, phase 1 layer, and phase 2 layer, respectively. A_{g1} , A_{p1} , A_{p2} and A_{g2} is solar absorptance of glass 1 layer, phase 1 layer, phase 2 layer and glass 2 layer, respectively. L_{g1} , L_{p1} , L_{p2} and L_{g2} is the thickness (m) of glass 1 layer, phase 1 layer, phase 2 layer and glass 2 layer, respectively. θ is the zenith angle.

The transmittance and absorptance of the glass layer are calculated by [34]

$$T_i = \frac{(1 - \rho_{i1})(1 - \rho_{i2}) \exp(-\alpha_i L_i)}{1 - \rho_{i1} \rho_{i2} \exp(-2\alpha_i L_i)} \quad (5a)$$

$$A_i = 1 - \rho_{i1} - \frac{(1 - \rho_{i1})\rho_{i2} \exp(-2\alpha_i L_i)}{1 - \rho_{i1}\rho_{i2} \exp(-2\alpha_i L_i)} - T_i \quad (5b)$$

Where ρ_{i1} and ρ_{i2} are the reflectance of entrance surface and exit surface of media i . α_i is the absorption coefficient of media i , which expresses the absorption ability of media i (m^{-1}). L_i is the thickness of media i (m).

The interface reflectance of media i and j are calculated based on Fresnel's relations [35].

$$\rho_{i-j} = \frac{(n_i - n_j)^2}{(n_i + n_j)^2} \quad (6)$$

Where, n_i and n_j are the refractive index of the media i and j .

The mathematical boundary conditions for the calculation domain are given as following.

In the exterior surface of outer glass is exposed to solar radiation, and the boundary condition at $x=0$ is given as

$$-k_g \frac{\partial T}{\partial x} = q_{\text{rad}} + h_{\text{out}} (T_{\text{out}} - T_{\text{a,out}}) \quad (7)$$

Where, q_{rad} is radiative heat exchange between exterior surface of outer glass with the outdoor environment (W/m^2). h_{out} , T_{out} and $T_{\text{a,out}}$ is the convective heat transfer coefficient of the exterior surface of outer glass ($\text{W/m}^2 \text{ K}$), temperature of the exterior surface of outer glass (K), and ambient temperature (K), respectively.

The radiative heat exchange with the outdoor environment q_{rad} is given by

$$q_{\text{rad}} = q_{\text{rad, air}} + q_{\text{rad, sky}} \quad (8)$$

Where, $q_{\text{rad,air}}$ and $q_{\text{rad,sky}}$ is radiative heat exchange with the air and sky (W/m^2), respectively.

The radiation heat flux $q_{\text{rad,sky}}$ and $q_{\text{rad,air}}$ is respectively given by [36]

$$q_{\text{rad,sky}} = \varepsilon \sigma F_{\text{sky}} \beta (T_{\text{out}}^4 - T_{\text{sky}}^4) \quad (9a)$$

$$q_{\text{rad,air}} = \varepsilon \sigma F_{\text{sky}} (1 - \beta) (T_{\text{out}}^4 - T_{\text{a,out}}^4) \quad (9b)$$

Where, ε is the surface emissivity of glass. σ is the Stefan–Boltzmann constant. F_{sky} is the view factor between the glazing unit and the sky dome. β is a factor that splits the heat exchange with the sky dome between sky and air radiation. T_{sky} is the sky temperature (K). The parameter, F_{sky} , β , T_{sky} is respectively established by [36]

$$F_{\text{sky}} = \frac{1 + \cos \theta}{2} \quad (10a)$$

$$\beta = \sqrt{\frac{1 + \cos \theta}{2}} \quad (10b)$$

$$T_{\text{sky}} = 0.0552 T_{\text{a,out}}^{1.5} \quad (10c)$$

Where, θ is the angle between the glazing unit and sky. For the leveled glazing roof, $\theta = 0^\circ$.

In the inner surface of internal glass near to indoors environment, the boundary condition at $x=x_3$ is given as [32]

$$-k_g \frac{\partial T}{\partial x} = h_{\text{in}} (T_{\text{in}} - T_{\text{a,in}}) + \varepsilon \sigma (T_{\text{in}}^4 - T_{\text{a,in}}^4) \quad (11)$$

Where, h_{in} , T_{in} and $T_{\text{a,in}}$ is the convective heat transfer coefficient of the inner surface of internal glass ($\text{W/m}^2 \text{ K}$), temperature of the inner surface of internal glass (K), and indoors air temperature (K), respectively.

