Mater Renew Sustain Energy (2015) 4:6
DOI 10.1007/s40243-015-0047-8

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REVIEW PAPER

Phase change materials (PCMs) integrated into transparent building elements: a review

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Received: 5 January 2015 / Accepted: 23 March 2015 / Published online: 2 April 2015

Abstract Phase change materials (PCMs) represent an innovative solution that can contribute to the improvement of the energy performance of buildings. Recently a trend towards integrating PCMs into transparent envelope components is observed. This study aims to present the main solutions proposed in the literature for applications in the past few years for PCMs integrated into transparent buildings elements. The temporal development of this application as well as the fundamental principles of its operation is described in detail. The concept of the existing transparent PCM systems is presented, and the rationale of selecting appropriate materials is discussed. This is followed by the current practices in testing the thermal performance of transparent PCMs. The future trends in terms of the current barriers and the potential improvements are discussed. To this end the future technologies of transparent PCMs are also considered.

Keywords Phase change materials (PCMs) · Transparent · Building elements

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Introduction

The promotion of buildings' energy efficient design is one of the main priorities of the research community in the building sector. A novel approach, which in recent years gaining more and more ground, is the use of phase change materials (PCMs). PCMs have the ability to change their phase (typically from solid to liquid and vice versa) at room temperature. This results to the storage of the amount of latent energy which is required to change the phase of the material. PCMs represent a highly efficient solution, as their use improves building shell's energy management. In particular, the use of these materials enables the better management of the energy flow to and from the building, decelerating in this way the rate of thermal losses. PCMs thermal performance is a challenging scientific field as the phase change is accompanied by a change of the materials' key properties, such as the heat capacity and thermal conductivity.

PCMs are used in a range of applications in the technical and building sector. In the latter case, they are mainly used in opaque components, typically in walls and ceilings. Lately, the use of PCM-doped infrared reflective coatings was reported [1]. However, in the recent years, a trend towards integrating these materials into transparent envelope components or employing transparent PCM in building systems is being observed. This review work focuses on the transparent glazing systems that incorporate PCMs, and considering the fact that these building components, particularly in warm dominant climates, are more vulnerable to thermal losses due to their higher thermal transmittance and higher radiation losses, this incorporation is of special importance.

The synthesis and the characteristics of stearic acid (SA)/expanded graphite (EG) composites as thermal energy storage materials were reported in Fang et al. [2]. The authors denoted that the properties of these composites can be used in the exterior walls of buildings so that the cooling load of air-conditioning system is reduced. Similarly, the aim of the work of Chwieduk [3] was to point out ways of substituting thick and heavy thermal mass external walls, which are typical in buildings in high latitude countries, by thin and light thermal mass PCM-incorporated walls that meet the same comfort levels throughout the whole year.

Additionally, Kuznik and Virgone [4] investigated experimentally the thermal performances of a PCM copolymer composite wallboard in a full-scale test room. The results indicated that the PCM-incorporated wallboard achieves the lowering of the air temperature in the room by up to 4.2 °C and also enhances the natural convection in the room. The authors also stated that the specific PCM is particularly interesting for its use in renovation building projects.

The work of Medina et al. [5] concerned with the merging of two building technologies, structural insulated panel and PCM, into a new product. The results of the thermal performance evaluation of their new product indicated that the peak heat flux reductions achieved with 10 and 20 % PCM incorporation were 37 and 62 % respectively, while the average reductions in daily heat transfer were 33 and 38 % for concentrations of 10 and 20 % PCM, respectively. The thermophysical properties and the process of melting of a PCM, an epoxy resin/paraffin spheres composite in particular, were investigated numerically and experimentally, using a transient hot plate apparatus and differential scanning calorimetry respectively [6]. Based on their findings the authors concluded that this material can be used to improve comfort, save energy in buildings and reduce the weight of wallboards. Xu and Li [7] developed a paraffin/diatomite/multi-wall carbon nanotubes composite PCM for its incorporation into thermal energy storage cement-based composites. The use of this kind of composite was found to have beneficial effects for improving the thermal conductivity and heat storage, without affecting the thermal properties, chemical compatibility and thermal stability of the cement-based composites.

Several reviews have been published on the use of PCM in buildings. Zalba et al. [8] presented the history of thermal energy storage with solid–liquid phase change. Materials used by researchers as potential PCM and commercial PCM were described, together with their thermophysical properties. Farid [9] published a review about PCM building applications, which provides an insight to efforts to develop new classes of PCMs for use in energy storage in building applications. Tyagi and Buddhi [10] published a comprehensive review of various possible methods for heating and cooling in buildings. The thermal performance of various types of systems like PCM Trombe wall, PCM wallboards, PCM shutters, PCM building blocks, air-based heating systems, floor heating, ceiling boards, etc., was presented. The main focus of Kenisarin and Mahkamov [11] review was the assessment of the thermal properties of various PCM, methods for heat transfer enhancement and design configurations of heat storage facilities to be used as a part of solar passive and active space heating systems, greenhouses and solar cooking.

