Analysis on Applicability of Phase Change Material Glazing Unit in Different Climate Conditions

Zhenhao ZHANG[1,3], Mustapha KARKRI[2*], Laurent IBOS[2], Yi WANG[1,3], Yanqiu HUANG[1,3]

[1]State Key Laboratory of Green Building in Western China, Xi'an University of Architecture and Technology
13 Yanta Road, Xi'an, Shaanxi Province, (China)
[2]CERTES, Université Paris Est Créteil Val de Marne
61 Av. Du Général de Gaulle, 94010 Créteil Cedex, (France)
[3]School of Building Services Science and Engineering, Xi'an University of Architecture and Technology
13 Yanta Road, Xi'an, Shaanxi Province, (China)
[*](Corresponding author: mustapha.karkri@u-pec.fr)

Abstract - Thermal performance of phase change material (PCM) glazing in different climate conditions is studied in this paper. Inner surface temperature (T_{sur}) and total heat flow entering the room (Q_{total}) are the evaluation indicators. According to the results: (1) PCM glazing has better performance than ordinary glazing, T_{sur} and Q_{total} decreased by 1-19% and 4-80%, respectively; (2) PCM glazing is more suitable for strong mean solar radiation intensity (MSRI) conditions from the perspective of T_{sur}; (3) however, when viewed from Q_{total}, PCM glazing is more compatible with weak MSRI conditions.

Nomenclature

C	specific heat capacity, J.kg^{-1}.K^{-1}
T	temperature, K
t	time, s
Q_r	radiative heat source, W.m^{-2}
L_f	latent heat of PCM, J.kg^{-1}
h	convective heat transfer coefficient, W.m^{-2}.K^{-1}
I	radiation intensity, W.m^{-2}.sr^{-1}
q_r	radiative heat flux in glazing unit, W.m^{-2}
T_m	melting point of PCM, K
n	refractive index
B	volume fraction of liquid PCM

Greek symbols

λ	thermal conductivity, W.m^{-1}.K^{-1}
ρ	density, kg.m^{-3}
α_m	transition function
ε	surface emissivity
Ω	direction of radiation
κ	absorption coefficient, m^{-1}
σ_s	scattering coefficient, m^{-1}
ρ_d	surface diffuse reflectance
τ	surface transmittance

Index and exponent

g	glass
p	PCM
s	solid state
l	liquid state
amb	ambient environment
s	location

1. Introduction

Worldwide, building energy consumption accounts for about 29% of total energy consumption (IEA 2019), of which 60-80% of building energy consumption is due to heat loss from building envelope [1]. Among them, about 30-40% of the building heat loss occurs at glazing unit [1]. In order to improve thermal performance of glazing, the concept of PCM glazing was first proposed 20 years ago [2], and main research directions are briefly described below.

https://doi.org/10.25855/SFT2022-095

Study of thermal and optical parameters of PCMs. Different climate regions have different requirements for phase change temperature [3-5]. Usually, high phase change temperature is more suitable for summer, while the lower one is better for winter [3-4]. The absorbance, reflectance and transmittance of PCM were studied by Francesco Goia et al. [6]. Linyang Wei et al. has found the absorption coefficient has a greater impact than refractive index [7]. Similar results were reported by Yuan Gao et al. [5].

Analysis of application effect of PCM glazing in a certain climate. According to Daniel Uribe et al., PCM glazing can possess good performance in summer, while they have no significant effect in winter [8], the conclusion is similar with some research [9]. However, not all studies have concluded PCM is not suitable for winter: Francesco Goia et al [10], PCM glazing provided better indoor thermal conditions during most of the time in a whole year.

PCM layer thickness study. Changyu Liu et al. investigated the suitable thickness of PCM layer in northeast China [4], and the thickness of 12–20 mm is recommended. Dong Li et al. also conducted a similar study in northeast China [11], but their findings were different: increasing the thickness from 9 mm to 16 mm had no significant effect.

