Thermal performance of a PCM-filled double glazing unit with different optical
properties of phase change material

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Abstract:

Phase change material (PCM) applied in the glazing structure can decrease building energy consumption and improve indoor thermal comfort by enhancing its thermal energy storage capacity. In the present work, thermal performance of a PCM-filled double glazing unit with different optical properties of phase change material was investigated numerically. The results show that optical properties of PCM play an important role in the thermal performance of double glazing unit filled with PCM, and effect of PCM phase is also strong. Effect of refractive index of PCM on the temperature of double glazing unit is weak, but the effect of extinction coefficient of PCM on the temperature and transmitted energy of double glazing unit is strong. Compared 200m^{-1} with 5m^{-1} of extinction coefficient, time to the highest temperature is 30 and 300 minutes earlier in liquid and solid PCM of double glazing unit, and time to the highest transmitted energy is delayed 40 minutes in liquid PCM double glazing unit, but is nearly same in solid PCM double glazing unit.

Keywords: Phase change material (PCM), double glazing unit, optical properties

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Nomenclature

$A_{g1}, A_{p1}, A_{p2}, A_{g2}$	solar absorptance of glass 1 layer, phase 1 layer, phase 2 layer and glass 2, -	n_g, n_{p1}, n_{p2}	refractive index of glass, phase1 and 2 of PCM, -
$c_{p,g}, c_{p,p}$	specific heat of glass and PCM, J/(kg K)	$S(t), QL$	thickness of liquid PCM, m; latent heat of PCM, J/kg
F_{sky}, F_{ground}	view factor between the glazing unit and the sky dome, between the glazing unit and the surrounding surfaces, -	$q_{rad}, q_{rad,air}, q_{rad,sky}, q_{rad,ground}$	radiative heat exchange between exterior surface of outer glass with the outdoor environment, with the air, sky and ground of outer glass, w/m ²
H, h_{out}, h_{in}	specific enthalpy of PCM, J/kg; convective heat transfer coefficient of the exterior surface of outer glass, inner surface of internal glass, W/(m ² K)	$T_{g1}, T_{p1}, T_{p2}, T_{g2}$	solar transmittance of glass 1 layer, phase 1 layer, phase 2 layer and glass 2, -
$I_{sol}, I_{g \rightarrow p}, I_{p,l \rightarrow p,s}, I_{p \rightarrow g}$	solar radiation, radiative heat flux of coupled surface between outer glass and PCM, liquid–solid interface in the PCM region, coupled surface between internal glass and PCM, w/m ²	T, T_{ref}, T_s, T_l	temperature, reference temperature, temperature that the phase of PCM starts to change from solid to liquid, PCM completely changed into liquid, K
$k_g, k_p, k_{p,l}, k_{p,s}$	thermal conductivity of glass and PCM, liquid PCM near to liquid–solid interface, thermal conductivity of solid PCM near to liquid–solid interface, W/(mK)	$T_g, T_p, T_{p,l}, T_{p,s}$	temperature of the coupled surface of outer glass, coupled surface of PCM, liquid PCM near to liquid–solid interface, solid PCM near to liquid–solid interface, K
$L_{g1}, L_{p1}, L_{p2}, L_{g2}$	thickness of glass 1 layer, phase 1 layer, phase 2 layer and glass 2, m	$T_{out}, T_{a,out}, T_{sky}, T_{in}, T_{a,in}$	temperature of the exterior surface of outer glass, ambient, sky temperature, inner surface of internal glass, indoors air, K

Greek letters		Subscript	
α_g ,			
α_{p1} ,	extinction coefficient of glass, phase1 and 2 of PCM, m^{-1}	a	air, -
α_{p2}			
β	liquid fraction, -; a factor that splits the heat exchange with the sky dome between sky and air radiation,-	con	convective
ρ_g, ρ_p	density of glass and PCM, kg/m^3	g, p	glass and PCM, -
$\rho_1, \rho_2,$ ρ_3, ρ_4	interface reflectance for surface between air and glass, for surface between phase 1 of PCM and glass, for surface between phase 1 and phase 2 of PCM, for surface between phase 2 of PCM and glass, -	in, out	inner surface and exterior surface, -
τ	time, s	rad	radiative, -
$\emptyset$	radiative source term, W/m^3	sol	solar radiation intensity, -
ε	surface emissivity of glass,-	l, s	liquid and solid PCM, -
σ	Stefan–Boltzmann constant,-		
θ	angle between the glazing unit and the ground,-		

1. Introduction

Nowadays, energy and environment are two keys in the development of human beings. The energy production from coal and fossil fuel is the preponderant factors for CO₂ emission into the atmosphere, which is widely believed to be contributing to global warming [1, 2]. Building is one of the leading sectors of the energy consumption, and especially about 40% of total fossil energy per each year in China

was consumed in building sector in the last five years [3, 4]. Furthermore, the energy consumption of buildings is still increasing with the developing demand for the life style and the living standards, which will be estimated about 20×10^{12} MJ in 2020 in China [5]. 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 level of thermal comfort in a wide range of weather conditions [6, 7].