Sharma et al. [12] review summarizes the investigation and analysis of the available thermal energy storage systems incorporating PCM for use in different applications. Zhu et al. [13] presented an overview of the previous research work on dynamic characteristics and energy performance of buildings due to the integration of PCM. Wang et al. [14] presented the concept of ideal energy-saving building envelope, which is used to guide the building envelope material selection and thermal performance design. Finally, a review on the use of PCM for the free cooling of buildings is presented by Aroul et al. [15].

This review paper aims to present the latest developments in the application of PCMs in transparent components. This is not considered in any of the above reviews. A brief history of the PCMs and the fundamentals of operation of PCM-incorporated glazing systems will be primarily presented in sections “PCM-incorporated transparent glazing development and fundamentals of operation” and “Current practices of transparent PCM-incorporated systems”, respectively. The main solutions that have been implemented in recent years and materials used in transparent phase change components as well as their main properties will be referred in section “Current practices in testing the thermal performance of transparent PCM-incorporated systems”. A discussion regarding the current barriers, the considerations for their further development, as well as the near-future trends is presented in section “Future trends”, while the findings of this review paper are given in the last section.

PCM-incorporated transparent glazing development and fundamentals of operation

Transparent PCM and PCM-incorporated transparent glazing development

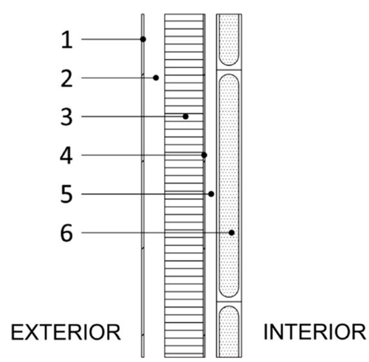
The first documented use of a PCM as a form of latent heating was by Dr. Maria Telkes in 1948 [16]. The Hungarian research associate of Massachusetts Institute of Technology (MIT) became one of the pioneers in this field through the construction of the very first PCM heated house with architect Eleanor Raymond. The Solar One building housed approximately 4 m^2 of Glauber salts, which were ventilated with fans to deliver warm air inside the building in winter, and cool air in summer. In fact, this system was able to keep the house warm for approximately 11 sunless days. After 3 years, the house failed because the utilized PCM lost most of its energy storage capacity [17]. Since then, the development of PCMs for passive heating has been widely studied [18, 19]; however, their application developments had been slow. Harland et al. [16] attributed this slow development to the high costs of PCMs that was an obstacle to become a design option.

The earliest mention in literature regarding translucent PCM was found in Manz et al. [20]. The authors of this study proposed a two-layered passive wall system, combining a salt hydrate phase change material and a transparent honeycomb-type insulation material (Fig. 1). The PCM was filled into glass containers, which were commercially available glass blocks. A few years later, Ismail and Henriquez [21] were the first to report on the results of an experimental investigation on simple and composite glass windows filled with PCM.

PCM-incorporated transparent glazing fundamentals of operation

The passive solar mechanism of PCM glazing systems is offered by the outer and inner insulating glazing units. The outer insulated glazing unit with suspended prismatic filter between the panes of glass reflects the higher angle sunlight back out, transmitting the low-angle sunlight into the inner unit that is filled with sealed polycarbonates into which the PCM is encapsulated. As a result, the strong sunlight of the summer is kept out of the building, while the lower angle winter sunlight is allowed to be captured by the PCM as shown in Fig. 2 [22]. A PCM material with a (low) melting point close to the comfort or operational temperature in the building and high latent heat of fusion has the great latent heat storage potential. This potential is enabled by the phase transition between the liquid and the solid state and thus allows an increase of the thermal inertia of the glazing system [23].

During the melting process from solar radiation, the specific heat of PCM increases to more than one hundred times to absorb a large quantity of energy [24]. By nighttime the external temperature decreases below the melting point of the PCM, so that the PCM starts to solidify, releasing into the building its stored energy. By the next morning, the PCM typically solidifies completely to start the cycle again [22]. The net effect of this process is the reduction of heat flow from outdoor to indoor space during daytime [24].



