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Responsive glazing systems: Characterisation methods and winter performance

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ABSTRACT

Responsive envelope components are promising technologies for improving the energy and indoor comfort performance of buildings. As far as the transparent envelope is concerned, several experimental and numerical researches have been carried out in recent years, focusing on the integration of Phase Change Materials (PCM) in glazing systems. To overcome some limitations highlighted during previous experimental campaigns, a new concept was prototyped, and the energy and comfort performance of a full-scale prototype was experimentally assessed in an outdoor test cell facility. In this paper, the focus is placed on the evaluation of the cold-season behaviour. The proposed glazing system comprises a triple-glazed unit with a PCM-filled cavity and a thermotropic glass placed on the outer side. The thermotropic glass acted as a switchable shading system capable of regulating the phase transition of the PCM by modulating the amount of solar radiation impinging on the PCM layer. The thermophysical and optical behaviour of the technology was monitored with the PCM alternately placed in the inner or the outer cavity of the triple-glazed unit and compared against a reference triple-glazing unit. In parallel to the measurements on the glazing with PCM and thermotropic glass, a triple-glazed unit equipped with a thermotropic glass was also monitored, giving a total of three different glazing systems under analysis. Representative days were selected in order to analyse the performance of the proposed technologies under significant and comparable boundary conditions. The equivalent thermal conductance of each technology was evaluated. The energy performance was assessed by means of both a long-term analysis and daily analyses on cloudy and sunny days. In addition, the visible transmittance of the three technologies was estimated through hourly measurements of vertical illuminance performed during a cloudy and a sunny day. Moreover, implications on thermal comfort conditions were evaluated ex-post by means of numerical simulations based on experimental data. The results showed that, during cloudy winter days, the position of the PCM did not influence the overall performance of the prototype since it never changed phase. On the other hand, during sunny winter days, the glazing with the PCM in the outer position underwent phase transition and presented a slightly better performance.

1. Introduction

1.1. Background

Glazing systems are key components of the building envelope, affecting the energy and environmental performance of buildings in several ways. On the positive side, they allow natural light to be exploited for daylighting; however, on the negative side, they are responsible for the largest component of heat gain and heat loss.

Due to the opposing requirements that arise during the different seasons (allow/reject solar gain, reduce heat loss, control light gain), the most promising direction of research and development for glazing technologies in the improvement of energy and indoor environmental performance is towards solutions that allow a dynamic behaviour to be achieved, as shown in a recent study on the energy-saving potential of an ideal dynamic glazed system (Favoino et al., 2015).

Several possibilities can be exploited to turn glazing systems into responsive and dynamic components. The integration of mechanical shading systems is probably the most popular option and, when combined with ventilated cavities, good performance can be achieved (including solar energy exploitation through the thermal energy of the ventilation flow).

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Nomenclature

C	thermal conductance (W/(m^2 K))
E	specific energy (Wh/m^2)
Ev	vertical illuminance (lx)
H	specific incident daily solar radiation (kWh/m^2)
HF	monitored surface 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	transmittance (–)
ρ	reflectance (–)
ϑ	temperature (°C)

Superscripts

$*$	referred to an equivalent value
$+$	referred to heat flux/energy gain
$-$	referred to heat flux/energy loss

Subscripts

air	referred to air
average	referred to an average value
e	solar
ex	excursion
in	referred to the indoor environment
n	referred to normalised energy
out	referred to the outdoor environment
surf	referred to the surface
tot	total including long-wave and short-wave radiation
v	visible
24	referred to daily energy

Acronyms

HDD	Heating Degree Day
IR	Infrared
PMV	Predicted Mean Vote
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

Another approach is based on the adoption of active layers that modify the optical properties of the glazing, usually acting on the transmittance and absorptance of the layer (Baetens et al., 2010). Some of these technologies are based on self-triggered adaptive mechanisms (i.e. passive-dynamic, or responsive, technologies) or on a controllable external stimulus (i.e. active-dynamic technologies). Among the most investigated passive technologies, it is worth mentioning thermochromic, thermotropic, and photochromic layers. The most common active-dynamic technologies are electrochromic, light particle devices, and liquid crystal devices.

When focusing on responsive glazing technologies, thermochromic/thermotropic layers have been the most widely investigated and tested materials. While thermochromic materials present a dependency of the solar/visible absorption coefficient on the layer's temperature (the higher the temperature, the higher the absorption coefficient), thermotropic materials present different transmission modes depending on the temperature of the layer (direct-to-direct transmission occurs at low temperature levels, whereas at high temperature levels the diffuse transmission becomes dominant, and the total reflectivity of the layer increases).

Several authors studied thermotropic glazing with a focus on the material level. Muehling et al. (2009) presented the preparation and the optical characterisation of a glass–resin–glass thermotropic system. Seeboth et al. (2010) reviewed materials and technologies for thermotropic and thermochromic glazing. Weber and Resch (2012) studied the effect of material composition on the performance of thermotropic systems with fixed domains for overheating protection. Gladen et al. (2014) performed a parametric analysis to identify potential material combinations for manufacturing thermotropic glazing for application on flat plate solar collectors.

The optical and thermophysical performance of thermotropic systems has also been assessed by means of in-situ measurements (Raicu et al., 2002) and numerical simulation (Allen et al., 2017; Georg et al., 1998). In different investigations, the optimal configuration of thermotropic glazing was found to provide significant energy savings and improve the comfort of the occupants (Inoue, 2003), including the case of a real building application for retrofitting purposes (Nitz and Hartwig, 2005). Thermotropic glass panes were often tested or simulated when integrated in a simple double-glazing unit (DGU) (e.g. Yao and Zhu, 2012), but applications in more complex structures or functions (e.g. a thermotropic glazing that included a heating layer for active dimming control) were also investigated (Inoue et al., 2008).

Dynamic optical and thermophysical properties can also be achieved through the integration of a responsive layer in place of the usual air/gas cavity in multi-pane glazing systems. An example of such an approach is given by the inclusion of a Phase Change Material (PCM) layer (Goia et al., 2014a,b, 2013; Li et al., 2016c; Silva et al., 2016), whose aim is primarily to improve the exploitation of solar energy through a better control of the direct heat gain.

The concept of PCM glazing is centred around the particular way in which the PCM layer interacts with the impinging solar radiation; it acts as a solar shading device, as a storage medium, and as a moderator of the glazing surface temperature. A PCM glazing system is therefore expected to reduce gains/losses of energy compared to a standard glazing system and to smooth the indoor surface temperature, both in summer and winter. It filters and buffers the incident solar radiation which, during the daytime, may exceed the instantaneous heating demand of the building – shifting the solar gain towards the late afternoon and/or evening, when transmission and ventilation losses are higher. In summer, the PCM layer reduces cooling loads and the indoor surface temperature of the glazing, with a positive impact on both energy demand and comfort conditions. In summary, the introduction of a PCM layer into the glazing system noticeably increases the inertial behaviour of the window.

The first experimental activities related to the integration of PCMs in transparent buildings date back to the late 1990s (Ismail and Henrı, 1998; Manz et al., 1997). Although some intrinsic limitations of the material's properties – such as low thermal conductivity and volume change during the phase transition (Cuce and Riffat, 2015) – need to be carefully considered, the optical