Glazing units are an indispensable part of a building which provides passive solar gain and air ventilation, for example window system [8]. However, in generally the thermal performance of glazing units are very poor among the building components, and hence they play a significant role in the energy demand of buildings. Their influence on energy loss from building envelope becomes much more drastic when the glazing area is large, for example the heat loss through the glazing envelope accounted for 30% of the energy consumption of the building envelope [9, 10]. The thermal performance of a glazing unit is depending on the thermal mass of glazing structure. The effectiveness of thermal mass is based on its ability to absorb and store heat, and dampen the temperature fluctuations within a space. It is widely accepted that thermal mass is beneficial to buildings with respect to increasing thermal comfort and reducing energy consumption [11]. In order to improve thermal mass of glazing units, there are several methods such as optimizing the air layer thickness of double glazing [12], filling the cavity between panes with a participating gas [13], water [14] or aerogel [15], coating pane surface with low emissivity materials [16-18], using

multiple pane windows [19–21]. Another alternative practice to enhance thermal mass of glazing units is to increase its thermal storage capacity, which offers improved heat transfer control, results in energy use and energy demand reductions, enhanced occupant comfort, and increased equipment operating life. An effective approach to increase the thermal storage capacity of glazing units is to incorporate phase change material (PCM) in the glazing structure [22-24]. The aim of the PCM-filled glazing unit concept is thus to absorb part of the solar radiation for thermal energy storage, while letting visible radiation enter the indoor environment for daylighting. Therefore, a variety of numerical and experimental work of thermal energy storage solutions for the integration of PCM into glazing unit have been developed, which have been attracted more and more attention as a potential technology for minimizing energy consumption in the buildings[25-35].

Ismail et al. [25] experimentally investigated optical and energy performance of glass windows filled with air and PCM in the wavelength range of 300–2800 nm by using Perkin–Elmer Lambda, and they found that the transmittance and reflectance of glass windows filled with PCM have large reductions in the infrared and ultraviolet radiations while maintaining good visibility compared with filling air, and the reduction of the transmitted energy of glass windows filled with PCM is of the order of 50%. They noticed that the increase in the thickness of the PCM layer has a marginal effect on the energy transmitted from the optical view point, although the thermal effect is very noticeable. Ismail et al. [26] also developed one dimensional radiation and heat conduction model of double glass window filled with PCM, and

numerically found that the solar heat gain coefficient of double glass window filled with PCM is in the range of 0.65–0.80, when the external and internal ambient temperatures are respectively 35 and 24°C, and the incident solar radiation is 600 W/m², however the authors did not state the detailed optical and thermal parameters of PCM.

Li et al. [27] proposed two optical parameters to calculate the solar absorptance and transmittance of the glass window filled phase change material (PCMW), and investigated the energy performance of PCMW in the hot summer and cold winter area of China. The authors concluded that in the representative sunny summer day, the peak temperature on the interior surface of the PCMW reduced by 10.2°C, and the heat entered the building through the PCMW reduced by 39.5%, comparing with the hollow window, when the solar absorptance and transmittance of the PCMW is at constants 0.19 and 0.76. Zhong et al. [28] investigated the effects of thermophysical parameters of PCM on the dynamic heat transfer of PCMW, and indicated that the thermal insulation and load shifting effects of PCMW enhanced with the increasing fusion latent heat of PCM and the optimal melting temperature of PCM applied in PCMW was 25–31°C. Moreover, minimization of temperature difference between liquid phase and solid phase could improve PCMW thermal performance. Goia et al. [29] introduced optical properties of PCM in solid and liquid phase state to a numerical model, which describes the thermo-physical behaviour of a PCM layer in combination with other transparent materials to perform numerical analyses on

various PCM glazing systems configurations, and found that a good agreement between simulations and experimental data is achieved.

Goia et al. [30-33] and Gowreesunker et al. [34] contributed a lot to the fundamental aspect of energy and optical properties of PCM glazing units. For example, Goia et al. [30, 31] measured the spectral and angular behaviour of different PCM glazing samples that are characterized by different thicknesses of PCM by commercial spectrophotometer and a dedicated optical test bed, and found that when the PCM is in liquid state and in solid state, the relevant difference in the spectral feature of PCM can be seen. When the PCM is in the solid state, the reflectivity of the system is far higher (up to three times) than when it is in the liquid state. The absorption coefficient of the solid PCM is much higher than that of the liquid PCM. The thickness of the PCM layer has a high impact on the absorption coefficient and transmittance, but which has a weak effect on the reflectivity. Goia et al. [32, 33] proposed a full-scale prototype of a PCM glazing system and analyzed its energy performance. And they found that the experimental results have highlighted a good ability of the PCM glazing to store solar energy and to smooth and delay peak values of the total heat flux. Gowreesunker et al. [34] investigated the thermal and optical performance of a PCM-glazed unit using the T-history method and spectrophotometry principles, and they found that (i) during rapid phase changes, the transmittance spectra from the PCM are unstable, while under stable conditions visible transmittance values of 90% and 40% are obtained for the liquid and solid phases, respectively; (ii) the radiation scattering effects are dominant in the solid phase of the