Layer Id	Description	Thickness [mm]
1	Glass pane	-
2	Air gap	-
3	Transparent insulation material	-
4	Glass pane	-
5	Air gap	-
6	PCM in a glass container	-

Fig. 1 Layout of TIM–PCM external wall system (Manz et al. [20])

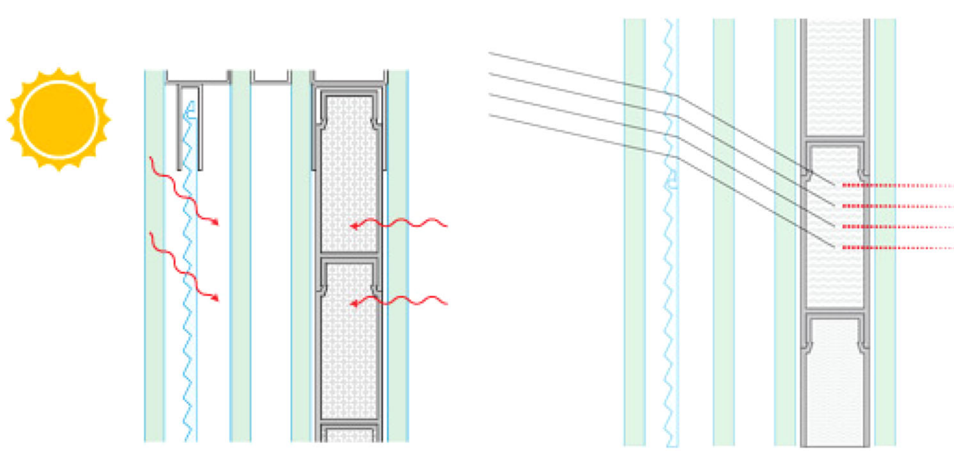


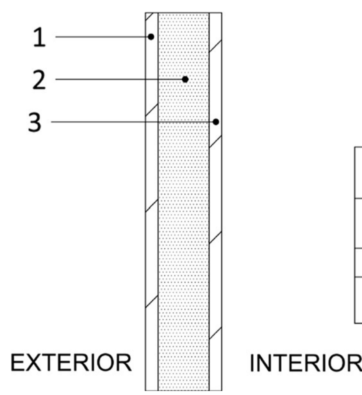
Fig. 2 Fundamentals of operation of transparent PCM (Figure reprinted with the written permission of the copyright holder)

Current practices of transparent PCM-incorporated systems

Concept of existing transparent PCM-incorporated wall systems

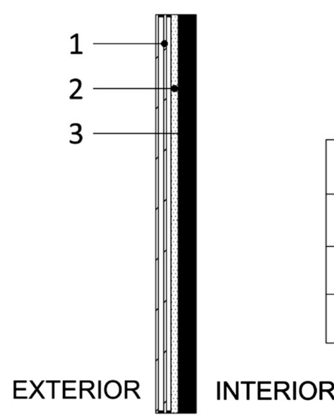
Several transparent building elements incorporating translucent, or see-through, PCM have been proposed in the literature the recent years. Transparent PCM is a material that allows light to pass through but absorbs the infrared part of the spectrum and this increases the temperature of the PCM up to the point of melting, which as in all PCMs is done at constant temperature. The PCM can be transparent to the internal space, and act like a window, or it may be transparent to an opaque material (i.e., the wall element) in front of which it is installed. Ismail and Henriquez [21] presented a relatively simple and effective concept. The suggested layout consisted of a double glass window, separated by a gap of certain width, filled with a PCM of certain fusion temperature, as shown in Fig. 3.

Weinlaeder et al. [25] encapsulated PCMs in transparent plastic containers. The containers were placed behind a conventional double glazing with an air gap of about 10 mm as shown in Fig. 4. Numerical analysis of a double glazing containing PCM in the spacing between the two panes, shown in Fig. 5, was performed by Goia et al. [26]. A numerical procedure based on a 1D nodal model was



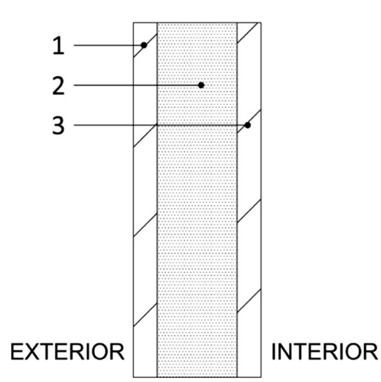
Layer Id	Description	Thickness [mm]
1	Glass	-
2	PCM Layer	-
3	Glass	-

Fig. 3 Layout of double glass window with PCM (Ismail and Henriquez [21])



Layer Id	Description	Thickness [mm]
1	Double Glazing	-
2	Plastic container with PCM	16
3	Wall heating/cooling	-

Fig. 4 Layout of PCM-facade-panel (Weinlaeder et al. [25])



Layer Id	Description	Thickness [mm]
1	External glass pane	3/16
2	PCM Layer	10/16
3	Internal glass pane	3/16

Fig. 5 Layout of PCM glazing (Goia et al. [29])

developed, neglecting heat and shortwave radiation transmission along the x and y axes. In their standard model, three nodes were associated to each glass pane, while the PCM layer was represented by means of five nodes.

In Goia et al. [27], a prototype of a simple PCM glazing system was proposed, while its behavior was compared with that of a conventional reference double glazed unit. The analysis indicated that the PCM glazing system provided better indoor thermal conditions than the conventional system for most of the time during the various seasons. In addition, it was found that the higher the outdoor solar irradiance, the greater the benefits offered by PCM glazing unit.