Generally, previous study usually limits the research to a certain climate, then the effect of season/weather, physical parameters and layer thickness of PCM will be analyzed. In contrast, there is a lack of research in different climate. Thus, numerical simulation has been conducted to analyze the application effect of PCM glazing under different climate conditions in this paper.

2. Methodology

2.1. Physical model

Incident solar radiation can be divided into three parts: reflecting, absorbing and transmitting portion. In this study, the glazing unit consists of two layers of glass (each layer has a thickness of 4 mm) and one layer of PCM (layer thickness of 14 mm), shown in figure 2.1.

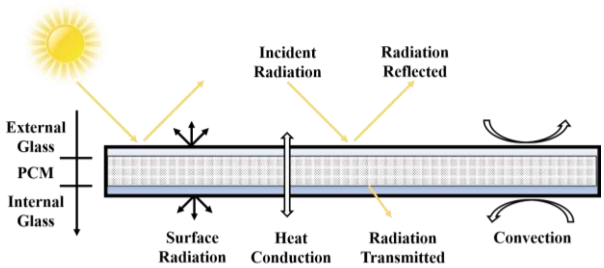

Figure 2.1: *Physical model of PCM glazing unit*

2.2. Mathematical model

The mathematical model for glazing unit consists of two parts: (1) energy conservation equation (for temperature field); (2) radiation transfer equation (for radiation intensity distribution). Solar radiation absorbed by glazing unit can be derived from radiation transfer equation, which will be the radiative heat source term in energy conservation equation.

2.2.1. Heat transfer inside glazing unit

The heat transfer process of glazing unit is described in equation (1a) for glass region and equation (1b) for PCM region.

$$\rho_g C_g \frac{\partial T}{\partial t} + \nabla \cdot \left(-\lambda_g \nabla T\right) - Q_r = 0 \tag{1a}$$

$$\rho_p C_p \frac{\partial T}{\partial t} + \nabla \cdot \left(-\lambda_p \nabla T\right) - Q_r = 0 \tag{1b}$$

where, ρ is density, (kg.m^{-3}); C is specific heat capacity at constant pressure, (J.kg^{-1}.K^{-1}); T is temperature, (K); t is time, (s); λ is thermal conductivity, (W.m^{-1}.K^{-1}); Q_r is radiative heat source term, which gives the net amount of solar radiation absorbed by glazing, (W.m^{-2}).

Regarding the calculation in the region of PCM, there are also the following formulas,

$$\rho_p = [1 - B(T)]\rho_{p,s} + B(T)\rho_{p,l} \tag{2a}$$

$$\lambda_p = [1 - B(T)]\lambda_{p,s} + B(T)\lambda_{p,l} \tag{2b}$$

$$C_p(T) = \begin{cases} C_{p,s}, \text{ if } T < T_m - \Delta T/2 \\ \dfrac{1}{\rho}\left\{\left[1 - B(T)\right]\rho_s C_{p,s} + B(T)\rho_l C_{p,l}\right\} + L_f \dfrac{\partial \alpha_m}{\partial T}, \text{ if } T_m - \Delta T/2 \le T \le T_m + \Delta T/2 \\ C_{p,l}, \text{ if } T > T_m + \Delta T/2 \end{cases} \tag{2c}$$

$$B(T) = \begin{cases} 0, \text{ if } T < T_m - \Delta T/2 \\ (T - T_m + \Delta T/2)/\Delta T, \text{ if } T_m - \Delta T/2 \le T \le T_m + \Delta T/2 \\ 1, \text{ if } T > T_m + \Delta T/2 \end{cases} \tag{2d}$$

$$\alpha_m = \tfrac{1}{2} \bullet \{B(T)\rho_{p,l} - [1 - B(T)]\rho_{p,s}\}/\rho_p \tag{2e}$$

where $B(T)$ is volume fraction of liquid PCM; L_f is latent heat, (J.kg^{-1}); T_m is melting point of PCM, (K); ΔT is transition interval of PCM, (K); α_m is a transition function, which is equal to -1/2 before phase transformation and 1/2 after phase transformation, together with latent heat makes specific heat capacity in phase transition process much higher than that in solid and liquid state. Table 2.1 summarizes the main thermal physical parameters of PCM.