PCM, while radiation absorption dominates in the liquid phase; (iii) the optical/radiation performance of PCM can be successfully modelled using the liquid fraction term as the main variable; (iv) the addition of PCM improves the thermal mass of the unit during phase change, but risks of overheating may be a significant factor after the PCM has melted; (v) although the day-lighting aspects of PCM-glazed units are favourable, the change in appearance as the PCM changes phase may be a limiting factor in PCM-glazed units. Gowreesunker et al. also used the optical constants (i.e. extinction coefficient and refractive index) to calculate the optical properties (absorptance, transmittance and reflectance) of PCM layer.

The recent studies show that optical performance of PCM in different phase statement plays an important role in the thermal performance of PCM glazing units [30-35], and the characterization of the optical properties of the PCM affect considerably the thermal performance of the PCM glazing units. In fact, the optical constants of PCM are the basic parameters to calculate optical properties of PCM layer. In the present work, the thermal performance of a PCM-filled double glazing unit with different optical constants of PCM in Northeast China, i.e. extinction coefficient and refractive index, have been investigated numerically.

2. Physical and mathematical models

2.1 Geometric description

Fig. 1 shows the details of the modeling double glazing unit, which shows a double glazing unit filled 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 glasses 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 unit 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, being the PCM, both when in liquid state and in solid state, 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. And the optical properties of glass and PCM are wavelength independent.

(5) The scattering effect of PCM is omitted.

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

For the double glazing unit, the heat transfer is calculated in 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/m^3), thermal

conductivity (W/m K) and specific heat (J/kg K) of glass, respectively. $\emptyset$ is radiative source term (W/m³).

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

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

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

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

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

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

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

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_l 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,

$$\emptyset = \frac{A_{g1} I_{\text{sol}}}{L_{g1}} \quad (4a)$$

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

$$\emptyset = \frac{T_{g1} A_{p1} I_{\text{sol}}}{L_{p1}} \quad (4b)$$

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

$$\emptyset = \frac{T_{g1}T_{p1}A_{p2}I_{sol}}{L_{p2}} \quad (4c)$$

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

$$\emptyset = \frac{T_{g1}T_{p1}T_{p2}A_{g2}I_{sol}}{L_{g2}} \quad (4d)$$

Where, I_{sol} is solar radiation (W/m^2). T_{g1} , T_{p1} , T_{p2} and T_{g2} is solar transmittance of glass 1 layer, phase 1 layer, phase 2 layer and glass 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.

The transmittance and absorptance of the glass layer are calculated by [36]

$$T_{g1} = \frac{(1 - \rho_1)(1 - \rho_2)\exp(-\alpha_g L_{g1})}{1 - \rho_1\rho_2\exp(-2\alpha_g L_{g1})} \quad (5a)$$

$$A_{g1} = 1 - \rho_1 - \frac{(1 - \rho_1)\rho_2\exp(-2\alpha_g L_{g1})}{1 - \rho_1\rho_2\exp(-2\alpha_g L_{g1})} - T_{g1} \quad (5b)$$

$$T_{g2} = \frac{(1 - \rho_1)(1 - \rho_4)\exp(-\alpha_g L_{g2})}{1 - \rho_1\rho_4\exp(-2\alpha_g L_{g2})} \quad (5c)$$

$$A_{g2} = 1 - \rho_4 - \frac{(1 - \rho_4)\rho_1\exp(-2\alpha_g L_{g2})}{1 - \rho_1\rho_4\exp(-2\alpha_g L_{g2})} - T_{g2} \quad (5d)$$

Where, ρ_1 , ρ_2 and ρ_4 are the interface reflectance for surface between air and glass, and for surface between phase 1 of PCM and glass, and for surface between phase 2 of PCM and glass, respectively. α_g is the extinction coefficient of glass material(m^{-1}).

