Numerical investigation of thermal and optical performance of window units filled with nanoparticle enhanced PCM

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ABSTRACT

Filling window units with phase change material (PCM) improves the thermal performance of windows, but on the other hand it has a deteriorative effect on the optical performance due to poor heat conductivity of PCM. A novel method to tackle this drawback of PCM is to disperse nanoparticles in the PCM. In this study, a model was developed to evaluate the thermal and optical performances of window units filled with nanoparticle enhanced PCM (NePCM). The effect of different types of nanoparticles, volume fractions of nanoparticles and sizes of nanoparticles on the thermal and optical performances of windows such as temperature, heat flux, solar transmittance, absorptance and reflectance were numerically investigated and compared with the referent case (i.e. pure PCM). The results showed that the optical and thermal performances of window units filled with nanoparticle dispersed paraffin wax are improved compared to that of with pure paraffin. However, the improvement is nearly the same regardless of nanoparticle type. The effect of volume fraction and size of nanoparticle is significant during the sunset and sunrise periods. Considering both thermal and optical performances of window units, it is recommended to disperse CuO nanoparticles with the volume fraction of below 1% and nanoparticle size of below 15 nm in PCM.

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1. Introduction

Windows are indispensable parts of buildings since they enhance the buildings’ aesthetical architecture, provide passive solar energy gain and air ventilation and increase natural lighting [1–3]. However, due to their poor thermal resistance, low thermal inertia and high transmission of solar radiation, they usually have poor thermal performance compared to those of opaque parts of the building envelope such as roofs and walls. Accordingly, windows play a significant role in the energy loss through building envelopes, particularly for the ones with large window area where energy loss becomes much more drastic. Thus, it is essential to decrease the energy loss through the windows by improving their thermal resistance performance, which is unquestionably beneficial to reduce the energy consumption of buildings [4–7].

A significant amount of effort has been devoted to improve the thermal resistance performance of windows, such as installing double glazing window by employing different glasses (monolithic, tempered and laminated) [8–11], using multiple glass panes [12,13], filling the cavity between glass panes with different materials including absorbing gas [14], air [15], water [16,17], aerogel [18,19] or PCM [20–26]. Filling the cavity between glass panes with PCM is a promising approach to increase the thermal performance of windows, because the PCM in the window unit can absorb some part of solar energy for thermal energy storage [27,28], and still allow visible light transmission to the indoor environment for day lighting [29,30]. Li et al. [23] investigated the thermal performance of window filled with PCM and compared to that of without PCM. They found that the peak temperature on the interior surface of the window reduces by 10.2 °C, the thermal energy entered into the building through the window reduces by 39.5%, thus the annual energy consumption of building decreased 40.6%. It was concluded that the method of filling cavity of window units with PCM is a potential technology for minimizing energy consumption and improving natural lighting in the buildings. However, there is a considerable difference between the spectral features of the liquid and solid PCM states. Goia et al. [29] studied the reflectivity and absorptivity of windows filled with PCM. It was shown that the reflectivity of PCM in the solid state is far higher (up to three times) than that of in the liquid state. Besides, the absorption coefficient of window filled with solid PCM is also much higher. A similar conclusion was drawn by Gowreesunker et al. [30] where it was
indicated that the transmittance spectra of the PCM in the window during rapid phase changes are unstable and visible transmittance values of 90% and 40% are obtained for the liquid and melting phases, respectively, under stable conditions.

The most recent studies have reported that optical and thermal parameters of PCM play an important role in the optical performance of PCM-filled glazing unit, and the characterization of the optical performance of PCM-filled glazing unit considerably affects its thermal performance [31–33]. These researches have showed that improving thermal parameters of PCM is an effective method to enhance thermal and optical performances of double glazed window units filled with PCM. For instance, the thermal conductivity of paraffin wax which is one of the most common PCM materials employed in window units is only about 0.2–0.4 W/(m K). There are various methods to enhance the thermal conductivity of PCM, which apparently affects the melting time and play a significant role in controlling the optical performance of PCM-filled window units, including the dispersion of nanoparticles with a very high conductivity in PCM [34–43], integration of metal matrix or porous matrix in PCM [44,45]. For instance, Colla et al. [34] investigated the feasibility of a new challenging use of Aluminum Oxide (Al2O3) and Carbon Black (CB) nanoparticles to enhance the thermal properties and concluded that nanoparticles have big effect on the thermal performance of PCM. Wu et al. [41] experimentally investigated the HFE7100 jet impingement with metallic PCM and concluded that nano PCM slurry can increase the thermal capacity of the fluid and provide a significant heat transfer enhancement.

Among these methods, the dispersion of high conductive metal nanoparticles in PCM has attracted a lot of attention of researchers particularly in solar utilization applications due to better stability, rheological property and thermal conductivity.

