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Investigation of effective parameters on thermal performance of multilayered glazing units integrated with Phase Change Material

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Abstract —**The building sector accounts for more than 33.33% of final energy consumption, globally as the largest energy consumption sector. Among building elements, windows are considered as a key one in improving energy efficiency of the buildings and providing thermal comfort especially in the buildings with large glazing area. In order to increase the energy saving through fenestration systems, numerous active and passive techniques have been introduced and investigated by many researchers. Integration of energy efficient material like PCM (phase change material) into the glazing units is considered as one of these techniques. PCMs or phase change materials are potential to store and release a significant amount of energy during the phase change process due to their high heat of fusion. According to the studies investigated for this research, two types of PCMs are utilized in building constructions: Solid-Liquid PCMs (S-L PCMs) and Solid-Solid PCMs. Compared with S-L PCMs, the S-S PCM has advantages including: no leakage, less phase segregation, small volume change and no variation of optical properties. This research investigated the studies concerning the PCM-incorporated into glazing units (PCM_GU) and it highlighted the effective parameters on the energy performance of PCMs utilized in glazing units.**

Keywords- Phase change material, energy saving, glazing units, PCM-integrated buildings, Heating/cooling load reduction

1. Introduction

During recent years, energy demand and consumption increased significantly due to the rapid population growth, consequently leads to severe environmental issues like global warming. According to International Energy agency (IEA) [1], the energy consumption of the buildings in terms of cooling load will be increased between 300% and 600% in developing countries and around 150% globally in 2050. In order to enhance energy efficiency of the buildings and ameliorate environmental problems, active and passive techniques are increasingly utilized in new constructions and as a renovation approach in existing buildings. Integration of PCM into building constructions can be considered as one of these techniques due to their capability of latent heat storage. All of the PCM types are not suitable for building construction and they have to fulfill the required features. Sharma et al. [2] and Kośny [3] determined four major groups of necessary properties of PCMs to be utilized in building constructions. These groups include: thermal properties, chemical properties, physical properties, economical properties. Each category of properties is summarized in Table 1.

Table 1, Necessary properties of PCMs to be utilized in building constructions **[4]**

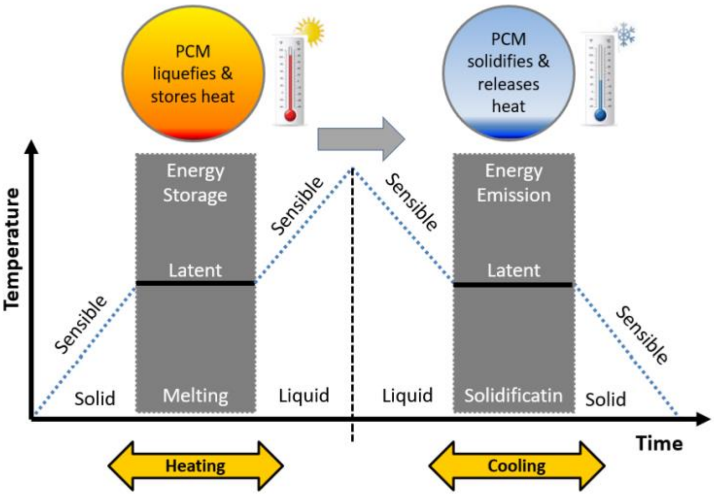
Thermal Properties	Chemical Properties	Physical Properties	Economical Properties
Melting point should be the temperature range of operating environment	Long-term chemical stability	Phase stability	Available
Another entry The coordination in heating or cooling temperatures of operation to cross the heat during the cycles	Compatibility with other materials and components	High density	
High latent heat to minimize the size of PCM as thermal mass storage	Non-flammable, non-oxidizing, non-explosive and also nontoxic.(According to fire safety codes)	Small volume change	
High thermal conductivity to improve the charge and discharge cycles			

During this study, the studies concerning PCM incorporated into the fenestration systems are investigated and the major factors that influence the energy performance of PCM are discussed.

2. The concept of PCM

PCMs or phase change materials have the potential to absorb and release heat during the phase transition process (almost from solid to liquid and vice versa) while maintaining the temperature at an approximately constant range due to the isothermal behavior. During the melting (charging) process PCMs absorb heat and conversely, during the freezing (discharging) process they release it [5] as shown in Figure 1. PCMs are capable to repeat the cycle continuously without losing their properties [6], consequently could be utilized to control indoor temperature [7].