The transmittance and absorptance of the PCM layer of are calculated by [36]

$$T_{p1} = \frac{(1 - \rho_2)(1 - \rho_3)\exp(-\alpha_{p1} L_{p1})}{1 - \rho_2\rho_3\exp(-2\alpha_{p1} L_{p1})} \quad (6a)$$

$$A_{p1} = 1 - \rho_2 - \frac{(1 - \rho_2)\rho_3 \exp(-2\alpha_{p1}L_{p1})}{1 - \rho_2\rho_3 \exp(-2\alpha_{p1}L_{p1})} - T_{p1} \quad (6b)$$

$$T_{p2} = \frac{(1 - \rho_3)(1 - \rho_4) \exp(-\alpha_{p2}L_{p2})}{1 - \rho_3\rho_4 \exp(-2\alpha_{p2}L_{p2})} \quad (6c)$$

$$A_{p2} = 1 - \rho_3 - \frac{(1 - \rho_3)\rho_4 \exp(-2\alpha_{p2}L_{p2})}{1 - \rho_3\rho_4 \exp(-2\alpha_{p2}L_{p2})} - T_{p2} \quad (6d)$$

Where, ρ_3 is the interface reflectance for surface between phase 1 and phase 2 of PCM. α_{p1} and α_{p2} is the extinction coefficient of phase 1 and phase 2 material(m^{-1}), respectively.

The interface reflectance are calculated based on Fresnel's relations [37-39].

$$\rho_1 = \frac{(n_g - 1)^2}{(n_g + 1)^2} \quad (7a)$$

$$\rho_2 = \frac{(n_g - n_{p1})^2}{(n_g + n_{p1})^2} \quad (7b)$$

$$\rho_3 = \frac{(n_{p1} - n_{p2})^2}{(n_{p1} + n_{p2})^2} \quad (7c)$$

$$\rho_4 = \frac{(n_g - n_{p2})^2}{(n_g + n_{p2})^2} \quad (7d)$$

Where, n_g , n_{p1} and n_{p2} is the refractive index of glass material, phase1 and phase 2 of PCM, respectively.

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

$$-k_g \frac{\partial T}{\partial x} = q_{rad} + h_{out}(T_{out} - T_{a,out}) \quad (8)$$

Where, q_{rad} is radiative heat exchange between exterior surfaces 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

$$q_{\text{rad}} = q_{\text{rad,air}} + q_{\text{rad,sky}} + q_{\text{rad,ground}} \quad (9)$$

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

The radiation heat flux $q_{\text{rad,air}}$, $q_{\text{rad,sky}}$ and $q_{\text{rad,ground}}$ is respectively given by [29]

$$q_{\text{rad,sky}} = \varepsilon \sigma F_{\text{sky}} \beta (T_{\text{out}}^4 - T_{\text{sky}}^4) \quad (10a)$$

$$q_{\text{rad,air}} = \varepsilon \sigma F_{\text{sky}} (1 - \beta) (T_{\text{out}}^4 - T_{\text{a,out}}^4) \quad (10b)$$

$$q_{\text{rad,ground}} = \varepsilon \sigma F_{\text{ground}} (T_{\text{out}}^4 - T_{\text{a,out}}^4) \quad (10c)$$

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. F_{ground} is the view factor between the glazing unit and the surrounding surfaces, and assuming that all the surfaces are at the same temperature. 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} , F_{ground} , β , T_{sky} is respectively established by [29]

$$F_{\text{sky}} = \frac{1 + \cos \theta}{2} \quad (11a)$$

$$F_{\text{ground}} = \frac{1 - \cos \theta}{2} \quad (11b)$$

$$\beta = \sqrt{\frac{1 + \cos \theta}{2}} \quad (11c)$$

$$T_{\text{sky}} = 0.0552 T_{\text{a,out}}^{1.5} \quad (11d)$$

Where, θ is the angle between the glazing unit and the ground, for example, $\theta = 90^\circ$

for a vertical glazing unit).

In the inner surface of internal glass near to indoors environment, the boundary condition at $x=x_3$ is given as [26]

$$-k_g \frac{\partial T}{\partial x} = h_{in}(T_{in} - T_{a,in}) - \varepsilon \sigma (T_{in}^4 - T_{a,in}^4) \quad (12)$$

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

In the coupled surface between outer glass and PCM, when PCM is solid or liquid, the boundary condition at $x=x_1$ is given as [26]

$$-k_g \frac{\partial T_g}{\partial x} + I_{g \rightarrow p} = -k_p \frac{\partial T_p}{\partial x} \quad (13a)$$

Where, $I_{g \rightarrow p}$ is radiative heat flux of coupled surface between outer glass and PCM (W/m^2). T_g and T_p is temperature of the coupled surface of outer glass, temperature of coupled surface of PCM (K), respectively.

In the coupled surface between outer glass and PCM, when the first liquid layer of the PCM near the internal face of the external glass sheet is formed, the boundary condition at $x=x_1$ is given as [26]

$$-k_g \frac{\partial T_g}{\partial x} + I_{g \rightarrow p} = -k_p \frac{\partial T_p}{\partial x} + \rho_p H \frac{dS(t)}{dt} \quad (13b)$$

Where, $S(t)$ is thickness of liquid PCM (m).