Temperature time lag is an important parameter to analyze the thermal performance of the double glazing unit, including the roof. Temperature time lag is the phase difference of the temperature waves on the interior surfaces of the double glazing roof, which is calculated by Eq. (12a). Moreover, the average relative value

and the max relative value are also key parameters to analyze the thermal performance of the double glazing roof, which is calculated by Eq. (12b) and (12c). For instance, one measure is adopted to improve the roof structure, when the two parameters of temperature and heat flux are big, it illustrates that the measure has big effect on the heat transfer process of the roof [37].

$$\varphi = \tau_{g,\max} - \tau_{a,\max} \quad (12a)$$

$$\xi_{ave} = \frac{1}{k} \sum_{i=1}^k \frac{\gamma_i^2 - \gamma_i^1}{\gamma_i^1} \quad (12b)$$

$$\xi_{\max} = \text{Max}_{1 \leq i \leq k} \left\{ \frac{\gamma_i^2 - \gamma_i^1}{\gamma_i^1} \right\} \quad (12c)$$

Where φ is the temperature time lag of the double glazing unit comparing with the outdoors air. $\tau_{g,\max}$ is the time of the interior surface maximum temperature of the double glazing unit. $\tau_{a,\max}$ is the time of the maximum temperature in the outdoors temperature wave. ξ_{ave} and $\xi_{\max}$ is the average relative value and the max relative value, respectively. i is the node number, γ_i^1 and γ_i^2 is the compared parameter value and the standard value.

2.3 Method of solution and validation of numerical procedure

The equations together with the boundary conditions are solved by using an explicit finite difference scheme as the procedure of reference [36] is used. PCM region is divided into 12 equally spaced increments. Each glass sheet thickness is also divided into 6 equally spaced increments. The numerical procedure is validated with the experimental parameters in the literature [33]. The outdoor air temperature and solar radiation intensity, temperature on the interior surfaces of the double glazing

filled with PCM can be attained from Fig.6 to Fig.8 in the reference [33]. The thermophysical properties of materials can be attained from Table 2 in the reference[23].The extinction coefficient and refractive index of glass is 19 m^{-1} and 1.5 [38], respectively. The emissivity of the glass is 0.88 [32]. The refractive index of PCM is 1.3, and the extinction coefficients of solid and liquid PCM is 50 and 40 m^{-1} , respectively [38]. The initial temperature of the domain is 23°C . The simulation was kept running until the solution becomes periodic, which needs two days to reach the periodic condition. The comparison of heat flux (without transmitted solar energy) and temperature on the interior surfaces of the double glazing filled with PCM between numerical results in this work and available in the literature [33] are shown in Fig.3.

As shown in Fig.3 (a) and (b), the simulation result of heat flux and temperature almost keep the same trend with the experimental result in literature [33]. However, there is also some difference between the experimental and numerical results, and the directions of heat flow in numerical and experimental results are sometimes opposing. Based on the experimental result, the average relative value of the heat flux and temperature in the present work is 34% and 2.7%. Compared with the average relative value of temperature, the average relative value of heat flux is bigger. Before 11:00, the average relative value of heat flux is 55.5%, but after 11:00, the average relative value is 14.1%, which shows that the calculation precision of heat flux in the model is different in the different time. There are several reasons for this phenomenon as follows: (1) the effect of initial temperature in the double glazing filled with PCM in

the experimental is not omitted, which results in the bigger average relative value of heat flux during the early time; (2) the exact optical parameters of PCM are not given in the literature, and the wavelength effect on optical parameters of PCM and glass is also omitted in the model, which may be resulting the bigger average relative value of heat flux.

(a)

(b)

Fig.3. Heat flux and temperature on the interior surfaces of the double glazing filled with PCM in this work and the literature [33] (a: heat flux; b: temperature)

3. Results and discussion

In order to analyze the thermal performance of double glazing roof filled with

PCM, the effect of semi-transparent property and zenith angle is investigated, five different PCM thickness combined with two different extinction coefficients of solid and liquid PCM are selected to fulfill it.

In this modeling work, the grid length of both the glass and PCM is 1mm. The measured average hourly variations of the ambient air temperature, total radiation and Zenith angle on June 22 in Daqing city is depicted as Fig. 4. The h_{out} and h_{in} is 19 and 8.7 W/m²·K [3], respectively. The indoors air temperature is 26°C. The thermophysical properties of materials are shown in Table 1. The extinction coefficient and refractive index of glass is 19 m⁻¹ and 1.5 [38], respectively. The emissivity of the glass is 0.88 [32]. The initial temperature of the domain is 23°C. The simulation was kept running until the solution becomes periodic, which needs between two days and four days to reach the periodic condition.

