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Experimental analysis of an external dynamic solar shading integrating PCMs: first results

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Abstract

This paper presents the first results of an experimental analysis on dynamic translucent solar shadings with PCM, aimed at demonstrating its potential on reducing internal solar heat gains. The study is focused on the assessment of the thermal performance of the prototype panel during the solid phase of the PCM through an experimental campaign in a test cell facility. The total daily solar heat gains were reduced by more than 50% compared to the non-shaded reference triple glazing unit and the internal surface temperature of the glazing decreased of more than 6°C during the maximum external incident solar radiation.
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Keywords: PCM, dynamic solar shading, energy storage, façade, experimental analysis

1. Introduction

Within the latest years highly glazed façades have become very popular among architects and building owners due to the aesthetic value and internal daylighting quality. The adoption of large transparent envelope components in lightweight constructions, highly diffused in tertiary buildings, has caused a number of problems related to building energy efficiency and indoor comfort. Glazed façades, characterised by poor thermal inertia and high heat transfer coefficient, present a weaker energy performance if compared to opaque building elements. Despite considerable improvements in glazing technology, large transparent surfaces in the building envelope, can still be a cause of a significant increase in internal solar heat gains, which often results in overheating problems and thermal discomfort. A considerable reduction of transmitted solar radiation can be achieved if an external shading device is applied.

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Nevertheless, most of the existing shading solutions decrease noticeably the light transmission and/or could cause a glare discomfort due to the high contrast between the shaded and non-shaded surfaces.

Despite growing interest in the adoption of PCMs into a building structure, most of the solutions concentrate on opaque elements. However, as many PCMs demonstrate considerably high transmission for the visible light, an integration of PCMs and a solar shading has been analysed in few case studies. Different PCM glazing systems have been investigated, such as PCM blinds or shutters [1, 2, 3, 4, 5], inner PCM façade panel [6], window air cavity filled with PCM [7, 8, 9, 10, 11]. The main benefits of those solutions are the improvement of the thermal inertia of the façade and the reduction and time shift of the internal solar heat gains. The idea of incorporating PCMs into the transparent façade could be though further investigated. This paper presents the first results of an experimental analysis of an external translucent solar shading with PCM which could provide a reduction in internal solar heat gains while still allowing high value of natural light passing through the façade.

2. The proposed PCM prototype

The proposed prototype is composed of a selected PCM enclosed in a transparent polycarbonate hollow panel with a light transmission coefficient of 81% [12]. The transparent polycarbonate panel is: weather resistant, temperature resistant, UV resistant, moreover it is light-weight and has high impact resistance. As it combines a high level of mechanical, optical and thermal properties it is a suitable material for an external application.

The prototype is an external shutter aimed at reducing solar heat gains. The PCM melting temperature should be therefore above the external temperature, so the change of phase would occur due to the absorption of the solar radiation. A commercial paraffin wax (Rubitherm RT27) with the nominal melting temperature of 27 °C was selected. According to the producer [13] phase change range of the RT27 is 25-28 °C and the heat storage capacity is around 179 kJ/kg within the temperature range 20-35 °C. Paraffin waxes present preferable optical characteristics. According to some research in optical properties of several PCMs [6, 14, 15] paraffin in solid state presents low transmission coefficient in the infrared spectrum and a considerably high transmission for the visible light. For example a 15 mm paraffin layer transmit in solid state 35% of the infrared light and 55% of the visible light [14]. However, it must be noticed that the transmission coefficient for the whole solar spectrum increases when the PCM undergoes a phase change process.

The square panel has an area of 0.36 m^2 with a cavity thickness of 10 mm filled with approximately 2.4 kg of PCM. The prototype weight roughly 3kg, which results in less than 9 kg/m^2 and therefore makes it possible to extend its use as a movable shading device.

3. Experimental set-up and measurements

The thermal energy performance of the prototype was evaluated based on an experimental campaign. Measurements were conducted using an outdoor test cell facility TWINS – Testing Window INnovative System in the dept. of Energy, Politecnico of Torino [16]. The indoor environment of the test cell was controlled by means of a full air HVAC system with a tolerance of ±1 ◦C. The experiment was installed on a triple glazing unit, 1.40 m long and 0.75 m high, south exposed. The tested panel (0.6x0.6 m) shaded only half of the window in order to use the unshaded part of the façade as a reference (Fig. 2). The prototype was positioned 8 cm from the external glazing of the window to ensure the natural air flow behind the shading panel. The first experimental tests have been carried out for a prototype with the PCM with nominal melting temperature of 27 °C. Afterwards, in order to investigate the influence of the PCM in the polycarbonate on the solar transmission, an empty polycarbonate panel with the same dimensions was installed on the façade.