Figure 1, The concept of PCM during melting-solidification cycles **[4]**



3. PCM application in building construction

PCM utilization in building construction consists of various fields like insulation, roof material, wall finishing, solar system, playing fields, radiant heat, and raised flooring panels [4]. Applied PCMs in building enclosures lead to a reduction of air-conditioning energy consumption per unit area [10]. Castell et al. [8]indicated that PCMs can reduce annual energy consumption more than 15% in a building with air-conditioning system. PCM utilization in building enclosures is not only in opaque enclosures but also it can be used in transparent systems like glazing units. According to Kośny [3], PCMs can be considered as an efficient option in fenestration systems as the glazing units can consume a significant amount of energy in the building [3].

4. The effect of PCM on energy saving

The potential of PCMs in terms of saving heat and energy is noticeable. For instance; in the same condition of temperature variations and thickness, PCMs are capable to store about six times more energy than concrete and three times more energy than water [9]. Therefore, they are capable to save and release a significant amount of heat per limited volume. [5] In conclusion, PCM is a less volume, lightweight material in comparison to the conventional material like concrete and can be utilized in passive or active systems [4] to improve the energy demand management and shift the peak-load.

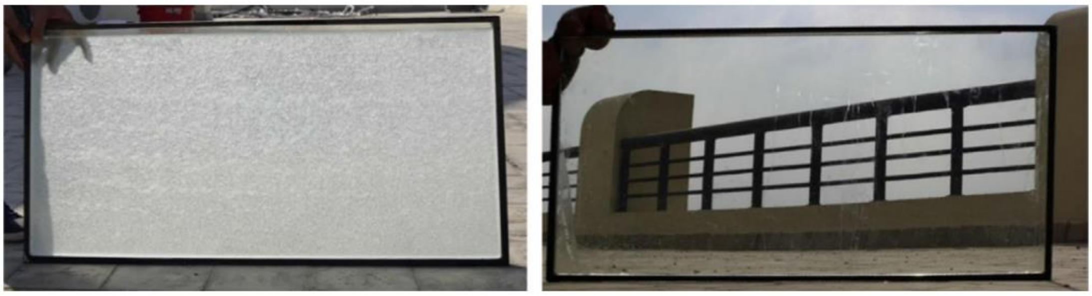
5. PCM in glazing units

The thermal performance of PCM windows is the same as transparent or translucent Tromb walls. The purpose of incorporation of PCM into glazing units is to utilize their high latent heat of fusion to reduce thermal load generated by fenestration system through the absorbance of heat gain before it reaches to the interior space. The PCM window consists of a single or multilayers of glazing like conventional glass and a layer of transparent or translucent PCM [3]. According to the studies investigated in this research, current application of PCM in fenestration systems involves solid-liquid PCMs (S-L PCMs) and/or solid-solid PCMs (S-S PCMs).

5.1 *S-L PCM*

In order to use the S-L PCMs in fenestration systems, it is almost embedded inside the window cavities. According to Kośny [3], during the day, PCM absorb heat and changes its phase from solid to liquid and also its translucency changes [usually from opaque to transparent]. During the night, or when the ambient temperature is decreased, the melted PCM releases the absorbed heat and changes its phase to liquid. Similarly, the translucency changes [usually from transparent to opaque]. Figure **2** shows a double glazing window (DGW) which is filled with S-L PCM in solid and liquid phases.

Figure 2, A DGW filled with S-L PCM. left: PCM in liquid phase. right: PCM in solid phase **[10]**



5.2 *S-S PCM*

Solid-Solid phase change material or S-S PCM is a film material has a thin, transparent or translucent coating and is embedded on the window pane (Figure **3**) or utilized stand-alone as a transparent or translucent surface of the building's enclosure (Figure **4**). According to Fallahi et al. [11], S-S PCMs -Like other PCMs- are able to absorb and release heat during the reversible phase transition process. The main difference between solid-solid PCMs and solid-liquid PCMs is that S-S PCMs can retain their bulk solid properties in certain temperature ranges therefore; they are referred as "solid-state" PCMs as well. Their phase change cycle involves from a (solid) crystalline or semi-crystalline phase, to another (solid) amorphous, semi-crystalline, or crystalline phase.