(a)

(b)

Fig.4. Mean hourly variation of ambient temperature and solar energy

Table 1 Thermophysical properties of materials

material	Melting temperature(°C)	Density (kg/m ³)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Latent heat (J/kg)
glass[22]	-	2500	0.96	840	-
PCM[21]	27-29	850	0.21	2230	205000

3.1 Effects of semi-transparent property

For investigating the effect of the semi-transparent property of PCM on thermal performance of glazing roof containing PCM, two conditions are considered including opaque roof and semi-transparent roof. Thickness of the glass and PCM is 18mm and 20mm, and zenith angle $\theta_s = 0$ at all hours. The refractive index of liquid and solid PCM is 1.3 and 1.4. And the extinction coefficient of solid and liquid PCM is 30 and 5 m^{-1} , respectively.

(a)

(b)

Fig.5. Simulation results of the interior surface on double glazing roof with different semi-transparent property of PCM (a: interior temperature ; b: total transmitted energy)

Fig. 5 illustrates temperature on the interior surfaces of double glazing roof with different semi-transparent property. The trend of temperature curves on the interior surfaces of double glazing roof with different semi-transparent property has a

common characteristic. In Fig. 5(a), Temperature time lag φ of model with and without considering semi-transparent property is 140 and 90 min, which illustrates that considering semi-transparent property has a big effect on temperature time lag.

Based on the semi-transparent model, the average relative value and the max relative value of the opaque model is 3.8% and 17.5%, respectively, which illustrates that the effect of considering semi-transparent property on temperature is slight, especially before 5:00 and after 18:00. While at 5:00-18:00, the temperature value of the opaque model is bigger than the one of the semi-transparent model. The main reason is that solar energy is almost all absorbed by the roof without transmitted into indoor, and the heat transfer resistance between outside and indoor increases invisibly, as shown in Fig. 5(b), the heat flux of the opaque model is smaller than the one of the semi-transparent model. Based on the value of the semi-transparent model, the average and the max relative value of the other one is 88.3% and 25 times, which illustrates that considering the semi-transparent property has a big effect on the heat flux of the roof.

3.2 Effects of zenith angle

For investigating the effect of the zenith angle of the sun on thermal performance of glazing roof containing PCM, two conditions are considered including angle independence and angle dependence. When the angle dependence is considered, θ_s values with different time are shown in Fig. 4(b). Thickness of the glass and PCM is 18 mm and 20 mm. The refractive index of liquid and solid PCM is 1.3 and 1.4. And the extinction coefficient of solid and liquid PCM is 30 and 5 m^{-1} .

(a)

(b)

Fig.6. Simulation results of the interior surface on double glazing roof with zenith angle of sun (a: interior temperature; b: total transmitted energy; c: transmitted solar energy; d: solar transmittance)

Fig. 6 illustrates temperature on the interior surfaces of double glazing roof with different zenith angle of sun. The trend of two curves almost keep the same except for solar transmittance of the angle independence model in Fig. 6 (d). The main reason is that when the angle independence model is used, the angle is 0 at all hours and lacks of continuous change at 4:00 and 20:00, its changing trend is not continuous as the angle dependence model. In Fig. 6(a), temperature time lag φ of angle dependence model and angle independence model is 100 and 140min, which illustrates that considering angle dependence has a big effect on temperature time lag. Based on the angle dependence model, the average relative value and the max relative value of the angle independence model is 3.3% and 11.1%, respectively, which illustrates that the

effect of angle dependence on temperature is weak. While the temperature value of the angle independence model is bigger than the one of the angle dependence model. The main reasons are as follows: the first is that in the angle independence model, effective solar radiation quantity is big; the second is that in the angle independence model, solar radiation is vertical incidence, which leads the interface reflectance reduces and volume absorptance glazing roof rises. As shown in Fig. 6(b) and (c), the total transmitted energy and transmitted solar energy of the angle independence model is bigger than the one of the angle dependence model. Based on angle dependence model, the average relative value and the max relative value of the total transmitted energy and transmitted solar energy is 10.34% and 6.74 times, 12.6% and 10.53 times, respectively, which explains effect of considering angle dependence on two heat flux is bigger than temperature. In Fig. 6(d), the result is almost as the same as the two heat flux. The value of the two models is bigger than 0.2 at most of the time in one day, especially at 7:30-19:00. The result shows that the solar transmittance of the double glazing roof in this condition is better.

3.2 Effects of thickness of PCM

For investigating the effect of thickness of PCM on thermal performance of glazing roof containing PCM, the conditions of five kinds of thickness of $\delta_1=8\text{mm}$, $\delta_2=12\text{mm}$, $\delta_3=16\text{mm}$, $\delta_4=20\text{mm}$, $\delta_5=25\text{mm}$ are investigated. Thickness of the glass is 18mm. The refractive index of liquid and solid PCM is 1.3 and 1.4. And the extinction coefficient of solid and liquid PCM is 30 and 5 m^{-1} , 100 and 30 m^{-1} , respectively.

