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Responsive glazing systems: Characterisation methods, summer performance and implications on thermal comfort

L. Bianco[a], Y. Cascone[a], F. Goia[b], M. Perino[a], V. Serra[a,*]

[a] TEBE Research Group, Department of Energy, Politecnico di Torino, Italy

[b] Department of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology – NTNU, Trondheim, Norway

A R T I C L E I N F O

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A B S T R A C T

In recent years, there have been several experimental and numerical researches on transparent envelope components that integrate phase change materials (PCMs). To address some of the drawbacks of these systems, new prototypes were created and their summer performance was monitored under Cfa climatic conditions (Turin, Italy). The proposed glazing system comprises a triple glazing unit with a thermotropic layer placed on the outer side, acting as a switchable shading system capable of regulating the phase transition of the PCM. The PCM is tested in both the inner and the outer cavity of the glazing, alternately. In this paper, the summer performance of these responsive glazing systems is reported, complementing the assessment of their performance under winter conditions, which was previously presented in another paper (Bianco et al., 2017). Two additional systems were also tested in parallel for reference purposes: a triple glazing unit with a thermotropic layer only, and a reference triple glazing unit. Direct solar transmission was assessed, and the correlation between glazing temperature and solar transmission coefficient of the thermotropic layer, when coupled with the triple glazing unit, was derived. The solar transmission as a function of the external surface temperature of the PCM glazing units was also evaluated. The energy performance was assessed by means of a long-term evaluation in addition to daily analyses during cloudy and sunny days. The capability of the aforementioned technologies to improve indoor thermal comfort was investigated, with the effect of the transmitted solar radiation impinging on the occupants also taken into account. The results highlight that the integration of a thermotropic layer in a triple glazing unit allows the cooling load through the transparent component to be reduced by one third when compared to a traditional triple glazing unit. The overall energy performance was found to be primarily affected by the position of the PCM; not only during winter season, but especially in summer, the PCM completed the phase transition only when placed in the outermost cavity. The thermal comfort conditions were improved, when evaluated in terms of traditional PMV, regardless of the position of the PCM layer. However, when the influence of the direct solar radiation impinging on the occupants was taken into account, the solution with the PCM layer located in the inner cavity presented a better performance.

1. Introduction

Transparent envelope components are key elements in buildings. They affect building energy performance and daylighting, and therefore have a significant effect on both thermal and visual comfort. To improve these aspects throughout the year, an accurate seasonal control of solar gains, heat losses and light gains is desirable. Dynamic glazing systems capable of modifying their thermo-optical properties according to defined boundary conditions are promising solutions to address this need (Favoino et al., 2015).

Dynamic behaviour in glazing systems can be achieved by several means. Thermochromic and thermotropic materials have been developed – characterised by the temperature dependency of their solar/visible absorption coefficient and their transmission mode (direct-to-direct or diffuse transmission), respectively (Seeboth et al., 2010). In this way, these systems can modulate the transmitted solar radiation, rejecting most of it during hot summer days, yet allowing a certain amount of solar gain to enter the building during cold winter days (Allen et al., 2017; Yao and Zhu, 2012).

Another way to achieve dynamic behaviour of glazing systems is by introducing a phase change material (PCM) within the gap of a double (Goia et al., 2014b; Gowreesunker et al., 2013) or triple glazing unit (S. Li et al., 2016), or within more-complex glazing components (Grynning et al., 2015, 2013). PCMs in glazing systems notably increase their

* Corresponding author.
E-mail address: valentina.serra@polito.it (V. Serra).

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Nomenclature

E	specific energy (Wh/m^2)
g	solar factor (–)
H	specific incident daily solar radiation (kWh/m^2)
HF	Heat Flux (W/m^2)
I	specific incident solar irradiance (W/m^2)
$\dot{q}$	specific heat flux (W/m^2)
t	time (h)
U	thermal transmittance ($W/m^2 K$)

Greek symbols

τ	transmission coefficient (–)
ϑ	temperature (°C)

Superscripts

*	referred to an equivalent value or a modified index

Subscripts

air	referred to air
average	referred to an average value
bn	beam normal
day	referred to day between sunrise and sunset
$\Delta\theta$	referred to temperature difference
e	solar
ex	excursion
i	referred to heat flux released to the indoor environment
in	referred to the indoor environment
n	referred to normalised energy
out	referred to the outdoor environment
sol	referred to solar energy
surf	referred to the surface
tot	total including long-wave and short-wave radiation
v	visible
24	referred to daily energy