Temperature sensors (thermocouples type TT) were placed on the internal and external surfaces of the PCM shading (TGU_PCMsh) and the triple glazing unit (TGU). Three pyranometers were used to measure the solar radiation incident on the external, transmitted through the shaded (TGU_PCMsh) and unshaded window (TGU). Two heat flux meters (HFM) sensors (HFP01) were used to measure the heat flux for the TGU_PCMsh and the TGU (Fig. 1). Heat flux meters and thermocouples were shielded to direct solar radiation with an aluminium tape.

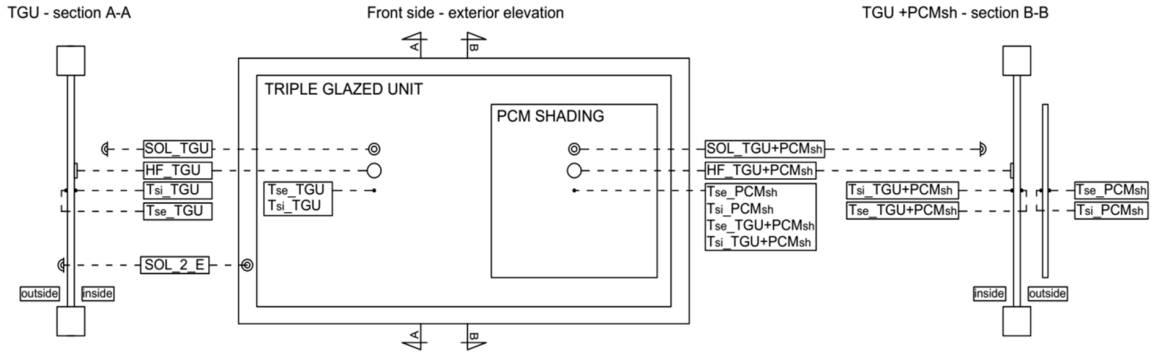

Fig. 1 Position of the sensors installed on TGU and on the PCM shutter

Fig. 2 An internal view of the test cell with the PCM shutter

4. Methods

4.1. Data analysis and boundary conditions

The study is focused on the thermal performance of the prototype during a solid phase of the PCM, which has been tested for several months, starting from November 2014. The prototype is aimed at reducing solar heat gains during mid and hot season, however, the shading system is able to improve the visual comfort avoiding glare risk during winter. Although the analysis was performed for the winter season, a selected week of January was characterised by mid-season boundary conditions Fig. 3a) allowing to test the panel under moderate weather. During that period following boundary conditions occurred: high, medium and low solar radiation, external air temperature in a range of 5 °C and 12 °C, except for the 10th January in which it reached 25 °C. For the whole period the outdoor air temperature was below the nominal melting temperature of the PCM. Data analysis was carried out by a comparison of the energy performance of the innovative prototype (TGU_PCMsh) with the reference conventional triple glass unit (TGU) and with the TGU shaded by an empty polycarbonate panel (TGU_noPCMsh) for selected typical days (Table 1 and Table 2). The analysis for the empty polycarbonate panel was performed for the period characterised by similar weather conditions (Fig. 3b). An equivalent thermal transmittance was either evaluated to characterize the heat transfer reduction of the PCM shutter.

4.2. Thermal energy performance

The assessment of the thermal performance of the PCM prototype is based on the data collected during the experimental campaign: transmitted solar irradiance, surface temperature and surface heat fluxes.

The evaluation of the influence of the PCM in the polycarbonate panel was based on the comparison of the solar transmission coefficient (τ_s) of the PCM prototype and the empty polycarbonate panel. The solar transmission coefficient was calculated as the ratio between the internal solar radiation and the external solar radiation (SOL_2_E). An average daily value was assessed for the three technologies analysed. Energy quantities, that cross the TGU_noPCMsh and TGU_PCMsh, were calculated as the integral of the total heat flux over the day. The total heat fluxes are calculated as the sum of the surface heat flux $\dot{q}$ in W/m^2 and transmitted solar irradiation SOL_TGU or SOL_TGU_PCMsh in W/ m^2 passing through the component. $E_{x,i}^{d}$ represent the specific energy passing through the component in Wh/m^2, calculated from 8 a.m. till the 8 a.m. of the following day. In order to evaluate the effect of the PCM shutter, the following energy quantities for the TGU_noPCMsh and TGU_PCMsh were considered:

- total specific daily energy passing through the component $E_{x,24}^{tot}$
- positive specific daily energy passing through the component $E_{x,24}^{+}$, energy that enters the indoor environment
- negative specific daily energy passing through the component $E_{x,24}^{-}$, energy that exits the indoor environment
- normalized daily energy that represents the difference of the energy passing through the façade with a shutter (TGU_PCMsh, TGU_noPCMsh) and the non-shaded façade (TGU), with respect to the reference TGU Σ_{24}^{d}