(a)

(b)

Fig.7. Simulation results of the interior surface on double glazing roof with different thickness of PCM (a: interior temperature ; b: total transmitted energy; c:transmitted solar energy; d: solar transmittance)

Fig. 7 illustrates temperature on the interior surfaces of double glazing roof with different thickness of PCM in the condition of extinction coefficients of solid and liquid PCM is 30 and 5 m^{-1} . The trend of temperature curves on the interior surfaces of double glazing roof with different thickness of PCM has a common characteristic. In Fig. 7(a), temperature time lag φ of different thickness of PCM is respectively 75.6, 81.6, 90, 100 and 112.8 min, which shows that with the thickness increasing, temperature time lag φ increases. Based on the interior temperature of the thickness 8mm, the average and the max relative value of the other four thickness is 1.67% and 9.32%, 3.21% and 14.1%, 4.67% and 17.7%, 6.4% and 21.4%, which illustrates that the thickness of PCM has little effect on the interior temperature of the glazing roof. In Fig. 7(b), the effect of thickness of PCM on total transmitted energy changes

periodically. For example, at 14:30-20:00, the effect is neglected; but 0:00-14:30 and 20:00- 24:00, the effect is big. Based on the total transmitted energy of the thickness 8mm at the two time stage, the average relative value of the other four thickness is 39.9%, 57.8%, 70.1%, 83.3%, respectively. In Fig.7(c) and Fig.7 (d), the trend of the effect of thickness on transmitted solar energy is almost as the same as in Fig.7 (b), the difference is that there is only big effect at 5:00-11:00. Based on the transmitted solar energy of the thickness 8mm, the average and the max relative value of the other four thicknesses is 7.61% and 19.7%, 14.3% and 30.5%, 20.3% and 41.4%, 26.8% and 50.3%, respectively.

Fig. 8 illustrates simulation results on the interior surfaces of double glazing roof with different thickness of PCM in the condition of extinction coefficients of solid and liquid PCM is 100, 30 m^{-1} . In Fig. 8(a), Temperature time lag of different thickness of PCM is 69.6, 73.8, 78.6, 87 and 100 min, respectively. Comparison with Fig.7 (a), temperature time lag is smaller with all thickness of PCM, the effect of thickness on temperature time lag also turns weaker. It can be analyzed in Fig. 8, based on the temperature, total transmitted energy and transmitted solar energy of thickness 8mm, the average relative value of the other four thickness is 1.98%, 3.8%, 5.5%, 7%; 41.2%, 59.7%, 72.6%, 86%; 22.6%, 38.4%, 49.7%, 59.8%, respectively. This result shows that when the extinction coefficients of solid and liquid PCM magnifies, the effect of thickness of PCM on temperature, total transmitted energy and transmitted solar energy all increases. At the same time, the effect time of total transmitted energy and transmitted solar energy also increases. For the total

transmitted energy, the effect is neglected only at 16:00-17:00; for the transmitted solar energy, it is at 17:30-18:30.

(a)

(b)

(c)

(d)

Fig.8. Simulation results of the interior surface on double glazing roof with different thickness of PCM on bigger extinction coefficients (a:interior temperature ; b: total transmitted energy; c:transmitted solar energy; d: solar transmittance)

4. Conclusions

In present study, the effect of semi-transparent property and zenith angle on thermal performance of a PCM-filled double glazing roof was investigated numerically. With the aim to investigate the thermal behavior of a PCM-filled double

glazing roof, the influence of PCM thickness was also studied.

- 1) Considering the semi-transparent property of glazing roof, the model has a big effect on thermal performance of a PCM-filled double glazing roof. The semi-transparent model could prolong the temperature time lag and improve the thermal inertia of the glazing roof. The semi-transparent model has also big effect on the interior temperature and the total transmitted energy. However the effect on interior temperature is only at 5:00-18:00.
- 2) The effect of considering the hourly variety of the zenith angle has been divided into two situations. The effect on the temperature time lag, total transmitted energy, transmitted solar energy and solar transmittance is big, but the effect on the interior temperature is small. The temperature value of the angle dependence model is smaller than the one of the independence angle. The first reason is that in the angle independence model, effective solar radiation quantity is big; the second one is that in the angle independence model, solar radiation is vertical incidence, which leads the interface reflectance reduces and volume absorptance glazing roof rises.
- 3) The effect of thickness of double glazing roof on its thermal performance is big except for the interior temperature. With the thickness increasing, temperature time lag increases. The effect of thickness on total transmitted energy and transmitted solar energy is different, especially in the time period. The big effect on total transmitted energy is mainly at 0:00-14:30 and 20:00-24:00. But the big effect on transmitted solar energy and solar transmittance is mainly at 5:00-11:00.

- 4) With the increasing of extinction coefficients of solid and liquid PCM, temperature time lag is smaller with all thickness of PCM. Meanwhile, the effect of thickness on thermal performance all turns bigger, except for the temperature time lag.

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