The aim of the study in Gowreesunker et al. [28] was the evaluation of the radiation heat transfer properties and performance of PCM glazing systems. The optical properties were evaluated using spectrophotometry and the thermal properties were assessed using the T-history method.

The aim of the work in Goia [29] was to investigate the location of the PCM layer and the nominal melting temperature of the PCM, which are two variables that play significant role in PCM glazing systems. Different PCM glazing configurations had been tested by means of a numerical analysis to assess their behavior with respect to the energy efficiency and thermal performance. The results indicated that the position of the PCM layer has a relevant influence on the thermophysical behavior of the PCM glazing system. PCM glazing systems, especially those with the PCM layer inside the outermost cavity can be beneficial in terms of thermal comfort, while a more complex evaluation is needed when the energy performance is addressed. The results of the work undertaken in Goia et al. [30, 31] 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.

Buddhi et al. [32] investigated the thermal performance of a wooden box having a PCM-integrated window in south direction. The PCM employed was commercial grade lauric acid, which enabled to keep the temperature of the experimental test cell higher during evening and night. An experimental and numerical simulation study of the application of PCMs in translucent building elements was also presented in Bontemps et al. [33]. In fact, the experimental study was conducted in a test cell split by a wall made of hollow glass bricks filled with PCM. The PCMs tested were fatty acid, paraffin, and salt hydrate.

Additionally, a theoretical thermal analysis of a window with a shutter containing PCM was presented in Alawadhi [24]. The results indicate that the melting temperature of PCM must be close to the upper temperature limit of windows during daytime, while the quantity of PCM should be adequate to absorb a lot of heat during the day, without the PCM melting. Also, the presented shutter of 0.03 m thickness was able to reduce the heat gain by 23.29 %. The potential of incorporating PCMs in structural cells of shading elements associated to southward façade window was also presented in Soares et al. [34]. It was concluded that numerical simulation can be used to define an optimal system configuration, with an optimal PCM melting temperature for any location and characteristic climatic data.

Heim [35] carried out simulations of a transparent insulation wall integrated with a PCM. His system comprised of an external glazing, a transparent insulation material (TIM) honeycomb structure, and a PCM-ceramic composite, which were separated by air gaps to form a triple zone building model. The results showed the properties of the PCM enabled 5 % more stable temperature for the internal space during winter. For the work of Weinlaeder et al. [36], an interior sun protection system consisting of vertical slats filled with PCM was monitored for more than 2 years. It was observed that the surface temperature on the interior side of the PCM-filled slats did not exceed the PCM melting temperature of 28 °C, while conventional systems often reached 40 °C. This proved the significant contribution of PCM technology in improving the thermal comfort of buildings.

Further to the incorporation of transparent PCM in transparent building elements, various PCMs have also been exploited as thermal storage materials for cooling, heating, thermal comfort, and thermal source in buildings [37]. Diarce et al. [38] investigated the thermal performance of a new type of ventilated active façade that includes a PCM in its outer layer, as shown in Fig. 6. Their prototype façade was designed to be suitable for use in building restoration. The external layer contains the PCM, inside an aluminum macroencapsulation system, and had a thickness of 20 mm. The ventilated air channel was situated between the external layer and the insulation material, and it was 60 mm thick. Insulation material (50-mm-thick plates of extruded polystyrene) was placed next to the air gap. The inner layer was a brickwork wall made of 70-mm-thick hollow common bricks, and a 2-mm-thick plasterboard lined the inner walls of the room. A new type of ventilated facade with macro-encapsulated PCM in its air cavity, as shown in Fig. 7, was presented by De Gracia et al. [39]. The ventilated facade presented an air channel of 15 cm thick which represented 0.36 m^2 of channel area. The inner layer was based on the alveolar brick constructive system while the outer envelope was made by a glass layer. An extra outer layer of expanded polyurethane panels was placed to cover the transparent glazing during the summer period since solar radiation inside the cavity was avoided for cooling purposes.

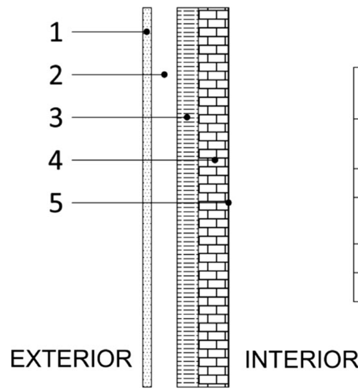


Fig. 6 Layout of ventilated active façade (Diarce et al. [38])

Layer Id	Description	Thickness [mm]
1	External sheet containing PCM	20
2	Ventilated air gap	60
3	Extruded polyestyrene insulation	50
4	Brickwork inner wall	70
5	Gypsum plasterboard	2