5.3 *Advantages of S-S PCM*

Unlike S-L PCMs, the S-S PCMs avoid leakage problems, so they can be blended with other materials without encapsulation. Moreover, their volume change and phase segregation are much lower in comparison to S-L PCMs. These features prevent degradation upon thermal cycling and consequently, extend their durability which is important for building applications that require long term performance [11]. Another study mentioned that although S-L PCM in liquid phase provides visual comfort and excellent view of sky, it negatively influences these factors in solid phase [12].

Figure 3, The DGW with translucent S-S PCM on the interior glazing **[13]**

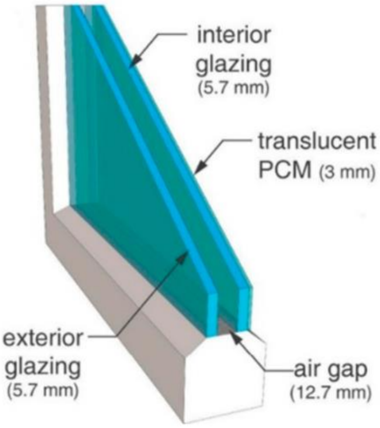


Figure 4, The solid-solid phase transition. Left: cold, crystalline, and opaque. Right: hot, amorphous, transparent **[14]**

6. Effective factors in PCM performance

Although the PCMs can improve the energy performance of the building, they will lead to some of the problems in case of inappropriate type of PCM selection. In order to achieve maximum energy efficiency of the PCM integrated in to the glazing units, a number of factors investigated by several researchers should be considered in terms of PCM selection. This paper investigated some of these items including: climate condition, phase transition temperature of PCM, position of PCM, window orientation, the thickness of PCM layer, solar irradiation and the form of fenestration system.

6.1 *Climate conditions*

Climate condition is one of the key factors in terms of PCM selection for building applications, especially in locations with changeable climates [15]. According to Madhumathi and Sundarraja [16] in hot and dry climates, due to the diurnal temperature difference, PCMs decrease the absorbed heat during the day and can perform more effectively in terms of interior thermal comfort. Another study also mentioned PCM as one of the most appropriate options for arid and semi-arid regions particularly in case of maximum solar irradiation and peak load [17].

Gao et al. [13] conducted a parametric study using EnergyPlus simulations to identify the energy saving contributions and optimize the optical and thermal properties of S-S PCM integrated into a double glazing window. The S-S PCM with 3mm thickness is located on the interior surface of the inner pane of the double glazing system (Figure **4**) and is evaluated in warm, mixed, cold climate conditions. The results showed that compared with conventional double glazing window, the aforementioned fenestration system with optimal properties in warm, mixed, cold climates is respectively potential to save up to 17.2%, 14.0%, and 5.8% energy for the HVAC system and 9.4%, 6.7%, and 3.2% energy for the whole building. Xia et al. [14] numerically investigated the thermal and optical performance of S-S PCM based coating located on the exterior surface of the building enclosure in warm and cold climate. The result indicated that the S-S PCM coating is capable to achieve more energy saving in warm climate compared to the cold climate.

6.2 *Phase transition temperature (PTT)*

Wieprzkowicz and Heim [12] conducted experimental and numerical investigations to study the effect of triple glazed PCM-window on cooling and lighting energy, thermal and visual discomfort, glare effect. Five different PCMs including RT18HC, RT22HC, RT25HC, RT28HC, and RT31 were utilized to fill the outermost cavity of the fenestration system. The researchers concluded that there is no optimal unit type of PCM for this system. The results also revealed that paraffin RT25HC and RT18HC demonstrated the most effective performance respectively for east and west orientation. According to thermal and visual comfort analysis, the PCM with the lowest melting temperature is the most suitable one for both west and east orientations. In order to obtain the most effective utilization of PCM properties, the researchers suggested dividing the window into two parts. The central or lower part of the window is suggested to be filled with the PCM selected based on the comfort factors to assure the highest possible view out and the upper half of the window should be filled with a PCM which provide overheating protection according to the energy demand results. Moreover, Xia et al. [14] suggested the optimal phase transition temperature for S-S PCM coating which is located on the roof should be set as the same as the desired temperature of the room.