To the best knowledge of the authors, there currently is no extensive research work that considers the optical and thermal performances of window filled nanoparticle-enhanced PCM. Therefore, this study aims to investigate the thermal and optical performances of window units filled with NePCM and compare with that of pure PCM by developing a numerical model. The impact of different types of nanoparticles (namely Cu, CuO and Al2O3) together with different volume fraction of nanoparticles (ranging from 0.1% to 10%) and size of nanoparticles (ranging from 5 nm to 25 nm) on the thermal and optical performances of windows were examined.
The outcomes of this study are believed to be useful for developing advanced window units which utilizes nanoparticle enhanced PCM.

2. Physical and mathematical models

2.1. Physical model

The optical and heat transfer mechanisms of the window filled with PCM and nanoparticles are shown in Fig. 1. As can be seen from Fig. 1, solar energy reaching the window surface is partly transmitted and partly reflected, and the remaining portion is absorbed by the two glasses and PCM dispersed with nanoparticles. The heat transfer process with the combination of thermal radiation and convection takes place on the boundary of the exterior and the interior surfaces. The absorbed heat will be transmitted inward and/or outward by the processes of conduction, convection and radiation exchange. For a transparent glass layer, the effective transmittance as well as the front and back reflection are quantified as the consequence of multiple reflections between the front and back surfaces and absorption through the layer.

2.2. Mathematical model

As the main purpose of this study is to explore the influence of nanoparticles on the thermal and optical performance of window units, a simplified yet still accurate model is developed. The following assumptions are made: (1) The heat transfer through the glazing unit is unsteady unidirectional heat transfer process. (2) The convection within the PCM layer and the radiative exchange between the surfaces of glasses facing the cavity filled with PCM are ignored. (3) Both liquid and solid states of PCM are highly non-transparent to the long-wave radiation. (4) The glass, nanoparticles and PCM are considered to be thermally homogeneous and isotropic media and thermal properties are temperature independent. (5) The scattering effect of PCM and the effect of nanoparticles on the optical constants of PCM and nanoparticles are omitted.

For the double glazing unit filled with PCM and nanoparticles, the heat transfer is calculated in three regions; the outer glass layer, internal glass layer and PCM layer in the middle, as shown in Fig. 2.

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

$$\rho_p c_p \frac{\partial T}{\partial t} = k_g \frac{\partial^2 T}{\partial x^2} + q$$  \hspace{1cm} (1)

where $t$ is time (s), $T$ is temperature (K), $\rho_p$, $k_g$ and $c_p$ are density (kg/m$^3$), thermal conductivity (W/m K) and specific heat (J/kg K) of glass, respectively. $q$ is radiative source term (W/m$^3$).

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

$$\rho_c c_p \frac{\partial H}{\partial t} = k_p \frac{\partial^2 T}{\partial x^2} + q$$  \hspace{1cm} (2)

where $H$ is the specific enthalpy of PCM (J/kg), $\rho_c$ is the density (kg/m$^3$) and $k_p$ is the thermal conductivity (W/m K) of PCM.

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

$$H = \int_{T_{ref}}^{T} c_p(T) dT + \beta Q_L$$  \hspace{1cm} (3a)

$$\beta = \begin{cases} 0, & T < T_s \\ \frac{T - T_s}{T_l - T_s}, & T_s < T < T_l \\ 1, & T > T_l \end{cases}$$  \hspace{1cm} (3b)

Here, $T_{ref}$ is the reference temperature (K), $c_p(T)$ is specific heat (J/kg K) of PCM, $Q_L$ is the latent heat fusion of PCM (J/kg), $\beta$ 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.

With the addition of nanoparticles to PCM, the thermophysical properties must be re-evaluated. Density and specific heat of NePCM are obtained by the following equations [35,46].
\[ \rho_{\text{NPCM}} = \phi \rho_{\text{np}} + (1 - \phi) \rho_{\ell} \]  
\[ (\rho C_p)_{\text{NPCM}} = (1 - \phi) (\rho C_p)_{\ell} + (\phi \rho C_p)_{\text{np}} \]  
\( \phi \) is being volume fraction, \( C_p \) is specific heat and subscripts “np” and “\( \ell \)” stands for nanoparticle and PCM, respectively.

The thermal conductivity of Nano-PCM is estimated as follows [35].

\[ \lambda_{\text{NPCM}} = \frac{\lambda_{\text{np}} + (S - 1) \lambda_{\ell} - (S - 1) \phi (\lambda_{\ell} - \lambda_{\text{np}}) \lambda_{\ell}}{\lambda_{\text{np}} + (S - 1) \lambda_{\ell} + \phi (\lambda_{\ell} - \lambda_{\text{np}})} + 4.22035 \times 10^5 (100 \phi)^{-0.0334} \phi \rho_{\ell} C_p \sqrt{\frac{K T}{\rho_{\text{np}}}} f(T, \phi) \]  
\( f(T, \phi) = (2.8217 \times 10^{-2} \phi + 3.917 \times 10^{-3}) \frac{T}{T_0} - 3.0699 \times 10^{-2} \phi - 3.91123 \times 10^{-3} \)  
where \( T_0 \) is the shape factor which equals to 3, \( K \) is Boltzmann constant, \( T_0 = (273 \text{ K}) \) is the reference temperature, \( \phi \) is nanoparticle size, \( \lambda_{\text{np}}, \lambda_{\ell} \) is thermal conductivity of nanoparticles and PCM, respectively.