Table 1 Typical days for TGU_PCMsh

Daily solar radiation	Date	H [Wh/m^2]
High H	12-01-15	5018
Moderate H	10-01-15	1807
Low H	13-01-15	448

Table 2 Typical days for TGU_no_PCMsh

Daily solar radiation	Date	H [Wh/m^2]
High H	30-01-15	5180
Moderate H	29-01-15	2061
Low H	26-01-15	885

5. Results and discussion

The results presented in this paragraph are related to TGU, TGU_PCMsh and TGU_noPCMsh technologies with the boundary conditions showed in Figure 3a) and 3b) respectively. In Figure 4a) it is showed that the transmitted solar radiation through the TGU can be significantly reduced by the adoption of the proposed PCM prototype. For the TGU_PCMsh an average value of solar transmission (τ_s) was approximately 0.17 while for the reference TGU it was 0.39-0.42 and for the empty polycarbonate it was equal to 0.32. During a sunny winter day light spot measurements were performed with a portable luxmeter, proving the transparent properties of the PCM prototype for the visible light. The visible transmittance of the system with the PCM shading was in the range of 0.24 and 0.42 while for the TGU of 0.41-0.58.

Figure 4 shows the ability in terms of shortwave solar energy reduction by the PCM compared to the non-shaded TGU and to the TGU shaded by the empty polycarbonate panel. Indeed, as the selected paraffin wax demonstrates the property to absorb a considerable amount of the infrared part of the solar spectrum, the PCM shutter reduced the total daily solar heat gains of more than 50% during the peak hours, twice more than when the empty polycarbonate panel was applied. Consequently, the internal surface temperature of the glazing behind the PCM shutter represent a lower value compared to the TGU without the shading. During the peak condition, registered 11th January at 3p.m. the difference raised to more than 6°C (Fig. 5a). Decreased internal surface temperature of the glazing resulted in a reduction of the heat flux passing through the TGU (Fig. 5b). Moreover the adoption of the shutter improved the thermal performance of the component (TGU_PCMsh) also during the night time. A reduction of the long-wave heat exchange was monitored. It was possible to calculate, with the linear regression method, an equivalent thermal transmittance of the TGU_PCMsh of 0.76 W/m^{2}K compared to 0.86 W/m^{2}K of the reference TGU with a coefficient of determination (R^2) of 0.86 and 0.85 respectively. Indeed the PCM shutter increased the thermal resistance of a triple glazing unit of 0.15 m^{2}K/W.

Energy quantities, passing through the TGU and TGU_PCMsh are summarized in Table 3. Experimental analysis of the proposed prototype shows a significant thermal improvement of the TGU_PCMsh compared with non-shaded TGU of approximately 55% for the period with high and moderate solar radiation. During cloudy days, a decrease in the performance of the system with the PCM shutter was observed. As the energy quantities represent a very low

value, the negative impact of the prototype is negligible. However, it is to underline that the measurements were performed for the mid season conditions. Therefore during a typical winter period the reduction of solar heat gains due to the shading could have a negative effect on the energy balance.

Despite the high solar radiation and the moderate external air temperature, the PCM did not reach the phase change temperature and remained solid during the whole measuring period.

Table 3 Net specific daily energy

Daily solar radiation	$E_{TGU+PCMsh,24}^{tot}$ [Wh/m^2]	$E_{TGU,24}^{tot}$ [Wh/m^2]	Σ_{24}^{tot} [%]	$E_{TGU+PCMsh,24}^{+}$ [Wh/m^2]	$E_{TGU,24}^{+}$ [Wh/m^2]	Σ_{24}^{+} [%]	$E_{TGU+PCMsh,24}^{-}$ [Wh/m^2]	$E_{TGU,24}^{-}$ [Wh/m^2]	Σ_{24}^{-} [%]
High H	1032	2270	-55%	1153	2442	-53%	-122	-173	-29%
Moderate H	324	727	-55%	405	837	-52%	-81	-110	-26%
Low H	-145	-82	77%	36	120	-70%	-181	-202	-10%

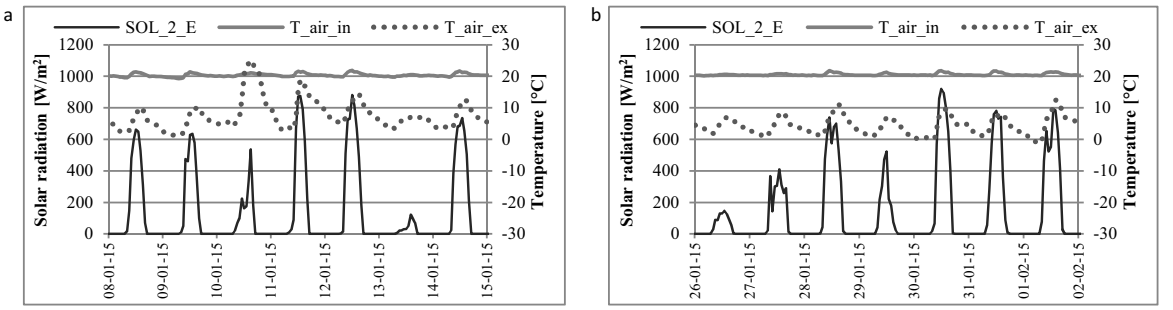

Fig. 3 The boundary conditions of the selected days for the energy performance assessment of: (a) TGU_ PCMsh; (b) TGU_noPCMsh