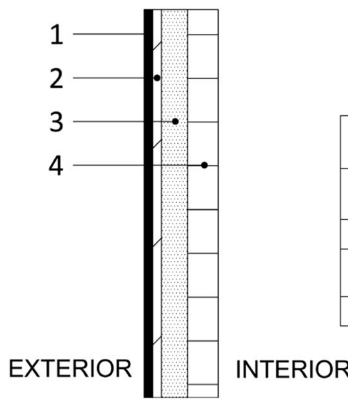


Fig. 7 Layout of ventilated facade with PCM (De Gracia et al. [39])

Layer Id	Description	Thickness [mm]
1	Opaque insulation panel	-
2	Glass layer	-
3	PCM panels and air channel	-
4	Alveolar brick	-

PCM materials used in transparent building elements

More than 50 % of incident solar radiation's energy is measured in the visible spectrum range. Based on this fact, the concept of a transparent element should allow visible radiation to be transmitted and invisible radiation in the infrared part of the spectrum to be absorbed and converted into heat. Therefore, the selected PCMs should not only have high heat capacity, but also favorable absorption and transmission under specific wave lengths. The light transmittance of water coincides perfectly with the sensitivity curve of the human eye. For this reason, high water content PCMs are mainly selected for transparent building elements. Subsequently, the same authors [20] used a salt hydrate PCM.

The categorization of PCMs as originally suggested by Abhat [40] is given in Fig. 8, and the main physical properties of the employed PCMs for transparent building elements are summarized in Table 1. The use of $CaCl_2$·$6H_2O$ as PCM was first proposed by Swanton [41]. Manz [42] gives an overview of the research work which has been carried out to improve the thermal properties of the pure substance with additives, especially in order to suppress supercooling and to reach long-term stability. Their experimental investigations were carried out using a commercially available PCM based on $CaCl_2 \cdot 6H_2O$ with additives of approximately 5 % of the mass. This material shows a melting enthalpy of 192 J g^{-1} and a melting temperature interval of 24–29 °C. Porisini [43] tested the long-term stability of this PCM in small quantities and found no change in thermal properties after 5650 melting/solidification cycles. Later, Buddhi and Sharma [44] presented the experimental measurements of the transmissivity of commercial grade stearic acid, which revealed that the low thermal conductivity and high transmissivity of the material enabled its employment as a transparent insulating material.

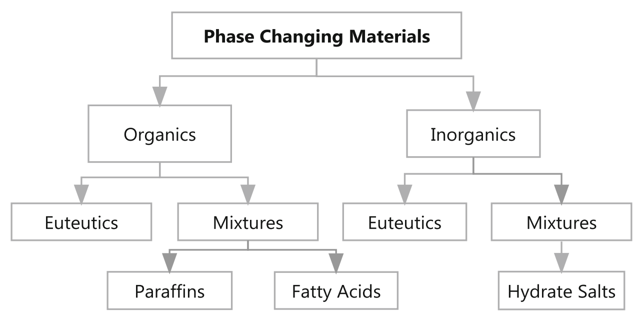


Fig. 8 Classification of PCMs (Zalba et al. [8])

Table 1 The main physical properties of the employed PCMs for transparent building elements

Work	PCM	Melting area (°C)	Congealing area (°C)	Heat storage capacity (kJ kg^{-1})	Specific heat capacity (kJ kg^{-1} K^{-1})	Density (kg l^{-1})	Heat conductivity (W m^{-1} K^{-1})
Manz et al. [20]	$CaCl_2{\cdot}6H_2O$	24–29		192			
Ismail and Henriquez [24]	Mixture of glycol						
Buddhi et al. [32]	Commercial grade lauric acid	42.2		181			
Heim [35]	Fatty acids	20/30/40		25			
Athienitis et al. [47]	Gypsum board (13 mm thick) soaked with butyl stearate	16.8–20.9		29.1			0.18
Weinlaeder et al. [25]	Paraffin wax RT25 [60]	22–26	26–22	148 ± 7.5 %	2	Sol. 0.88	0.2
						Liq. 0.76	
	$CaCl_2{\cdot}6H_2O$	27 ± 0.5		190 ± 19	Liq. 2.22 ± 0.11	Sol. 1.7 ± 0.17	Sol. 0.79 ± 0.03
					Sol. 1.50 ± 0.08	Liq. 1.53 ± 0.08	Liq. 0.48 ± 0.04
	$LiNO{\cdot}3H_2O$	30 ± 0.5		270 ± 27	Liq. 1.79 ± 0.09	Sol. 1.556 ± 0.156	Sol. 1.02 ± 0.05
					Sol. 1.23 ± 0.06	Liq. 1.4 ± 0.007	Liq. 0.56 ± 0.03
Bontemps et al. [33]	Fatty acid capric/myristic	21.4		162			
	Paraffin C 18–20 (Linpar)	25		170			
	Salt hydrate	27.5		192			
Goia [29]	Paraffin wax	Peak 33		140	2.5	0.8	0.2
Goia et al. [26]	Paraffin wax	Peak 25/30/35		140	2.5	0.8	0.2
Goia et al. [48]	Paraffin wax	35		160			
De Gracia et al. [39]	Salt hydrate SP-22	22	18	150			
Diarce et al. [38]	RT35 [60]	29–36	36–31	170	2	Sol. 0.86	0.2
						Liq. 0.77	
Goia et al. [27]	Paraffin wax	34		145			
Gowreesunker et al. [28]	RT27 organic paraffin [60]	25–28		184			
De Gracia et al. [49]	Salt hydrate SP-22	21.5	18				
Goia et al. [30]	Paraffin wax	35		170		Sol. 0.88	
Goia et al. [31]	RT35HC [60]	34–36	36–34	240 + 7.5 %	2	Sol. 0.77	0.2
						Liq. 0.67	