Latent heat of PCM containing nanoparticles is calculated as in [35, 47].

\[ l_{\text{NPCM}} = \frac{(1 - \phi) (\rho L)_{\text{PCM}}}{\rho_{\text{PCM}}} \]  
where \( L \) stands for the latent heat fusion of paraffin wax.

The radiative source term for each layer is calculated depending on the location (see Fig. 2). The radiative source term in the glass 1, phase 1, phase 2 and glass 2 are obtained by Eqs. (7a)–(7d), respectively.

\[ \theta = \frac{A_{\text{g1}} l_{\text{sol}}}{L_{g1}} \]  
\[ \theta = \frac{T_{g1} A_{\text{g1}} l_{\text{sol}}}{L_{g1}} \]  
\[ \theta = \frac{T_{g1} T_{g1} A_{\text{g2}} l_{\text{sol}}}{L_{g2}} \]  
\[ \theta = \frac{T_{g2} T_{g1} A_{\text{g2}} l_{\text{sol}}}{L_{g2}} \]  
Here, \( l_{\text{sol}} \) is solar radiation (W/m²), \( T_{g1}, T_{g1}, T_{g2} \) and \( T_{g2} \) represent the transmittances of glass 1, phase 1, phase 2 and glass 2 layers, respectively. \( A_{\text{g1}}, A_{\text{g1}}, A_{\text{g2}} \) and \( A_{\text{g2}} \) stand for the solar absorptances of glass 1, phase 1, phase 2 and glass 2 layers, respectively. \( L_{g1}, L_{g1}, L_{g2} \) and \( L_{g2} \) are the thicknesses (m) of glass 1, phase 1, phase 2 and glass 2 layers, respectively.

Transmittance and absorptance of the glass layer are calculated by [48].

\[ T_{g1} = \frac{(1 - \rho_1)(1 - \rho_2) \exp(-\sigma_{g1} L_{g1})}{1 - \rho_1 \rho_2 \exp(-2\sigma_{g1} L_{g1})} \]  
\[ A_{g1} = 1 - T_{g1} = \frac{(1 - \rho_1) \rho_2 \exp(-2\sigma_{g1} L_{g1})}{1 - \rho_1 \rho_2 \exp(-2\sigma_{g1} L_{g1})} - T_{g1} \]  
\[ T_{g2} = \frac{(1 - \rho_3)(1 - \rho_4) \exp(-\sigma_{g2} L_{g2})}{1 - \rho_3 \rho_4 \exp(-2\sigma_{g2} L_{g2})} \]  
\[ A_{g2} = 1 - T_{g2} = \frac{(1 - \rho_3) \rho_4 \exp(-2\sigma_{g2} L_{g2})}{1 - \rho_3 \rho_4 \exp(-2\sigma_{g2} L_{g2})} - T_{g2} \]  
\( \rho_1, \rho_2, \rho_3, \) and \( \rho_4 \) are being the interface reflectances of the surface between air and glass, and the surface between the phase 1 of PCM and glass, and the surface between phase 2 of PCM and glass, respectively. \( \sigma_{g1} \) is the extinction coefficient of glass material (m⁻¹).

The transmittance and absorptance of the NePCMs are calculated by [48].

\[ T_{p1} = \frac{(1 - \rho_1)(1 - \rho_2) \exp(-\sigma_{p1} L_{p1})}{1 - \rho_1 \rho_2 \exp(-2\sigma_{p1} L_{p1})} \]  
\[ A_{p1} = 1 - T_{p1} = \frac{(1 - \rho_1) \rho_2 \exp(-2\sigma_{p1} L_{p1})}{1 - \rho_1 \rho_2 \exp(-2\sigma_{p1} L_{p1})} - T_{p1} \]  
\[ T_{p2} = \frac{(1 - \rho_3)(1 - \rho_4) \exp(-\sigma_{p2} L_{p2})}{1 - \rho_3 \rho_4 \exp(-2\sigma_{p2} L_{p2})} \]  
\[ A_{p2} = 1 - T_{p2} = \frac{(1 - \rho_3) \rho_4 \exp(-2\sigma_{p2} L_{p2})}{1 - \rho_3 \rho_4 \exp(-2\sigma_{p2} L_{p2})} - T_{p2} \]  
where \( \rho_3 \) is the interface reflectance of the surface between the phase 1 and phase 2, \( \sigma_{p1} \) and \( \sigma_{p2} \) are the extinction coefficients of phase 1 and phase 2 materials (m⁻¹), respectively.