Acronyms

CDD	Cooling Degree Days
ERF	Effective Radiant Field (W/m^2)
PMV	Predicted Mean Vote (–)
PPD	Predicted Percentage of Dissatisfied (%)
RMSE	Root Mean Square Error
TGU	Triple Glazing Unit, reference technology
TGU_TT	Triple Glazing Unit with thermotropic glazing
TGU_TT + PCM(IN)	Triple Glazing Unit with thermotropic glazing and a PCM-filled cavity in the inner position
TGU_TT + PCM(OUT)	Triple Glazing Unit with thermotropic glazing and a PCM-filled cavity in the outer position
TT	thermotropic glazing

inertial behaviour, smoothing the indoor surface temperature and providing peak load shifting. The PCM interacts with the incident solar radiation, acting both as a solar shading device and a heat storage medium. When in solid state, the PCM blocks most of the incident solar radiation, which is absorbed, causing the PCM to undergo phase change and eventually melt. During this process, a great amount of heat is stored by the PCM, preventing it from turning into a cooling load during the summer season. Furthermore, during the phase transition, the optical properties of the PCM are subject to a change: the transmission coefficient increases. This allows a much greater amount of solar radiation to enter the indoor environment when the PCM is fully melted. During the night, the PCM solidifies and releases the stored heat. According to the glazing configuration, this heat can be released mostly towards either the external or internal environment.

The performance of PCM-enhanced glazing components was investigated by several experimental (Goia et al., 2014b, 2013; Gowreesunker et al., 2013; S. Li et al., 2016) and numerical (Goia, 2012; Ismail et al., 2008; Zhong et al., 2015) studies. A review of PCM technologies developed for transparent and translucent building envelope components can be found in Silva et al. (2016).

Ad-hoc numerical models were specifically developed to take the interaction of PCM with solar radiation into account (Goia et al., 2012a; Ismail and Henríquez, 2002; Liu et al., 2016). With regard to the transparent components, not only the thermophysical but also the optical properties of PCMs play an important role in the thermal performance of PCM-filled glazing units (D. Li et al., 2016a, 2016b). Therefore, solar and visible properties are needed for a complete and accurate analysis of the behaviour of such components (Goia et al., 2015, 2012b; Li et al., 2015) and for a comprehensive evaluation, both thermal and visual aspects should be considered (Giovannini et al., 2017).

Other than contributing to improvements in the energy performance of buildings, the inclusion of PCM in glazing systems can have a positive effect on thermal comfort (Goia et al., 2013). However, the melting temperature of the PCM needs to be carefully selected according to the climate. During summer in particular, if complete melting of the PCM within a double glazing unit occurs before sunset, then the internal surface temperature of the glazing may increase to a level that may negatively affect thermal comfort (Goia et al., 2013).

Even though PCM-filled double glazing units have been proven to be beneficial in several ways, the introduction of PCM in a double glazing unit results in a reduced thermal resistance, negatively affecting the thermal performance of the system. In addition, seasonal control of the direction of the heat flux released during the night-time discharging phase (mostly towards the indoor or outdoor environment) would be desirable (Goia et al., 2014b). To address this, a novel technology that combines a PCM-filled triple glazing unit with a thermotropic layer was proposed (Bianco et al., 2017; Goia et al., 2014a). The use of a thermotropic layer can offer better control of the charging phase of the PCM. In addition, combining a PCM with a gas-filled gap in a triple glazing unit improves the thermal resistance of the system and can also offer better control of the discharging phase according to the position of the PCM.

For the tests conducted on this newly proposed technology, PCM (paraffin wax with a melting range between 33 °C and 37 °C and peak melting temperature of 35 °C) was used in the inner or the outer cavity of the triple glazing, alternately, while the second cavity was filled with 90% Argon and presented a low-e coating. In this way, only a slight decrease of the thermal resistance of the glazing was achieved (compared to a conventional triple glazing unit). The melting temperature of the PCM was selected in accordance with a previous experimental study carried out in Turin, where it was demonstrated to be suitable for the local climate. The thermotropic layer, which was a commercially available product, was always placed as the outermost layer. The behaviour of the thermotropic layer alone, when coupled with a triple glazing unit without the inclusion of PCM, was also monitored. Overall, the following technologies were tested (refer to Appendix A):