	ρ_p	L_f	λ_p	C_p	T_m	ΔT
	kg.m^{-3}	J.kg^{-1}	W.m^{-1}.K^{-1}	J.kg^{-1}.K^{-1}	K	K
PCM	789	140000	0.18(s),0.22(l)	2300(s),2100(l)	301.15	2

Table 2.1: *Thermal physical parameters of PCM*

In order to solve the energy equation, boundary conditions are needed. There are two types of heat exchange between the surface of glazing unit and environment (including indoor and outdoor environment): convection and surface radiation, as shown in equation (3),

$$-\lambda_g \frac{\partial T}{\partial x} = h\left(T - T_{amb}\right) + \varepsilon\sigma\left(T^4 - T_{amb}^4\right) \tag{3}$$

where h is the convective heat transfer coefficient, and the value of h is 17 and 8 (W.m^{-2}.K^{-1}) for outdoor and indoor environment, respectively; ε is surface emissivity; $\sigma = 5.67 \times 10^{-8}$ (W.m^{-2}.K^{-4}) is Stefan's constant.

2.2.2. *Radiation transfer inside glazing unit*

In practical engineering, PCM will interact with solar radiation by three types of mechanisms: absorption, scattering, and emission. The balance of the radiation intensity in glazing can be written as: change in radiative intensity = gain due to emission − loss due to absorption − loss due to out-scattering + gain due to in-scattering, shown in equation (4),

$$dI(s,\Omega) = \kappa I_b(T)ds - \kappa I(s,\Omega)ds - \sigma_s I(s,\Omega)ds + \frac{\sigma_s}{4\pi}\int_{4\pi} I(s,\Omega')\cdot\phi(\Omega',\Omega)d\Omega' \quad (4)$$

where $I(s,\Omega)$ is radiation intensity in the location of s from Ω direction, (W.m^{-2}.sr^{-1}); $I_b(T)$ is the blackbody radiation intensity and calculated by Stefan-Boltzmann law; κ and σ_s are absorption and scattering coefficients, (m^{-1}); $\phi(\Omega',\Omega)$ is the scattering phase function, which gives the probability that a ray coming from one direction Ω' is scattered into the direction Ω.The boundary condition for equation (4) is radiative intensity entering glazing unit along the Ω direction as shown in figure 2.2, which is calculated by equation (5):

$$I(0,\Omega) = \varepsilon I_b(T) + \frac{\rho_d}{\pi} q_{r,out} + \tau I_{ext}(\Omega) \quad (5a)$$

$$q_{r,out} = \int_{n\cdot\Omega>0} I(\Omega)(n\cdot\Omega)d\Omega \quad (5b)$$

where ρ_d is surface diffuse reflectance; $q_{r,out}$ is the heat flux inside glazing striking the surface, (W.m^{-2}); τ is surface specular transmittance; I_{ext} is exterior radiation intensity, (W.m^{-2}.sr^{-1}).

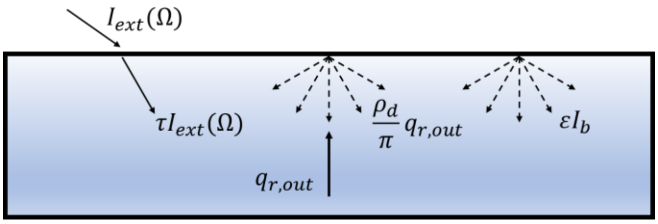

Figure 2.2: *Radiative intensity entering glazing unit along the Ω direction*

Radiative heat source term in equation (1) can be obtained from equation (6):

$$Q_r = \nabla\bullet q_r = \nabla\bullet[\int_{4\pi} I(s,\Omega)\Omega d\Omega] \quad (6)$$

The table 2.2 summarizes optical parameters of PCM and glass used in numerical simulation.