The interface reflectance is calculated based on Fresnel’s relations.

\[ \rho_1 = \frac{(n_g - 1)^2}{(n_g + 1)^2} \]  
\[ \rho_2 = \frac{(n_g - n_{p1})^2}{(n_g + n_{p1})^2} \]  
\[ \rho_3 = \frac{(n_{p1} - n_{p2})^2}{(n_{p1} + n_{p2})^2} \]  
\[ \rho_4 = \frac{(n_g - n_{p2})^2}{(n_g + n_{p2})^2} \]  
where \( n_g, n_{p1} \) and \( n_{p2} \) are the refractive indexes of glass, phase 1 and phase 2, respectively.

The optical parameters, namely solar reflectance \( R \), transmittance \( T \) and absorptance \( A \) are given as

\[ T = T_{g1} T_{p1} T_{p2} T_{g2} \]  
\[ A = A_{g1} + T_{g1} A_{p1} + T_{g1} T_{p2} A_{p2} + T_{g1} T_{p2} T_{g2} A_{g2} \]  
\[ R = 1 - T - A \]  

The thermal boundary conditions for the calculation domain are given in upcoming equations. The exterior surface of outer glass (at \( x = 0 \)), which is exposed to solar radiation, the boundary condition is given as

\[ -k \frac{\partial T}{\partial x} = q_{\text{rad}} + h_{\text{out}} (T_{\text{out}} - T_{a\text{out}}) \]  
Here \( q_{\text{rad}} \) is the radiative heat exchange between the exterior surface of outer glass with the outdoor environment (W/m²), \( h_{\text{out}} \) is the convective heat transfer coefficient of the exterior surface of outer glass (W/m² K), \( T_{\text{out}} \) and \( T_{a\text{out}} \) are the temperatures of the exterior surface of outer glass (K) and ambient (K), respectively. The radiative heat exchange with the outdoor environment \( q_{\text{rad}} \) is given by

\[ q_{\text{rad}} = q_{\text{rad,air}} + q_{\text{rad,sky}} + q_{\text{rad,ground}} \]  
where \( q_{\text{rad,air}}, q_{\text{rad,sky}} \) and \( q_{\text{rad,ground}} \) are radiative heat exchanges with the air, sky and ground (W/m²), respectively. The radiation
heat flux $q_{\text{rad,air}}, q_{\text{rad,sky}}$ and $q_{\text{rad,ground}}$ are given by Eqs. (14a)–(14c), respectively.

$$q_{\text{rad,sky}} = \varepsilon \sigma F_{\text{sky}} (T_{\text{out}}^4 - T_{\text{sky}}^4)$$  \hspace{1cm} (14a)

$$q_{\text{rad,air}} = \varepsilon \sigma F_{\text{sky}} (1 - \beta) (T_{\text{out}}^4 - T_{\text{a,out}}^4)$$  \hspace{1cm} (14b)

$$q_{\text{rad,ground}} = \varepsilon \sigma F_{\text{ground}} (T_{\text{a,in}}^4 - T_{\text{a,out}}^4)$$  \hspace{1cm} (14c)

where $\varepsilon$ is the surface emissivity of glass, $\sigma$ is the Stefan–Boltzmann constant, $F_{\text{sky}}$ and $F_{\text{ground}}$ represent the view factors between the glazing unit and the sky dome, and between the glazing unit and the surrounding surfaces, respectively, assuming that all the surfaces are at the same temperature. $\beta$ is a factor that splits the exchange with the sky dome between sky and air radiation. $T_{\text{sky}}$ is the sky temperature (K). These parameters are given as follows [32]:

$$F_{\text{sky}} = \frac{1 + \cos \theta}{2}$$  \hspace{1cm} (15a)

$$F_{\text{ground}} = \frac{1 - \cos \theta}{2}$$  \hspace{1cm} (15b)

$$\beta = \sqrt{\frac{1 + \cos \theta}{2}}$$  \hspace{1cm} (15c)

$$T_{\text{sky}} = 0.0552 T_{\text{a,out}}^{1.5}$$  \hspace{1cm} (15d)

$\theta$ is the angle between the glass unit and the ground. For example, $\theta = 90^\circ$ represents the vertical glazing unit.

The boundary condition at the inner surface of internal glass near to indoors environment ($x = x_1$) is given as

$$-k_p \frac{\partial T_p}{\partial x} = h_m (T_{\text{m,in}} - T_{\text{a,in}}) + \varepsilon \sigma (T_{\text{m,in}}^4 - T_{\text{a,in}}^4)$$  \hspace{1cm} (16)

where $h_m$ is the convective heat transfer coefficient of the inner surface of internal glass (W/m$^2$ K). $T_{\text{m,in}}$ and $T_{\text{a,in}}$ stand for temperatures of the inner surface of internal glass (K) and indoor air (K), respectively.