In the liquid–solid interface in the PCM region where the phase change occurs, the boundary condition at $x=x_1+S(t)$ is given as [26]

$$-k_{p,l} \frac{\partial T_{p,l}}{\partial x} + I_{p,l \rightarrow p,s} = -k_{p,s} \frac{\partial T_{p,s}}{\partial x} + \rho_p H \frac{dS(t)}{dt} \quad (14)$$

Where, $I_{p,l \rightarrow p,s}$ is radiative heat flux of liquid–solid interface in the PCM region

(W/m²), respectively. $T_{p,l}$ and $T_{p,s}$ is temperature of liquid PCM near to liquid–solid interface, temperature of solid PCM near to liquid–solid interface (K), respectively. $k_{p,l}$ and $k_{p,s}$ is thermal conductivity of liquid PCM near to liquid–solid interface, thermal conductivity of solid PCM near to liquid–solid interface(W/mK), respectively.

In the coupled surface between internal glass and PCM, when PCM is solid or liquid, the boundary condition at $x=x_2$ is given as [26]

$$-k_p \frac{\partial T_p}{\partial x} + I_{p \rightarrow g} = -k_g \frac{\partial T_g}{\partial x} \quad (15a)$$

Where, $I_{p \rightarrow g}$ is radiative heat flux of coupled surface between internal glass and PCM (W/m²), respectively.

In the coupled surface between internal glass and PCM, when the first liquid layer of the PCM near to the internal glass sheet is formed, the boundary condition at $x=x_2$ is given as [26]

$$-k_p \frac{\partial T_p}{\partial x} + I_{p \rightarrow g} + \rho_p H \frac{dS(t)}{dt} = -k_g \frac{\partial T_g}{\partial x} \quad (15b)$$

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 [29] 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 [28]. 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 [28]. The thermophysical properties of materials can be attained from Table 2 in the reference [28]. The extinction coefficient and refractive index of glass is 19 m^{-1} and 1.5 [34], respectively. The emissivity of the glass is 0.88 [26]. The refractive index of PCM is 1.3, and the extinction coefficients of solid and liquid PCM is 50 and 40 m^{-1} , respectively [34]. 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 [28] are shown in Fig.3.

Fig.3. Heat flux and temperature on the interior surfaces of the double glazing filled with PCM in this work and the literature [28] (a: heat flux; b: temperature)

As shown in Fig.3, the numerical and the literature results have different characteristic in different time region. Before the time at 7:00, the difference between numerical and the literature results is huge, and the reason is that the effect of initial temperature in the double glazing filled with PCM in the experimental is not omitted

when heat conduction plays an important role in the heat transfer process, but which is omitted in the calculation because it can be reached the rational periodic condition. In the time region 7:00-11:00, the numerical results have a good agreement with the literature results, and the reason is that the effect of initial temperature in the double glazing filled with PCM in the experimental can be eliminated after running 7 hours, and both phase change of PCM and radiation transfer play an important role in this heat transfer process. However, in the time region 11:00-14:00, the difference between numerical and the literature results is also huge, and the reason is that radiation transfer plays an important role in this heat transfer process when the phase of PCM is liquid in this time region, but we can not give the exact optical parameters of PCM, which leads to the bigger numerical error. In the time region 14:00-22:00, the numerical results have a good agreement with the literature results, and the reason is that both phase change of PCM and radiation transfer play an important role in this heat transfer process. Based on the experimental result, the average relative error value of the heat flux and temperature in the present work is 34% and 2.7%, respectively.

3. Results and discussion

In this modeling work, thickness of the glass and PCM are 6mm and 12m, and $\theta=0$. The measured average hourly variations of the ambient air temperature and total radiation on June 22 in Daqing city is depicted as Fig. 4. The h_{out} and h_{in} is 7.75 and 7.43W/m²·K[27], 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 [34], respectively. The emissivity of the glass is 0.88[26]. The initial temperature of the domain is 23°C .

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

Table 1 Thermophysical properties of materials

material	Melting temperature($^\circ\text{C}$)	Density (kg/m^3)	Thermal conductivity ($\text{W}/\text{m K}$)	Specific heat capacity ($\text{J}/\text{kg K}$)	Latent heat (J/kg)
glass[29]	-	2500	0.96	840	-
PCM[28]	27-29	850	0.21	2230	205000

3.1 Effects of refractive index of liquid PCM

For investigating the effect of refractive index of PCM on thermal performance of glazing units containing PCM, the conditions of five kinds of refractive index of liquid PCM, 1.3, 1.6, 2.0, 2.5 and 3.0, are investigated when the refractive index of solid PCM is 1.3. And the extinction coefficients of solid and liquid PCM are 30 and 5 m^{-1} , respectively.