PCM incorporated in glazing products

Currently, there are commercially available types of glazing such as Delta®-Cool 28 or GlassX® that incorporate PCM. The PCM incorporated in the GlassX products is comprised of $CaCl_2{\cdot}6H_2O$ salt hydrates that are completely sealed in clear polycarbonate. The products have a latent thermal storage of up to 4268 kJ/m^2, meaning that a period of 8 h passes before heat is transmitted [45]. This property shifts the peak energy demand of the summer later at night and thus reduces the interior room temperatures by at least 5 °C. While in winter, the solar gains are maximized by charging up the PCM during the day in order to release it back into the building throughout the night as it solidifies. The manufacturers of GlassX® claim that their products reduce a building's heating and cooling loads by 30–50 % with only 1/3 coverage on a south-facing façade compared to opaque, insulating walls such as brick, wood, or metal panels [45]. Regarding Delta®-Cool 28, the manufacturers demonstrated its application in translucent Polymethyl Methacrylate (PMMA) panels in a glass facade system of a zero energy office building in Kempen, Switzerland. Every other window panel was equipped with PCM for reducing the solar heating of the interior [46].

Current practices in testing the thermal performance of transparent PCM-incorporated systems

Both laboratory and outdoor testing facilities as well as specialized equipment were employed for the definition of the thermal performance of the proposed transparent building elements incorporating translucent PCM. Manz et al. [20] tested the PCM optical properties indoors in a laboratory using a spectrophotometer and Abbe refractometer, while the experimental investigation of the TIM and transparent PCM prototype facade was conducted in outdoor test facilities consisted of a cooling/heating apparatus and heat flow sensors. Their laboratory equipment allowed them to define also the refraction index of the PCM, while their outdoor test facility employed enabled them to measure also liquid mass flow temperatures, the heat flux, and the solar irradiance.

Ismail and Henriquez [21] characterized optically the different glass sheets of different thicknesses and panels of double sheets of different spacings and fillings employing only one laboratory equipment—a spectrophotometer. Consequently, their measurements were limited to the determination of transmittance, reflectance, and absorbance of the PCM. Athienitis et al. [47] had developed an outdoor test facility with two configurations of the double facade with photovoltaic panels that incorporated a differential scanning calorimeter (DSC), which recorded the latent heat and the transition temperatures of the glazing system. Weinlaeder et al. [25] and Goia et al. [26] set up their experiments for the PCM-integrated glazing systems in outdoor test cells. Temperature, heat flux, and incoming and transmitted solar radiation measurements were taken in the work of Weinlaeder et al. [25], while the outside test cell of Goia et al. [26], equipped with thermocouples, heat flux meters, and pyranometers collected data regarding the indoor surface temperatures of the glazing, the outdoor solar irradiance, the indoor surface heat flux, and also the transmitted solar irradiance of the PCM glazing system. For a subsequent work, Goia et al. [48] employed the Characterization of Advanced Transparent Materials (CATRAM) facility for the investigation of the proposed PCM-incorporated transparent system consisting of a halogen lamp and three array spectrometers.

Bontemps et al. [33] also configured outdoor test cells for the testing of the wall made of glass bricks filled with PCMs. Their equipment included fluxmeters and thermocouple for the measurements of heat flux and indoor temperature. Additionally meteorological data were taken from a nearby meteorological station. De Gracia et al. [39] used house-like cubicles with thermocouples, a moisture/temperature transducer, an electrical network analyzer, a heat pump, an air flow velocity–temperature transmitter, a pressure transmitter, and heat flux sensors for the investigation of their ventilated facade with macro-encapsulated PCM. Additional equipment, including solar pyranometers and an anemometer, was used for the data collection of the outdoor weather conditions. Their testing facility and equipment allowed them to take a range of measurements to evaluate the performance of the ventilated facade with macro-encapsulated PCM, which are given in Table 2. The active ventilated facade with a PCM, suggested by Diarce et al. [38], was studied in a PASLINK test cell with temperature probes and also employed air velocity sensors and pyranometers. Thus, in their work Diarce et al. [38] presented data of the global vertical radiation, the outdoor temperatures, and the temperatures inside the PCM at the bottom and the top of the façade.