	ε	κ	σ_s	n
	-	m^{-1}	m^{-1}	n
PCM	-	30	5	1.4
Glass	0.8	10	0	1.4

Table 2.2: *Optical parameters of PCM and glass*

2.2.3. *Classification method of climate conditions*

This section is mainly about the classification method of climate conditions. First, two climate stations were randomly selected in each province of China (23 provinces in total). Then three types of summer climate data, including daily mean temperature (MT), daily mean solar radiation intensity (MSRI), and diurnal temperature range (DTR) were collected. The relationship between these data was then analyzed, as shown in figure 2.2-2.4.

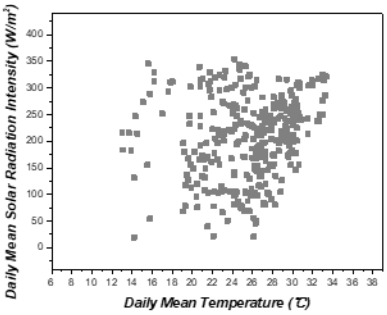

Figure 2.2: *MSRI and MT*

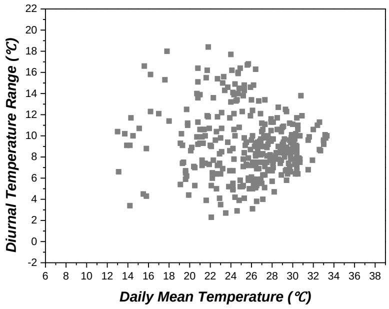

Figure 2.3: *DTR and MT*

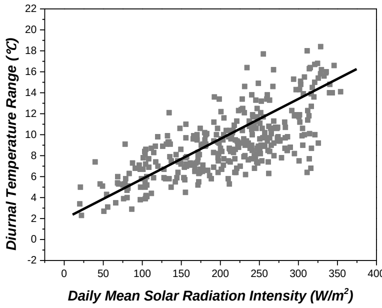

Figure 2.4: *DTR and MSRI*

From figure 2.2-2.3, no obvious relationship has been found. However, a significant positive correlation exists between DTR and MSRI, i.e., strong MSRI is usually accompanied by large DTR, while weak MSRI is normally accompanied by small DTR. Considering fact that thermal performance of PCM glazing is closely related to DTR and MSRI, the working conditions in the simulation are set as shown in table 2.3.

	MT	*Case number*
Strong MSRI & Large DTR	High MT	Case 1 & Case 2
	Medium MT	Case 3 & Case 4
	Low MT	Case 5 & Case 6
Weak MSRI & Small DTR	High MT	Case 7 & Case 8
	Medium MT	Case 9 & Case 10
	Low MT	Case 11 & Case 12

Table 2.3 *Working conditions in numerical simulation*

3. Results and discussions

3.1. Validation of numerical model

The numerical simulation software used in this study is COMSOL®. In order to ensure the accuracy of simulation results, the grid independence test is firstly carried out. Then the simulation data was compared with experimental data from previous literature [12], shown in figure 3.1-3.2. It can be seen from the figure that the maximum error from experiment and simulation is about 1.5°C, which is acceptable. One of main reason for the error may be that the climate data used in simulation are the average value per hour, rather than real-time data.