Fig. 5 illustrates temperature on the interior surfaces of double glazing units with different refractive index of liquid PCM. In Fig. 5, the trend of temperature curves on the interior surfaces of double glazing units with different refractive index of liquid PCM has a common characteristic before 10:00 or after 18:00, and the temperature values of the interior surface at the same time with different refractive index of liquid PCM are nearly same. The reason is that the percentage of liquid phase PCM in the double glazing units is very small before 10:00 or after 18:00, so the role of refractive index of liquid PCM is not effective. However with the percentage of liquid phase PCM in the double glazing units increasing at 10:00-18:00, the refractive index of liquid PCM plays a weak role in the temperature of the interior surface. For example, the temperature of the interior surfaces of double glazing units at 13:30 for refractive index of liquid PCM, 1.3, 1.6, 2.0, 2.5 and 3.0, is 31.72, 31.82, 31.36, 30.39 and 29.94°C, respectively. It also can be seen from Fig. 5, the time to the highest temperature of the interior surface with different refractive index of liquid PCM is very near. This result shows that the effect of refractive index of liquid PCM on the temperature of the interior surface of double glazing units is very small.

Fig.5. Temperature of the interior surface on double glazing units with different refractive index of liquid PCM

Fig. 6 shows transmitted energy of the interior surfaces of double glazing units with different refractive index of liquid PCM. It can be seen in Fig.6, during the time before 10:00 or after 18:00, due to the small percentage of liquid phase of PCM in the double glazing units, the total transmitted energy and solar energy of the interior surfaces of double glazing units with different refractive index of liquid PCM are nearly same. In contrast, during the time 10:00-18:00, there is clearly different in the total transmitted energy and solar energy of the interior surfaces of double glazing units with different refractive index of liquid PCM. For example, the total transmitted energy and solar energy of the interior surfaces of double glazing units at 12:00 for refractive index of liquid PCM 1.3, 2.0 and 2.5, are 564.34 and 499.48 W/m², 537.66 and 477.19 W/m², 471.61 and 419.85 W/m², respectively. This result also shows that solar energy is an important attribution in the total transmitted energy of the interior surfaces of double glazing units, which results that the time to the highest transmitted

energy with different refractive index of liquid PCM are near to 12:00. And with the refractive index of liquid PCM increasing, the total transmitted energy and solar energy of the interior surfaces of double glazing units decreases, which indicates that the refractive index of liquid PCM plays an important role in the transmitted energy of the interior surfaces of double glazing units.

Fig.6. Transmitted energy of interior surface on double glazing units with different refractive index of liquid PCM (a: total energy; b:solar energy)

3.2 Effects of refractive index of solid PCM

For investigating the effect of refractive index of PCM on thermal performance of glazing units containing PCM, the conditions of five kinds of refractive index of solid PCM, 1.3, 1.6, 2.0, 2.5 and 3.0, are investigated when the refractive index of liquid PCM is 1.3. And the extinction coefficients of solid and liquid PCM are 30 and 5 m^{-1} , respectively.

Fig. 7 plots temperature curves of the interior surfaces of double glazing units with different refractive index of solid PCM. As shown in Fig. 7, because the solar energy is zero before 3:00 and after 20:00, so the temperature values of the interior

surface at the same time with different refractive index of solid PCM are same. However with the effect of solar energy on the double glazing units at 3:00-20:00, the refractive index of solid PCM plays its role in the temperature of the interior surface. For example, the temperature of the interior surfaces of double glazing units at 13:30 for refractive index of liquid PCM, 1.3, 1.6, 2.0, 2.5 and 3.0, is 31.72, 31.67, 31.89, 32.37 and 32.92°C, respectively. This result shows that the effect of refractive index of solid PCM on the temperature of the interior surface is also very weak.

Fig.7. Temperature of the interior surface on double glazing units with different refractive index of solid PCM

Fig. 8 shows transmitted energy of the interior surfaces of double glazing units with different refractive index of solid PCM. It can be seen in Fig.8, due to the zero solar energy before 3:00, the total transmitted energy and solar energy of the interior surfaces of double glazing units with different refractive index of solid PCM are nearly same. In contrast, during the time 3:00-12:00, under the effect of solar energy it is clearly different in the total transmitted energy and solar energy of the interior

surfaces of double glazing units with different refractive index of solid PCM. In this time region, with the refractive index of solid PCM increasing, the total transmitted energy and solar energy of the interior surfaces of double glazing units decrease, and the time from solid to liquid PCM need more. The reason is that the interface reflectance is increasing with the refractive index of solid PCM increasing, which results in the transmitted solar energy entering into double glazing units decreasing. For example, the total transmitted energy and solar energy of the interior surfaces of double glazing units at 10:00 for refractive index of solid PCM 1.3, 2.0 and 2.5, are 399.04 and 361.01, 358.84 and 323.13, 305.83 and 272.57 W/m², respectively. The total transmitted energy and solar energy of the interior surfaces of double glazing units at 12:00 for refractive index of solid PCM 1.3, 2.0 and 2.5, are 564.33 and 499.48, 557.21 and 492.04, 538.20 and 471.21W/m², respectively. During 12:00-18:30, the total transmitted energy and solar energy of the interior surfaces of double glazing units with different refractive index of solid PCM are nearly same, because the phase of PCM is completely liquid. However, during 18:30-20:00, with the refractive index of solid PCM increasing, the total transmitted energy and solar energy of the interior surfaces of double glazing units decrease, due to the solidifying of PCM. This result shows that the refractive index of solid PCM plays an important role in the transmitted energy of the interior surfaces of double glazing units.