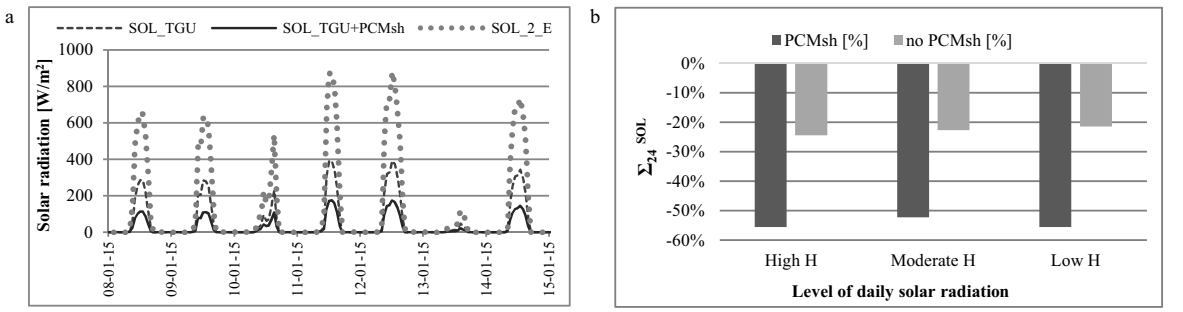

Fig. 4 (a) hourly profile of the solar radiation; (b) normalized solar energy passing through the PCMsh and no_PCMsh

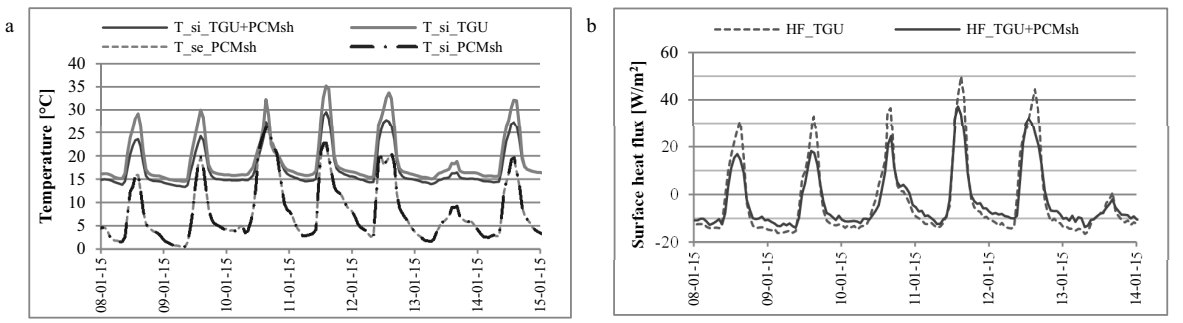

Fig. 5 (a) hourly profile of the surface temperatures; (b) hourly profile of the surface heat flux

6. Conclusions

The study was focused on the thermal performance of a solar shading integrating phase change materials during the solid phase of the PCM. The results show high potential of the panel in reducing solar heat gains. A considerable amount of the infrared part of the solar spectrum is absorbed by the panel, converted into heat and stored in the material. Both the polycarbonate panel and the solid PCM present a high value of visual light transmission so the shading panel still provides high illuminance level inside the building and thus could contribute to reduce energy demand for lighting if compared to traditional shading. Experimental analysis of the proposed prototype shows a significant thermal improvement of the TGU of approximately 55% for the period with high solar radiation. Moreover, the internal surface temperature of the glazing behind the PCM shutter demonstrated lower values compared to the TGU without the shading, which could also improve the thermal comfort in summer. However, further research must be conducted to evaluate its thermal influence on the façade when PCM is in the mushy and liquid state. Afterwards further optimization of the prototype, regarding the transition temperature and the amount of PCM, could be implemented to achieve better thermal performance. Finally it is to underline that the experimental campaign was performed for a triple glazing unit and the façade already demonstrates high thermal properties. Nevertheless the benefits of adopting the proposed PCM technology could be even more significant for a window with a lower solar factor or with lower thermal resistance, such as commonly used double glazing technology.

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