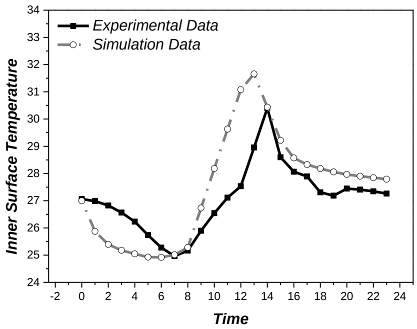

Figure 3.1: *Summer sunny day*

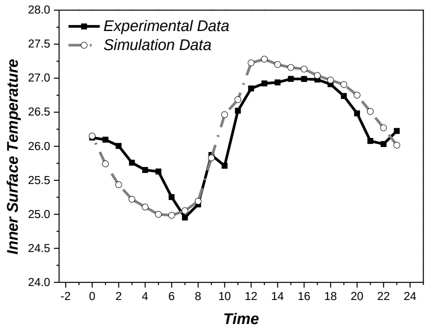

Figure 3.2: *Summer rainy day*

3.2. Comparison between PCM glazing and conventional glazing

This section will focus on comparing thermal performance of PCM glazing unit with conventional glazing (i.e., double layer glazing unit with the cavity filled with air), T_{sur} (℃) and Q_{total} (W) will be the evaluation indicators, where Q_{total} is the sum of convective and radiative heat exchange between inner surface of glazing and indoor environment, and the transmitted parts of solar radiation. Figure 3.3-3.4 have shown the simulation results from case 4, which is the condition of strong MSRI, large DTR and medium MT.

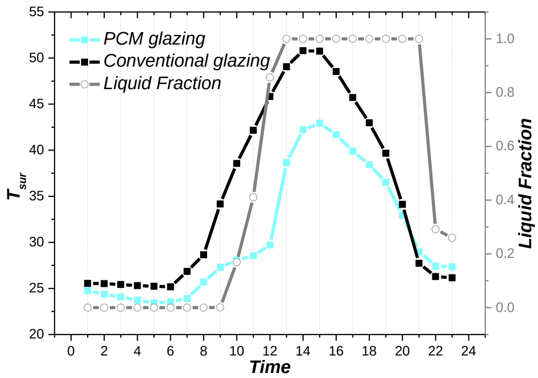

Figure 3.3: *Comparison between PCM glazing and conventional glazing by T_{sur}*

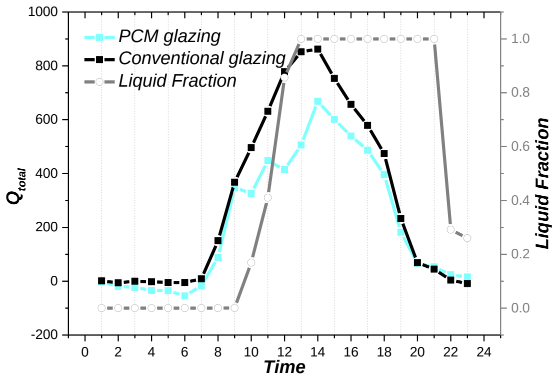

Figure 3.4: *Comparison between PCM glazing and conventional glazing by Q_{total}*

According to the results in figure 3.3, the application of PCM significantly reduces T_{sur}, peak difference between PCM glazing and conventional glazing reaches to about 16℃, 24-hour average difference is 5℃. The conclusions regarding Q_{total} are still very similar, with a peak difference of 364 W and a 24-hour average difference of 20 W for the two kinds of glazing unit, respectively. In addition to the "weakening effect" on T_{sur} and Q_{total}, the simulations also showed another function of PCM glazing: the peak value is delayed by about 1 hour after the use of PCM, both in terms of T_{sur} and Q_{total}. In fact, not only in case 4, but also in all climate conditions, PCM glazing has shown a better thermal performance compared with conventional glazing: T_{sur} and Q_{total} are reduced by 1%-19% and 4%-80%, respectively.

There are two main reasons for the ability of PCM glazing to reduce T_{sur} and Q_{total}: (1) high absorption coefficient (usually 30-40 m^{-1}) of solid PCM for solar radiation outside the visible wavelength range and (2) strong heat storage capacity compared to conventional glazing. High absorption coefficient makes it difficult for solar radiation to enter indoor environment directly, while strong heat storage capacity enables PCM glazing to store the absorbed heat inside the glazing cavity. However, high absorption coefficient and strong heat storage capacity are characteristics that only belong to solid PCM, and both of these characteristics will become insignificant when PCM is liquefied. This phenomenon is also reflected in figure 3.3-3.4, where the value of T_{sur} and Q_{total} of PCM glazing increased dramatically when the liquid phase fraction becomes 100%.