Fig.8. Transmitted energy of interior surface on double glazing units with different refractive index of solid PCM (a: total energy; b:solar energy)

3.3 Effects of extinction coefficients of liquid PCM

The conditions of four kinds of extinction coefficients of solid and liquid PCM, 30 and 5, 30 and 50, 30 and 100, 30 and 200 m^{-1} , are investigated. And the refractive index of PCM is 1.3.

Fig. 9 illustrates temperature curves of the interior surfaces of double glazing units with different extinction coefficients of liquid PCM. In Fig. 9, the trend of temperature curves on the interior surfaces of double glazing units with different extinction coefficients of liquid PCM has a common characteristic before 10:00, and temperature values of the interior surface at the same time with different extinction coefficients of liquid PCM are nearly same. The reason is that the percentage of liquid phase PCM in the double glazing units is very small before 10:00, so the role of extinction coefficients of liquid PCM is not effective. With the percentage of liquid phase PCM in the double glazing units increasing during 10:00-19:00, the extinction coefficients of liquid PCM plays an important role in the temperature of the interior

surface. With the extinction coefficients of liquid PCM increasing, the temperature of the interior surfaces of double glazing units increases. For example, the temperature of the interior surfaces of double glazing units at 13:30 for extinction coefficients of liquid PCM 5, 50, 100 and 200 m^{-1} , is 31.72, 39.61, 44.45 and 48.4 $^{\circ}\text{C}$, respectively. After 19:00, even the phase of PCM is solid, but the trend of temperature curves on the interior surfaces of double glazing units with different extinction coefficients of liquid PCM are also different due to absorb and store a lot of solar energy in the PCM. It also can be seen from Fig. 9, the time to the highest temperature of the interior surface with different extinction coefficients of liquid PCM is clearly different. For example, the time of highest temperature of the interior surface with extinction coefficient 200 m^{-1} is 30 minutes earlier than that of 5 m^{-1} . This result shows that the effect of extinction coefficient of liquid PCM on the temperature of the interior surface is violent.

Fig.9. Temperature of the interior surface on double glazing units with different extinction coefficients of liquid PCM

Fig. 10 shows transmitted energy of the interior surfaces of double glazing units with different extinction coefficients of liquid PCM. As shown in Fig.10, due to the zero solar energy before 10:00, the total transmitted energy and solar energy of the interior surfaces of double glazing units with different extinction coefficients of liquid PCM are nearly same. In contrast, during the time 10:00-19:00, under the effect of extinction coefficients of liquid PCM, there is clearly different in the total transmitted energy and solar energy of the interior surfaces of double glazing units with different extinction coefficients of liquid PCM. In this time region, with the extinction coefficients of liquid PCM increasing, the total transmitted energy and solar energy of the interior surfaces of double glazing units decrease, and the time to the highest total transmitted energy of the interior surfaces of double glazing units is delayed, but the time to the highest solar energy of the interior surfaces of double glazing units is not influenced. The reason is that the absorption ability of solar energy in PCM layer is increasing with the extinction coefficients of liquid PCM increasing, which results in the transmitted solar energy entering into indoors environment decreasing, and the temperature of PCM layer increasing. For example, the total transmitted energy and solar energy of the interior surfaces of double glazing units at 13:30 for extinction coefficients of liquid PCM, 5, 50, 100 and 200m^{-1} , are 549.65 and 478.93, 451.36 and 279.09, 389.46 and 153.16, 336.80 and 46.13W/m^2 , respectively. The time to the highest total transmitted energy of the interior surfaces of double glazing units with extinction coefficients of liquid PCM 200m^{-1} is 40 minutes later than that of extinction coefficients of 5m^{-1} . This result shows that the extinction coefficients of

liquid PCM plays a key role in the transmitted energy of double glazing units.

Fig.10. Transmitted energy of interior surface on double glazing units with different extinction coefficients of liquid PCM (a: total energy; b:solar energy)

3.4 Effects of extinction coefficients of solid PCM

The conditions of four kinds of extinction coefficients of solid and liquid PCM, 5 and 5, 30 and 5, 100 and 5, 200 and 5m^{-1} , are investigated. And the refractive index of PCM is 1.3.