6.3 *Orientation*

According to Gao et al. [13], the orientation of PCM window can influence optimal properties of the PCM. When the PCM window is facing west or east, the optimal phase change temperature is increased due to the reduced solar altitude angles. The lowest optimal phase change temperature belongs to the PCM windows located in the north orientation. Xia et al. [14] indicated that S-S PCM coating can contribute to reduce the undesirable heat exchange in all orientation. Moreover, in order to achieve the maximum energy saving and thermal efficiency they suggested to utilize the S-S PCM coating on the roof. As mentioned above, Wieprzkowicz and Heim [12] modelled and experimentally investigated the triple glazed PCM-window facing east and west orientations. The result showed that for east oriented PCM window paraffin RT25HC has the most effective performance however; RT18HC is the most effective PCM in west-facing PCM windows. They also indicated that according to the thermal and visual comfort analysis, the PCM with the lowest melting temperature could be the best option for both east and west orientations. In addition, Iennarella et al. [18] proposed a novel system called transparent Responsive Building Elements (RBE) in order to minimize the energy consumption of lighting and HVAC systems. The energy performance of this novel system was investigated for different orientations. The results showed that the advantages performance of this system for south, west, east orientations was evident however its performance reduced for north orientation due to the scarce activation of PCM during the summer. The study also revealed that the reduction of active layers' thickness from standard thickness (60 mm for aerogel and 27 mm for PCM) to 15mm (for both of them) doesn't make negative effect on the combined lighting, cooling and heating performance for south, north, east orientations however, the reduced thickness of active layers was performed less than standard thickness for west orientation.

6.4 *PCM position*

Goia [19] conducted numerical simulations to investigate the influence of PCM glazing configurations in a humid subtropical climate (Cfa). The simulations are carried out for various triple glazing configurations, where one of two cavities is filled with a PCM and the other one is filled with Argon. The thickness of each cavity is 15mm and the simulations are conducted for “typical days” of each season. The result revealed that the position of PCM layer has an influence on thermo-physical behavior of PCM window. The PCM windows (especially the ones with the PCM inside the outermost cavity) can be beneficial in terms of thermal comfort.

6.5 *Solar irradiation*

Goia et al. [20] carried out experimental and numerical investigations to compare the thermal performance of PCM-incorporated Double glazing window with a conventional double glazing window. Figure **5** represents the test cells including double glazing unit clear glass (DGU_CG) and double glazing unit PCM (DGU_PCM). The result revealed that the PCM glazing window is capable of thermal comfort improvements, and its performance would be more efficient during the time that solar irradiation increases. However, the DGU_PCM performance is the same as conventional double glazing units during the cloudy days. Moreover, the study indicated that incorporation of PCM into glazing units can minimize the glare risk and improve eye comfort.

Liu et al. [21] studied thermal and optical performance of PCM-double glazing window by conducting experimental investigations. They evaluated the effect of several factors like solar irradiation and melting temperature. The result showed that the transmittance of PCM in liquid phase is almost 1 and melting temperature of PCM doesn’t have any effect on it, while the PCM’s melting temperature has a significant impact on the transmittance in solid phase. Moreover, the result revealed that the transmittance of the double glazing window with PCM in liquid phase is 50%. Another research has studied the energy performance of a triple-pane window filled with PCM (TW+PCM) in both sunny and rainy summer days of Nanjing, China. This system is compared with two reference windows including double-pane window filled with PCM (DW+PCM) and triple pane window (TW). All of the three configurations are located on the south facing wall. The authors indicated that in the summer sunny day, the peak temperature on the interior surface of TW+PCM reduces 2.7°C and 5.5°C respectively in comparison to DW+ PCM and TW. Moreover, heat entered the building reduces 16.6% and 28% respectively. The TW+PCM also has the potential to reduce temperature fluctuation of the interior surface and heat entered the building in the rainy summer day [22].

Figure 5, Test cells employed by Goia et al. **[20]**, composing DGU clear glass and DGU-PCM

6.6 *PCM quantity/thickness*

This parameter determines the amount of saved energy. The amount of PCM should be: Not small; due to limited heat stored and early reach to full liquid state and; Not large; due to the restriction of heat from passing through the element, more time for discharge however, negative impact on the mechanical strength.

Bolteya et al. [10] conducted experimental investigations to study the thermal efficiency of a double glazing unit filled with Phase change material (PCM-filled DGU). Then, the effect of PCM layer thickness on thermal efficiency of this system was evaluated by using ANSYS FLUENT. The result revealed that the PCM has a significant effect on room temperature. The peak temperature time lag of the internal layer in PCM-filled DGU was around 3 hours more than the one for conventional double glazing system. Moreover, increasing the thickness of PCM layer can improve thermal performance however, for the PCM with more than 30mm the variation trend can be reversed.