3.3. Applicability analysis of PCM glazing in different climates

The main content of this section is to analyze the applicability of PCM glazing unit under different climate conditions. First, the analysis will start from the perspective of T_{sur}, shown in figure 3.5. The ordinate is the ratio of $T_{sur,\ with\ PCM}$ to $T_{sur,\ without\ PCM}$, represents the T_{sur} of PCM glazing and conventional glazing, respectively. Therefore, a smaller ratio means: PCM glazing is more applicable in the certain climate, whereas the larger the ratio, the less suitable it is. From figure 3.5, the average height of blue bars is lower than that of black, which means PCM glazing can perform better in a climate with strong MSRI and large DTR (T_{sur} is reduced by 13% on average) rather than the climate of weak MSRI and small DTR (T_{sur} is reduced by 6% on average) viewed from T_{sur}. There are two reasons for this. Firstly, one of the main differences between PCM glazing and ordinary glazing is that PCM have a high absorption coefficient of solar radiation. Therefore, the stronger the solar radiation is, the better PCM glazing will perform its characteristics. Secondly, PCM needs to release the absorbed heat to outdoor environment as soon as possible at night. At this time, large DTR conditions enable PCM to complete the heat release process in the shortest time and reduce the adverse effects of PCM glazing on indoor thermal environment at night.

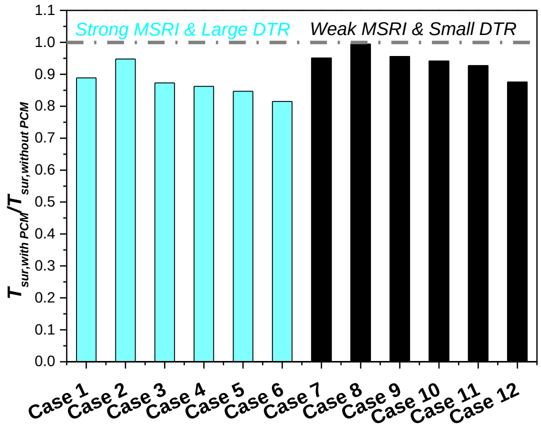

Figure 3.5: *Applicability analysis by* T_{sur}

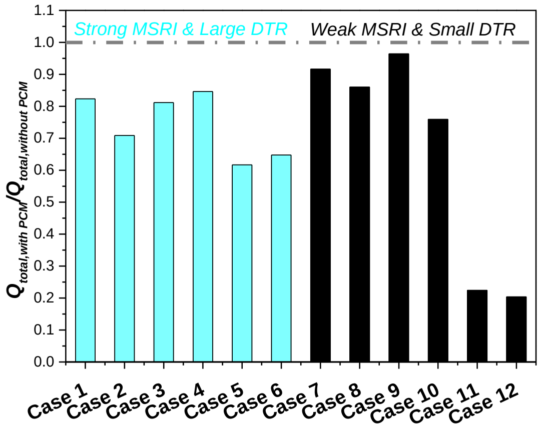

Figure 3.6: *Applicability analysis by* Q_{total}

Figure 3.6 then analyzes the applicability in terms of Q_{total}. As can be seen in the figure, the height of black bars is lower than blue bars. This indicates that PCM glazing can have better applicability in weak MSRI and small DTR conditions (Q_{total} is decreased by 35% on average) compared to strong MSRI and large DTR conditions (Q_{total} is decreased by 26% on average).. This conclusion seems to be inconsistent with the general law, that is, strong MSRI and large DTR are suitable for the characteristics of PCM. The reason for this result may be that: in this simulation, solar radiation intensity is too high in strong MSRI and large DTR conditions (mean value in a day: 242W/m^2-354W/m^2), and the heat storage capacity of PCM is not enough (perhaps the amount of PCM is not enough, or the specific heat capacity and latent heat of the selected PCM is not large enough). Under these two factors, PCM melts completely prematurely, as shown in figures 3.3-3.4: liquid fraction has already turned to 100% at 1:00 pm. The absorption coefficient and thermal storage capacity of PCM will be significantly reduced after melting process. Considering that the thermal conductivity of PCM is greater than that of air, if PCM in glazing unit are completely molten, it may fail to improve the indoor thermal environment and reduce building energy consumption, but also produce negative effects. Therefore, matching the heat storage capacity of PCM of glazing unit to the outdoor climate conditions is crucial for the application of PCM glazing. The heat storage capacity matched to climate parameters allows PCM to remain solid for a longer period of time to avoid overheating problems.