Fig. 11 illustrates temperature curves of the interior surfaces of double glazing units with different extinction coefficients of liquid PCM. In Fig. 11, the trend of temperature curves on the interior surfaces of double glazing units with different extinction coefficients of liquid PCM has a common characteristic before 3:00, and temperature values of the interior surface at the same time with different extinction coefficients of solid PCM are nearly same due to zero solar energy. After 3:00, with the effect of solar energy, the extinction coefficients of solid PCM play an important role in the temperature of the interior surface. During this time region, before the

phase of PCM is totally liquid, with the extinction coefficients of solid PCM increasing, the temperature of the interior surfaces of double glazing units increases. When the PCM is completely liquid, the temperature of the interior surfaces of double glazing units with extinction coefficient 100 and 200m⁻¹ firstly decreases, then keeps increasing. The reason is that a lot of solar energy in double glazing units with extinction coefficient 100 and 200m⁻¹ are stored before the PCM completely melting, which results in the temperature of double glazing units is much higher than outdoors environment. And when the phase of PCM is liquid, the absorption ability of solar energy of PCM is descending, which can not afford the high temperature environment of double glazing units, so the temperature of double glazing units decreases.

Fig.11. Temperature of the interior surface on double glazing units with different extinction coefficients of solid PCM

It also can be seen from Fig. 11, the time to the highest temperature of the interior surface with different extinction coefficients of solid PCM is clearly different, and with the extinction coefficients of solid PCM increasing, the time of highest

temperature of the interior surfaces of double glazing units is earlier. For example, the time of highest temperature of the interior surface with extinction coefficient 200m^{-1} is 300 minutes earlier than that of 5m^{-1} . This result shows that the effect of extinction coefficient of solid PCM on the temperature of the interior surface is also very strong.

Fig. 12 shows transmitted energy of the interior surfaces of double glazing units with different extinction coefficients of solid PCM. It can be seen in Fig.12, due to the zero solar energy before 3:00, the total transmitted energy and solar energy of the interior surfaces of double glazing units with different extinction coefficients of solid PCM are nearly same. In contrast, during the time 3:00-12:00, under the effect of solar energy there is clearly different in the total transmitted energy and solar energy of the interior surfaces of double glazing units with different extinction coefficients of solid PCM. In this time region, before the phase of PCM is totally liquid, with the extinction coefficients of solid PCM, the total transmitted energy and solar energy of the interior surfaces of double glazing units decrease, and the time from solid to liquid PCM need less. During 12:00-18:30, the total transmitted energy and solar energy of the interior surfaces of double glazing units with different extinction coefficients of solid PCM are nearly same, because the phase of PCM is completely liquid. However, during 18:30-20:00, with the extinction coefficients of solid PCM increasing, the total transmitted energy and solar energy of the interior surfaces of double glazing units decrease, due to the solidifying of PCM. This result shows that the extinction coefficient of solid PCM also plays an important role in the transmitted energy of the interior surfaces of double glazing units. However, the effect of extinction coefficients

of solid PCM on the time to the highest total transmitted energy and solar energy of the interior surfaces of double glazing units is very weak.

Fig.12. Transmitted energy of interior surface on double glazing units with different extinction coefficients of solid PCM (a: total energy; b:solar energy)

4. Conclusions

In present study, thermal performance of a PCM-filled double glazing unit with different optical properties of PCM was investigated numerically. With the aim to investigate the thermal behavior of a PCM-filled double glazing unit, the influence of extinction coefficient and refractive index of PCM with different phase state have also been studied. The following conclusions can be gained:

- 1) Solar energy is an important attribution in the total transmitted energy through double glazing unit filled with PCM, which has a key effect on the temperature and heat flux of double glazing unit filled with PCM.
- 2) The effect of refractive index of liquid and solid PCM on the temperature of the interior surface of double glazing unit filled with PCM is very weak, but which has an important effect on the transmitted energy of the interior surface of double

glazing unit filled with PCM. With the refractive index of liquid and solid PCM increasing, the total transmitted energy and solar energy of the interior surface of double glazing unit filled with PCM decrease.

- 3) The effect of extinction coefficient of liquid PCM on the temperature and transmitted energy of the interior surface of double glazing unit filled with PCM is violent. With the extinction coefficients of liquid PCM increasing, the temperature of the interior surface of double glazing unit filled with PCM increases, but the total transmitted energy and solar energy decrease. When the extinction coefficients of liquid PCM increases, the time to the highest total transmitted energy is delayed, and the time to the highest temperature is earlier, but the time to the highest solar energy is not influenced. The time to highest temperature of the interior surface with extinction coefficient 200m^{-1} is 30 minutes earlier than that of 5m^{-1} , however the time to the highest total transmitted energy is delayed 40 minutes.
- 4) The effect of extinction coefficient of solid PCM on the temperature and transmitted energy of the interior surface of double glazing unit filled with PCM is also very strong, but which is different with extinction coefficient of liquid PCM. When the extinction coefficients of solid PCM increases, and the time to the highest temperature is earlier, but the time to the transmitted energy is not influenced. The time to highest temperature of the interior surface with extinction coefficient 200m^{-1} is 300 minutes earlier than that of 5m^{-1} .

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