Furthermore Goia et al. [27, 30] employed the Testing Window INnovative System (TWINS) outdoor test cell facility equipped with heat flux sensors, thermocouples and pyranometers for measuring solar irradiance, while Goia et al. [27] also employed an infrared thermal camera for their measurements. In his research, Gowreesunker et al. [28] employed an environmental chamber with controlled air temperature along with thermistors, a spectrophotometer, a pyranometer, and a 150 W metal halide (iodide discharge) lamp to enable the comparison between a PCM-glazed unit and a traditional

Table 2 The employed testing facilities and measurements for the investigation of the thermal performance of PCMs for transparent building elements

Work	Investigated object	Test conditions	Equipment	Performed measurements
Manz et al. [20]	External wall system composed of transparent insulation material (TIM) and translucent phase change material (PCM)	Laboratory	Spectrophotometer	Spectral transmittance and reflectance
			Abbe refractometer	Refraction index of the PCM
		Outdoor test facility	Cooling/heating apparatus	Liquid mass flow temperatures
			Heat flow sensors	Heat flux
				Irradiance
Ismail and Henriquez [24]	PCM glass systems of thicknesses 3, 4, 5, 6 and 8 mm	Laboratory	Spectrophotometer	Transmittance
				Reflectance
				Absorptance
Athienitis et al. [47]	Double facades with phase change storage and photovoltaics	Outdoor test facility	Differential scanning calorimeter (DSC)	Latent heat
				Transition temperatures
Weinlaeder et al. [25]	Double glazings combined with PCM	Outdoor test facility		Temperature
				Heat flux
				Incoming solar radiation
				Transmitted solar radiation
Bontemps et al. [33]	Wall made of glass bricks filled with PCM	Outside test cells	Fluxmeters	Heat flux
			Thermocouple	Indoor temperature
			Meteorological station	Meteorological parameters
Goia et al. [26]	PCM glazing systems	Outside test cell	Thermocouples	Indoor surface temperatures of the glazing PCA
			Heat flux meters	Outdoor solar irradiance
			Pyranometers	Indoor surface heat flux
				Transmitted solar irradiance of PCM glazing
Goia et al. [48]	PCA incorporated transparent system	Characterization of Advanced TRAnsparent Materials (CATRAM) facility	Halogen lamp	Transmittance
			Three array spectrometers	Reflectance
				Absorptance
De Gracia et al. [39]	Ventilated facade with macro-encapsulated phase PCM in its air cavity	House-like cubicles	Thermocouples	Internal wall temperatures
			Moisture/temperature transducer	Indoor air temperature and humidity
			Electrical network analyzer	Electrical consumption of the HVAC systems
			Heat pumps	
			Thermocouples	Air temperature of the cavity
			Air flow velocity Temperature Transmitter	Air velocity of the cavity
			Pressure transmitter	Pressure drop across the air cavity
			Heat flux sensors	Outer and inner skin surface temperature
				External surface temperature
				Heat flux transferred to indoor
				Heat flux transferred to the front and back surface of a PCM panel
				Temperature of the PCM
				Front and back surface temperature of the PCM panels
			Solar pyranometers	Horizontal and vertical global solar radiation
			Moisture/temperature measuring transducer	Outer air temperature and humidity
			Anemometer	Wind speed and direction

Table 2 continued

Work	Investigated object	Test conditions	Equipment	Performed measurements
Diarce et al. [38]	Active ventilated facade with a PCM	PASLINK test cell	Temperature probes Air velocity sensors Pyranometers	Global vertical radiation Outdoor temperatures Temperatures inside the PCM at the bottom and the top of the facade
Goia et al. [27]	Prototype of a simple PCM glazing system	Test cell facility (TWINS—Testing Window INnovative System)	Thermocouples Heat flux meters Pyranometers Thermal infrared camera	Indoor surface temperature Surface heat flux Incident solar irradiance Spot measurements of the surface temperature field
Gowreesunker et al. [28]	PCM-glazed unit and traditional double glass unit	Environmental chamber with controlled air temperature	Thermistors Spectrophotometer Pyranometer 150 W metal halide (iodide discharge) lamp	Temperature measurements of the samples and the chamber temperature transmittance radiation heat flux
De Gracia et al. [49]	Ventilated facade with PCM			Thermal profiles of the PCM
Goia et al. [30]	PCM glazing prototype	Outdoor test cell facility (TWINS—Testing Window INnovative System)	Heat flux sensors thermocouples pyranometers	Surface heat fluxes Temperatures Incident and transmitted solar irradiance
Goia et al. [31]	Advanced dynamic glazing prototype integrating PCM and thermotropic layers	Outdoor test cell facility	Thermocouples heat flux meters pyranometers	Surface and air temperature measurements; Heat flux Outdoor and transmitted solar irradiance

double glass unit. Finally, the advanced dynamic glazing prototype integrating PCM and thermotropic layers proposed by Goia et al. [31] was also tested in an outdoor test cell facility, employing thermocouples, heat flux meters and pyranometers.