4. Conclusion

This paper analyzed the relationship between three climate parameters that are closely related to the thermal performance of PCM glazing and a significant positive correlation between MSRI and DTR has been found. Then PCM glazing is compared with conventional glazing: PCM glazing has shown better performance in all conditions. Finally, the applicability of PCM glazing was evaluated in different climate conditions. Unlike the conclusions drawn from T_{sur}, when Q_{total} used as the evaluation index, PCM glazing did not perform well under strong MSRI and large DTR conditions. This indicates whether the heat storage capacity of PCM glazing units matches the outdoor climate parameters plays a crucial role in its application effect. The cost of PCM glazing units will be increased and indoor light environment will be adversely affected, if excess PCM is filled into the glazing cavity. On the contrary, if the heat storage capacity of glazing unit is insufficient, PCM will be completely melted prematurely, which will make it not only unable to effectively improve indoor thermal environment and even have adverse effects.

References

[1] E. Cuce, S. B. Riffat, A state-of-the-art review on innovative glazing technologies, Renewable and Sustainable Energy Reviews, 41 (2015), 695-714.

[2] H. Manz, P. W. Egolf, P. Suter and A. Goetzberger, TIM–PCM external wall system for solar space heating and daylighting, 61 (1997), 369-379.

[3] S. Zhang, Y. Ma, D. Li, C. Liu, R. Yang, Thermal performance of a reversible multiple-glazing roof filled with two PCM, Renewable Energy, 182 (2022), 1080-1093.

[4] C. Liu, Y. Wu, J. Bian, D. Li, X. Liu, Influence of PCM design parameters on thermal and optical performance of multi-layer glazed roof, Applied Energy, 212 (2018), 151-161.

[5] Y. Gao, Q. Zheng, J. C. Jonsson, S. Lubner, C. Curcija, et al., Parametric study of solid-solid translucent phase change materials in building windows, Applied Energy, 301 (2021), 117467.

[6] F. Goia, M. Zinzi, E. Carnielo, V. Serra, Spectral and angular solar properties of a PCM-filled double glazing unit, Energy and Buildings, 87 (2015), 302–312.

[7] L. Wei, G. Li, M. Song, C. Wang, Study on dynamic thermal behavior of double glazing unit filled with phase change materials, Energy Research, 45 (2021), 20672–20685.

[8] D. Uribe, S. Vera, Assessment of the Effect of Phase Change Material (PCM) Glazing on the Energy Consumption and Indoor Comfort of an Office in a Semiarid Climate, Applied Sciences, 11 (2021), 9597.

[9] S. Zhang, W. Hu, D. Li, C. Zhang, Müslüm Arıcı, et al., Energy efficiency optimization of PCM and aerogel-filled multiple glazing windows, Energy, 222, (2021) 119916.

[10] F. Goia, M. Perino, V. Serra, Improving thermal comfort conditions by means of PCM glazing systems, Energy and Buildings, 60 (2013), 442–452.

[11] D. Li, Y. Wu, G. Zhang, Müslüm Arıcı, C. Liu, et al., Influence of glazed roof containing phase change material on indoor thermal environment and energy consumption, Applied Energy, 222 (2018), 343-350.

[12] K. Zhong, S. Li, G. Sun, S. Li, X. Zhang, Simulation study on dynamic heat transfer performance of PCM-filled glass window with different thermophysical parameters of phase change material, Energy and Buildings, 106 (2015), 87–95.

Acknowledgements

I am grateful to my supervisors Prof. Yi WANG and Prof. Mustapha KARKRI for their great patience in guiding me how to conduct research and also the continuous help from them. Besides, the research is funded by China Scholarship Council, grant number: 202107837002.