As mentioned in the previous sections, novel system called transparent Responsive Building Elements (RBE) was proposed by Iennarella et al. [18] to minimize the energy consumption of lighting and HVAC systems. The transparent RBE consists of three glazing parts: a low-E selective glass, a PCM filled double-pane glazing for solar control, an aerogel filled double-pane glazing for thermal insulation. The low-E glass is in a fixed position (“passive” layer) and the other two parts can move automatically behind it or in front of it (“active” layer). The researchers carried out the simulations in DIVA-for-Rhino to use in synergy two dynamic simulation tools, Energy Plus and Daysim. According to the results, the transparent RBE system is potential to reduce annual primary energy consumption compared to the double-pane low-E glazing system. Moreover, the result showed that PCM and the aerogel modules are active not only during the summer, but also they continuously during the whole year. In addition, the reduction of active layers’ thickness from standard thickness (60 mm for aerogel and 27 mm for PCM) to 15mm (for both of them) doesn’t make negative effect on the combined lighting, cooling and heating performance for all of the orientation except the west one.

Liu et al. [23] carried out experimental and numerical researches to study the thermal performance of a four-glazed unit that the middle cavity is filled with PCM. According to the research, the PCM thickness has a significant effect on thermal and solar transmittance performance of a multilayer glazing unit. The result showed that increasing the PCM thickness can improve the thermal performance of the glazing unit while the reduction of solar transmittance is considerable. Therefore, the researchers suggested utilizing the PCM with the thickness not larger than 20mm. Another study recommended utilizing PCM layers with the thickness less than 16mm to maintain optical performance of the fenestration [21].

6.7 *The fenestration shape*

Tafakkori and Fattahi [24] proposed some novel configurations of double-glazed windows to reduce the energy consumption of the building during a typical hot day on 15 July in the climate condition of Tehran. The configurations include: simple cubic (reference), partition-arranged simple cubic, simple cubic with cylindrical wall, trapezoidal prism, partition-arranged trapezoidal prism and trapezoidal prism with cylindrical wall. Also, the window cavities are considered to be filled with air or PCM. The results indicated that the proposed configurations are capable to reduce energy consumption of the building by around 20%. Moreover, utilizing PCM for window cavities instead of air can improve the thermal performance of the fenestration system and the drastic decrease of Nusselt number, by a factor of 4, was observed.

The aforementioned research papers are summarized in **Table2** and **Table3.** For each research, the investigated factors and a summary of the results are mentioned.

7. Conclusions

This study showed that the research on PCM windows is a constantly progressing field due to their beneficial aspects contributes to the building’s energy saving. The most investigated effective factors in terms of energy performance of PCM windows are explored and their contributions are explained. The main results of this paper include:

- In locations with the greater solar heat gain, PCM performs better. In addition, it is more efficient during summer and on clear days.
- The thickness of PCM is one of the main factors in terms of energy performance of PCM. Although several studies have stated that increasing the thickness of PCM layer can improve thermal performance, they also indicated that the variation trend can be reversed for the PCM with more than a specific amount of thickness.
- Compared with S-L PCMs, S-S PCMs are more applicable in the glazing units due to their advantages. S-S PCMs avoid leakage problems, so they can be blended with other materials without encapsulation. Moreover, small volume change and less phase segregation lead to extension of their durability which is important for building applications that require long term performance.

Much further empirical evidence is needed to investigate the factors influence on the efficiency of S-S PCM integrated into the glazing units. Qualitative post-occupancy studies are also particularly deficient. There is an evident need for research including evaluation of the occupants’ satisfaction with building comfort together with exploring their understanding and knowledge of the importance of PCM glazing units.