The boundary condition at the interface of the outer glass and PCM ($x = x_1$) depends on the phase state of PCM. The boundary condition is presented by Eq. (17a) when the state of PCM is fully solid or fully liquid, whereas it is given in Eq. (17b) when the first liquid layer of the PCM near the internal face of the external glass sheet is formed.

$$-k_p \frac{\partial T_p}{\partial x} + I_{p-g} = -k_g \frac{\partial T_g}{\partial x}$$  \hspace{1cm} (17a)

$$-k_p \frac{\partial T_p}{\partial x} + I_{p-g} = -k_g \frac{\partial T_g}{\partial x} + \rho_p H \frac{dS(t)}{dt}$$  \hspace{1cm} (17b)

where $I_{p-g}$ is the radiative heat flux between the outer glass and PCM (W/m$^2$). $T_{p}$ and $T_{g}$ represents the interface temperatures of outer glass and PCM (K), respectively, and $S(t)$ stands for the thickness of liquid PCM (m).

At the liquid–solid interface of the PCM region ($x = x_1 + S(t)$) where the phase change occurs, the boundary condition is given as

$$-k_p \frac{\partial T_p}{\partial x} + I_{p-l-p-s} = -k_{ps} \frac{\partial T_{ps}}{\partial x} + \rho_p H \frac{dS(t)}{dt}$$  \hspace{1cm} (18)

Here, $I_{p-l-p-s}$ represents the radiative heat flux of liquid–solid interface in the PCM region (W/m$^2$). $T_{ps}$ and $T_{ps}$ are the temperatures of liquid PCM and solid PCM near the liquid–solid interface (K), respectively. $k_{ps}$ and $k_{ps}$ are the thermal conductivities of liquid PCM and solid PCM near to liquid–solid interface (W/m K), respectively.

The boundary condition at the interface between the internal glass and PCM can be written similarly. When PCM is fully solid or fully liquid, the boundary condition at $x = x_2$ is given as

$$-k_p \frac{\partial T_p}{\partial x} + I_{p-g} = -k_g \frac{\partial T_g}{\partial x}$$  \hspace{1cm} (19a)

where $I_{p-g}$ is the radiative heat flux between the internal glass and PCM (W/m$^2$). However, when the first liquid layer of the PCM near the internal glass sheet is formed, the boundary condition at $x = x_2$ is given as

$$-k_p \frac{\partial T_p}{\partial x} + I_{p-g} + \rho_p H \frac{dS(t)}{dt} = -k_g \frac{\partial T_g}{\partial x}$$  \hspace{1cm} (19b)

The influence of the investigated parameters on the performance of double glazing unit was compared and assessed on both an absolute and relative basis by Eqs. (20a) and (20b), respectively.

$$\Delta(\varphi) = \frac{x_2 - x_1}{x_1}$$  \hspace{1cm} (20a)

$$\varphi(\varphi) = \frac{x_2 \varphi - x_1 \varphi}{x_1 \varphi}$$  \hspace{1cm} (20b)

where $x_1$ and $x_2$ are the compared parameter value and the reference value.

Temperature time lag ($\gamma_k$) which is a key parameter to evaluate the thermal inertia of glazing unit and characterizes the phase difference of the temperature waves on the interior surfaces of the double glazing roof is defined as:

$$\gamma_k = \frac{T_{g,max} - T_{a,max}}{\Delta(\varphi)}$$  \hspace{1cm} (21)

where $T_{g,max}$ and $T_{a,max}$ are the times of peak temperatures of the interior surface of the double glazing unit and the outdoor air, respectively.

### 2.3. Experimental validation of numerical procedure

The developed numerical method for investigation of optical and heat transfer analysis of glazing unit filled with NePCM is based on the finite difference method. In order to verify the accuracy and reliability of the present numerical model, the obtained results are compared with the experimental results of [49].

Fig. 3 shows the photograph of glazing unit setup utilized for the experimental validation. The glazing unit made of aluminum skeleton and glass is employed to contain Paraffin and Al$_2$O$_3$ nanoparticles in experiments. The experimental setup is composed of solar simulator, test rig and the data acquisition system. Two thermocouples (K-type) are placed on the surfaces of the glazed unit for monitoring the temperature variation during experiments. The Jinzhou Sunshine/TBQ-4–5 solar spectral radiometer is placed under the glazed unit for measuring the solar radiation through the test samples. The data acquisition system is composed of a computer and Agilent data logger that controlled by the data acquisition program. The data of all sensors are recorded with 60 s intervals.