It should be noted that in Goia et al. [27], the use of the infrared thermal camera also allowed spot measurements of the surface temperature field. De Gracia et al. [49] also presented the thermal profiles of the PCM. The employed testing facilities, equipment and measurements for the investigation of the thermal performance of PCMs for transparent building elements in literature are summarized in Table 2.

Future trends

Current barriers

Although PCMs integrated into transparent building elements are very promising, their application in buildings is still considered rather new. There are still several barriers that these systems have to overcome, in order to make them more interesting and penetrate the construction industry. The main design issue associated with these glazing systems regards the change in transparency of the PCM as it changes phase. Currently, only organic PCMs have been found to be transparent in the solid state and fully transparent to visible light in the liquid phase for their employment in glazing systems [28]. However, they allow high amounts of visible light to pass through but do not offer the same visibility as regular windows [50].

An additional problem with passive PCM systems is their reliability. Weinlaeder et al. [36] reported that passive PCM systems might not work in cases such as during long hot days when the PCM could not be completely discharged during the night. Additionally, Soares et al. [51] stated that most of the studies have been focused on the performance of these systems for extreme summer or winter conditions, eliminating their functionality during the rest of the seasons. Another barrier reported in literature is the low thermal conductivity of many promising PCMs, which vary in the values between 0.15 and 0.2 W/mK for organic PCMs and around 0.5 W/mK for inorganic salts. The low thermal conductivity decreases the rate of heat absorption and releases throughout the PCM, so that the product may not fully utilize its full latent heat storage [50]. The results of Evola et al. [52] experiments indicated that the PCM wallboards utilized only the 45 % of the possible latent heat storage, due to several factors including thermal conductivity.

Further work for improvements

After the identification of the weak points of PCMs integrated into building elements, some areas of improvement are as follows:

– More accurate assessment of the performance and potential of PCM systems in real dynamic conditions is required [50, 53]
– Development of validated simulation tools for the modeling of PCM performance is required [53]
– Integration of the PCM solutions within the established buildings' thermal regulation codes through the development of methodologies that take into consideration the latent heat loads from the PCMs [50].
– Economic feasibility of PCM applications in the built environment needs to be carried out [53].
– Further research on the flammability of PCM; definition of the ratio of PCM fulfilling the building fire standards [53].
– Increasing the thermal storage capacity for a given volume of a PCM. Although microencapsulation reduces the risk of liquid state PCMs from leaking, it produces a lower latent heat storage capacity. Subsequently, new methods or materials need to be discovered for the encapsulation of the PCM, or thinner shell for the capsules need to be developed [50].
– Enhancing the heat transfer of the PCM [50]. Fan and Khodadadi [54] reviewed methods regarding this aspect, with porous materials with high thermal conductivity such as graphite-based PCM systems and metal foams receiving particular interest [55, 56]. Also, materials with high thermal conductivity to the PCM, such as various carbon-based nano-fillers or porous structures have been studied for the enhancement of the overall thermal conductivity [57–59].

Future technologies

Building systems incorporating PCMs that harness solar thermal energy for heating during winter and optimized to reduce the overheating problem during summer are the most promising. Soares et al. [51] reported that the development of rotary, portable, movable and reconfigurable systems, mainly those associated with glazed façades, will be the next milestone in PCMs. Nanoencapsulation of PCMs, which has a similar concept to microencapsulation, and the combination of PCMs with nanofluids are also considered promising to improve PCM systems. Smaller size capsules would provide higher heat transfer speeds [50]. Another future trend of PCMs regards the adjustability of the phase change temperature for the improvement of the efficiency. A controllable or adaptive system would enable a dynamic change of the phase change temperature in response to user preferences, different climates and different seasons.

Conclusions

PCMs represent an innovative solution that can contribute to the improvement of the energy performance of buildings. A promising current trend concerns the integration of PCMs into transparent envelope components. This work introduces the evolution of PCMs technology for building applications, and thoroughly explains the concept of PCMs integrated into transparent buildings elements. The paper also reviewed the main solutions proposed by the literature in the past few years for PCMs integrated into transparent buildings elements. It can be concluded that PCM glazing systems provide better indoor thermal conditions than the conventional system, as they alleviated the peak heat temperatures of summer days, and release their stored energy during nighttime, when the outdoor temperatures typically drop. Finally, this work analyzes the barriers of the current PCMs technologies, and what can be done for their further development, as well as the near-future trends. In the next few years, rotary, portable, movable and reconfigurable glazing systems, nanoencapsulation of the PCMs, and systems with adjustable phase change temperature are anticipated to emerge.

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