Table 2, Summary of PCM-incorporated fenestration systems, part 1

Glazing System	The PCM type and PTT (°C)	Method	Climate code	orientation	Thermal Performance	The parameters investigated	Results	Ref.
TGW + S-L PCM	Paraffin wax (25,30,35)	N	Cfa	South	Cooling and heating	The position of PCM, The PCM melting temperature	The PCM windows (especially the ones with the PCM inside the outermost cavity) can be beneficial in terms of thermal comfort.	[19]
DGW + S-L PCM	Paraffin wax RT35HC (35)	N,E	Cfa	South	Cooling and heating	Solar irradiation	The performance of PCM window would be more efficient during the time that solar irradiation increases. Incorporation of PCM into glazing units can minimize the glare risk and improve eye comfort.	[20]
The transparent RBE	Not mentioned	Simulation in DIVA-for-Rhino	Cfb	variable	Cooling and heating	PCM thickness, orientation,	The advantages performance of this system was evident for all of the orientations except the north one due to the scarce activation of PCM during the summer. The reduction of active layers’ thickness from standard thickness (60 mm for aerogel and 27 mm for PCM) to 15mm (for both of them) doesn’t make negative effect on the combined lighting, cooling and heating performance for all of the orientation except the west one.	[18]
TGW + S-L PCM, DGW + S-L PCM	Paraffin wax MG29 (27-29)	E	Cfa	South	Cooling and heating	Type of glazing system (number of glazing panes), Solar irradiation	In the summer sunny day, the peak temperature on the interior surface of TW+PCM reduces 2.7°C and 5.5°C respectively in comparison to DW+ PCM and TW. Also, heat entered the building reduces 16.6% and 28% respectively.	[22]
DGW + S-L PCM	Paraffin wax (18,26,32)	E	Dwa	Not mentioned	Cooling	solar irradiation, PCM thickness, phase transition temperature	The transmittance of PCM in liquid phase is almost 1 and melting temperature of PCM doesn’t have any effect on it, while the PCM’s melting temperature has a significant impact on the transmittance in solid phase. In order to maintain optical performance of the fenestration, it is recommended to avoid utilizing PCM layers thicker than 16mm.	[21]
FGW (the middle cavity is filled with PCM)	(25-28)	N,E	Dwa	South	Heating	PCM thickness	Increasing the PCM thickness can improve the thermal performance of the glazing unit while the reduction of solar transmittance is considerable. Therefore, the researchers suggested utilizing the PCM with the thickness not larger than 20mm.	[23]

Table 3, Summary of PCM-incorporated fenestration systems, part 2

Glazing System	The PCM type and PTT(°C)	Method	Climate code	orientation	Thermal Performance	The parameters investigated	Results	Ref.
TGW + S-L PCM	Paraffin wax (18, 22, 25, 28. 31)	N,E	Dfb	West , east	Cooling	phase transition temperature, Orientation	For east oriented PCM window, paraffin RT25HC has the most effective performance however; RT18HC is the most effective PCM in west-facing PCM windows. According to the thermal and visual comfort analysis, the PCM with the lowest melting temperature could be the best option for both east and west orientations.	[12]
DGW + S-L PCM	Paraffin wax RT28HC (27-29)	E, N (ANSYS FLUENT)	BWh	South	Cooling	PCM thickness	The peak temperature time lag of the internal layer in PCM-filled DGU was around 3 hours more than the one for conventional DGU Increasing the thickness of PCM layer can improve thermal performance however, for the PCM with more than 30mm the variation trend can be reversed.	[10]
DGW + S-L PCM	Paraffin MG29 (27)	N	BWh	Not mentioned	Cooling	The form of fenestration system	The proposed configurations are capable to reduce energy consumption of the building by around 20%.	[24]
DGW + S-S PCM	Not mentioned	N (EnergyPlus)	Not mentioned	variable	Cooling and heating	orientation, climate condition,	The PCM window with optimal properties in warm, mixed, cold climates is respectively potential to save up to 9.4%, 6.7%, and 3.2% energy for the whole building. The optimal phase change temperature is increased in west and east facing windows due to the reduced solar altitude angles. The lowest optimal phase change temperature belongs to the PCM windows located in the north orientation	[13]
S-S PCM enclosure	Variable (20,30,40,50)	N	Dfa, Cfa	variable	Cooling and heating	climate condition, phase transition temperature	The S-S PCM coating is capable to achieve more energy saving in warm climate. S-S PCM coating can contribute to reduce the undesirable heat exchange in all orientation.	[14]

Nomenclature

Abbreviations

DGU	Double glazing unit
DGW	Double glazing window
FGU	Four-glazed unit
E	Experimental investigations
N	Numerical investigations
PCM	Phase change material
TGW	Triple glazing window

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