The indoor air temperature and solar radiation intensity is 15 °C and 650 W/m$^2$ in the experiment, respectively. Both $h_m$ and $h_{in}$ are 5.9 W/m$^2$ K. The thermophysical properties of paraffin and Al$_2$O$_3$ nanoparticles can be attained from Table 1. The extinction coefficient and refractive index of glass is 19 m$^{-1}$ and 1.5, respectively. The emissivity of the glass is 0.88. The refractive index of paraffin containing 0.005% Al$_2$O$_3$ nanoparticles is 1.4, and the extinction coefficients of solid and liquid paraffin containing 0.005% Al$_2$O$_3$ nanoparticles is 300 and 100 m$^{-1}$, respectively. The initial temperature of the domain is 15 °C. The simulation was kept running until the solution becomes steady, which needs 6 h to reach the steady condition. The solar transmittances and temperatures on the interior surfaces of the glazing unit filled with paraffin containing
Al$_2$O$_3$ nanoparticles are compared in Fig. 4 for numerical and experimental approaches. It is noted that two different temperatures are given in Fig. 4 since thermocouples placed on the surfaces of the glazed unit are affected by the radiation effect from the solar simulator during experiments. The equivalent temperature $T_{eq}$ is defined as

$$T_{eq} = T_{in} + \frac{\alpha_T T_{sol}}{h_{out}} - 7.3$$

where $\alpha_T$ is the absorption coefficient of the exterior surface of the thermocouple, which is 0.69 in present experimental conditions.

As shown in Fig. 4, the curves for simulated and experimental results follow a similar pattern thus illustrates that the numerical model built in this paper can simulate satisfactorily the thermal and optical performances of window units filled with nanoparticle.

### 3. Results and discussion

In the present work, the window unit is considered to be located horizontally ($\theta = 0^\circ$). The thicknesses of glass and PCM layers are 6 and 12 mm, respectively. The measured average hourly variations of the ambient air temperature and total solar radiation on June 22 in Daqing City is depicted in Fig. 5. The $h_{out}$ and $h_{in}$ are 7.75 and 7.43 W/m$^2$ K, respectively. The indoor air temperature is 26 $^\circ$C. The thermophysical properties of materials are presented in Table 1. The extinction coefficient and refractive index of glass is 19 m$^{-1}$ and 1.5, respectively. The refractive index of PCM is 1.4, and the extinction coefficients of solid and liquid states of PCM are 60 and 20 m$^{-1}$, respectively. The emissivity of the glass is 0.88. The initial temperature of the computational domain is 2 $^\circ$C. The simulations are performed until the solution becomes

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting temperature (°C)</th>
<th>Density (kg/m$^3$)</th>
<th>Thermal conductivity (W/m K)</th>
<th>Specific heat capacity (J/kg K)</th>
<th>Latent heat (J/kg)</th>
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<tr>
<td>Glass</td>
<td>–</td>
<td>2500</td>
<td>0.96</td>
<td>840</td>
<td>–</td>
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<tr>
<td>PCM</td>
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<td>850</td>
<td>0.21</td>
<td>2230</td>
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<td>400</td>
<td>383</td>
<td>–</td>
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<td>20</td>
<td>536</td>
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<tr>
<td>Al$_2$O$_3$</td>
<td>–</td>
<td>3700</td>
<td>35</td>
<td>880</td>
<td>–</td>
</tr>
</tbody>
</table>

![Fig. 3. Experimental setup (left: glazed unit; right: test facility).](image1)

![Fig. 4. Solar transmittance and temperature on the interior surfaces of the double glazing (a: solar transmittances; b: temperature).](image2)
periodic. It is observed that running the computations for two days are enough to reach a periodic solution.

3.1. Effects of nanoparticles

In order to investigate the effect of nanoparticles on thermal and optical performances of windows filled with PCM, three different types of nanoparticle are considered, including Cu, CuO and Al2O3. The volume fraction and size of nanoparticles are considered to be 5% and 15 nm. The solutions are obtained for the pure PCM (i.e. PCM without nanoparticles) also in order to be able to evaluate the contribution of nanoparticles.

Fig. 6 illustrates temperature and total energy flux of interior surface of windows containing PCM with and without nanoparticles. In all figures, t0 and q0 is temperature and total transmitted energy of window filled with paraffin, respectively. t and q is temperature and total transmitted energy of window filled with nanoparticles, respectively. Generally speaking, referring to Fig. 6a, during the most of the time of the considered day, the temperature of interior surface of window filled with NePCM is lower than that of pure paraffin, due to lower thermal diffusivity of the PCM containing nanoparticles. The results show that by adding nanoparticles to PCM, the peak temperature of the interior surface of window decreases while the time lag increases. For instance, the highest temperature of the interior surface of window during the considered day is observed for the case of pure PCM, which is 34.37 °C at 13:05. By utilizing the NePCM, the highest temperature reduces to 34.30 °C for Cu and CuO nanoparticles and 34.31 °C for Al2O3 nanoparticles. Besides, the time when the peak temperature is reached delays about 120 s compared to that of pure PCM.

As can be seen from Fig. 6b, the effect of the nanoparticles on the transmitted energy of the interior surface of window is weak where the transmitted energy of window containing nanoparticles is slightly higher than that of without nanoparticles due to the enhanced heat transfer capacity. However, for high solar intensities, the transmitted energy of window containing nanoparticles is nearly the same as that of pure PCM due to the fact that the solar energy plays a determinative role in the attribution of total transmitted energy through the glazing unit. The results indicate that PCM filled with nanoparticles in the window unit improves both the time lag and thermal resistance of window. However the effect of three different nanoparticles on the thermal performance of window is similar.

Fig. 7 shows optical results of window containing PCM with and without nanoparticles. The solar reflectance, solar absorbance and solar transmittance of window containing PCM with nanoparticles are only related to the liquid fraction of PCM. Therefore, the melting and solidifying time of PCM in the window can be estimated by analyzing the solar reflectance, solar absorbance and solar transmittance. As shown in Fig. 7, the effect of the nanoparticles on the optical performance of window is insignificant when the phase of PCM is fully solid or fully liquid. However, during the melting and solidification processes of PCM, the effect of the nanoparticles on the optical performance of window is visible for all the types of nanoparticles. The starting time of solidification and melting processes of NePCM is delayed, and the total phase change time is shortened compared to that of pure paraffin. The reason is that adding nanoparticles into PCM enhances the ability of thermal energy storage which results in delay in initiation of solidifying or melting of PCM. Also, it enhances the ability of heat conductivity and reduces latent heat fusion of PCM which causes a decrease in the total solidifying or melting time of PCM. For example, the starting time of melting and solidifying processes is 9:03 and 17:10, respectively, for pure PCM, while it is 9:09 and 17:13 for PCM containing nanoparticles. The required time to complete the melting and solidification processes which is 61 min and 78 min, respectively, for pure PCM is reduced by introducing nanoparticles. The reduction in melting and solidifying time is 20 min and 19 min for Cu nanoparticles, 19 min and 18 min for Al2O3 nanoparticles and 20 min and 20 min for CuO nanoparticles, respectively. It is interesting to note that although the reduction in phase change time is nearly the same, the optical performance attained by CuO, which has lowest thermal diffusivity, is slightly higher.
3.2. Effect of volume fraction of nanoparticles

In this section, the effect of volume fraction of nanoparticles on the thermal and optical performances of window unit filled NePCM is examined. For that purpose, computations are carried out for five different volume fractions of CuO (namely, 0.1%, 0.5%, 1%, 5% and 10%) with the size of 15 nm and obtained results are presented in Figs. 8–10. The comparative results are presented in order to evaluate the contribution of volume fraction of nanoparticles based on the results at volume fractions 0.1% of CuO.

Fig. 8 shows the daily temperature variation of the interior surface on window containing PCM dispersed with different volume fractions. As shown in the figure, the temperature decreases with the increase of volume fraction of the nanoparticle. The decrease is more profound during the sunset while it is insignificant during the sunrise due to the reason that heat conduction is the promi-
recent heat transfer mechanism during the sunset while heat radiation plays a significant role on the heat transfer during the sunrise. It is also observed that as the volume fraction of nanoparticle increases, the time of peak temperature experienced on the interior surface of window delays and the magnitude of peak temperature decreases. Taking the window filled with paraffin containing 0.1% CuO nanoparticles as a referent, where the peak temperature on the interior surface of window is 34.36°C at 13:07, the peak temperature decreases to 34.35°C, 34.34°C, 34.29°C and 34.25°C for the volume fraction of 0.5%, 1%, 5% and 10%, respectively, and time lag increases by 60 s for volume fraction of 0.5% and 1% and by 120 s for volume fraction of 5% and 10%. The results indicate that controlling the volume fraction of nanoparticles can improve the temperature of interior surface of window; however, it is noted that its effect is weak under solar radiation.

Fig. 9 illustrates the variation of total heat flux on the interior surfaces of window unit containing NePCM for different volume fractions of nanoparticle. As seen from the figure, the total heat flux differs particularly during the sunrise and sunset depending on the volume fraction of nanoparticles. When the volume fraction of nanoparticles is increased from 0.1% to 0.5%, the transmitted energy through window increases slightly. However, further increase in the volume fraction of nanoparticles causes a huge increase in the transmitted energy, especially during sunset time, which apparently decreases the thermal resistance performance of the window unit. However, the effect of volume fraction of nanoparticles on total transmitted energy is weak during the sunrise time. This is due to the fact that during the sunrise solar radiation contributes significantly to the total transmitted energy of the interior surfaces of window while during the sunset heat conduction is prominent heat transfer mechanism.

Fig. 10 shows the optical performance of window filled with NePCM for different volume fractions of nanoparticles. As shown in the figure, the effect of volume fraction on the optical performance of window is insignificant when PCM is in fully solid or fully liquid states. However, the initiation time of solidifying or melting...
depends on the volume fraction of nanoparticles. Increasing the volume fraction, the starting time of solidification and melting processes delays and the total required time shortens. For example, the starting times of melting and solidification are 9:02 and 17:10 for 0.1%, 9:03 and 17:11 for 0.5%, 9:04 and 17:11 for 1%, 9:08 and 17:13 for 5% and 9:10 and 17:15 for 10%, respectively. Taking the case with 0.1% nanoparticles as a referent where melting and solidifying last 61 min and 78 min, respectively, the reduction in phase change time is 3 min and 3 min for 0.5%, 6 min and 5 min for 1%, 20 min and 19 min for 5%, 31 min and 31 min for 10%, respectively.

3.3. Effect of nanoparticle size

In order to explore the effect of nanoparticle size on the thermal and optical performances of window filled with NePCM, numerical experiments are conducted for five different sizes of CuO nanoparticles which are 5 nm, 10 nm, 15 nm, 20 nm and 25 nm. The volume fraction of CuO nanoparticles is kept constant at 5%.

Temperature results for different nanoparticle sizes are presented in Fig. 11. As shown in the figure, the temperature of interior surface of window increases as nanoparticle size increases. It is observed that with the increase of nanoparticles size, the peak temperature increases slightly and the time to reach the peak temperature delays. For example, while the peak temperature of 34.25 °C occurs at 13:08 for the window filled with paraffin containing 5 nm size of nanoparticles, the peak temperature increases to 34.28 °C with no time lag for 10 nm and to 34.30 °C, 34.30 °C and 34.31 °C with 60 s time lag for 10 nm, 15 nm, 20 nm and 25 nm size of nanoparticles, respectively. The results reveal that controlling the nanoparticles size can improve the temperature of interior surface of window, but its effect is weak under solar radiation.

Fig. 12 illustrates the influence of nanoparticle size on the heat flux obtained on the interior surface of window filled with NePCM.

![Fig. 12. Total energy results of the interior surface on glazed windows with different nanoparticle size.](image1)

![Fig. 13. optical results of glazed windows with different size of nanoparticles (a: reflectance; b: transmittance; c: absorptance).](image2)
As seen from the figure, the total transmitted energy through the windows containing PCM with large nanoparticle size is slightly higher than that of with small nanoparticle size since the enhanced heat transfer capacity of PCM is directly related to nanoparticle size. However, under intense solar radiation, the transmitted energy through window is nearly the same regardless of the nanoparticle size. Based on the presented results, it can be claimed that by incorporating nanoparticles in the PCM filled in window cavity increases time lag as well as the energy consumption of window units.

Fig. 13 depicts the impact of nanoparticle size on the solar reflectance, solar absorbance and solar transmittance of window containing NePCM. As shown in Fig. 11, the effect of size of nanoparticles on the optical performance of window is weak when the phase of PCM is fully solid or fully liquid. However, the required time to complete the phase change (melting and solidification processes) differs depending on the nanoparticle size. The initiation time of melting and solidification processes together with the overall phase change time is presented in Table 2 for different nanoparticle sizes.

Referring to Table 2, it can be observed that as nanoparticle size increases, the phase change process begins at earlier times and the overall time to complete phase change increases. The reason is that increasing nanoparticles size enhances the ability of heat conduction, which results in initiation of melting and solidification of PCM at earlier times and also improves the ability of thermal energy storage, which causes an increase in the required time to complete phase change process.

4. Conclusions

In the present work, the thermal and optical performances of window filled with PCM containing nanoparticles were investigated. The effect of different types, volume fractions and sizes of nanoparticles on the thermal and optical behavior was numerically studied. The main conclusions can be drawn in the light of the obtained results are as follows:

- Compared with the window containing pure paraffin, the optical and thermal performances of window filled with paraffin and nanoparticles improve, and the peak temperature on the interior surface of window decreases, time lag of the window unit increases, however the total transmitted energy through the window increases. The effect of different types of nanoparticles on the thermal and optical performance of window is similar.
- The effect of volume fraction and size of nanoparticle on thermal and optical performances is different during the sunset and sunrise. Their effect is significant on the thermal performance during the sunset and on the optical performance during the sunrise.
- As the volume fraction of nanoparticle increases, the temperature of interior surface of window decreases, time lag increases which results in delay in starting time of melting and solidification processes and the overall melting and solidification times of PCM in the window shorten.
- As the size of nanoparticles increases, the temperature of interior surface of window rises, the melting and solidification processes begins at earlier stage and the required time to complete phase change processes increases.
- CuO nanoparticles are recommended for improving the thermal and optical performance of window filled with paraffin. The volume fraction under 1% and nanoparticles size under 15 nm is recommended considering both thermal and optical performances of window.

Conflict of interest

The authors declare that there are no conflicts of interest.

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Table 2

<table>
<thead>
<tr>
<th>Nanoparticle size</th>
<th>Initiation time of melting</th>
<th>Overall time (min)</th>
<th>Initiation time of solidification</th>
<th>Overall time (min)</th>
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</thead>
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<td>9:05</td>
<td>47</td>
<td>17:14</td>
<td>63</td>
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References


