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Marco Perino, Vincenzo Corrado

Politecnico di Torino - Department of Energy, TEBE research group. Torino – Italy (marco.perino@polito.it, vincenzo.corrado@polito.it)

Following the success of earlier events in the series, the 6th International Building Physics Conference (IBPC 2015) - the official conference of the International Association of Building Physics (IABP) – took place in the lively city of Torino, hosted by Politecnico di Torino and co-organized by ATI Piemonte and the Department of Energy - Politecnico di Torino.

IBPC 2015 was focused on the theme “Building Physics for a Sustainable Built Environment” and invited participation and paper submissions across a broad range of topics relevant to the main subject of Building Physics.

The conference provided a forum for scientists, researchers and practitioners from all over the world to disseminate technical information, new ideas, the latest developments and discuss future direction in the fields of building physics. The conference was attended by more than 650 delegates coming from 47 countries.

This issue contains 609 manuscripts selected and peer reviewed by the review committee of IBPC 2015.

The topics covered by the conference included: energy efficient design and retrofit of buildings, indoor environment control for comfort and/or preservation, IAQ and ventilation, building and architectural acoustics, noise control, lighting, visual and acoustic comfort, building material and components, energy and economic sustainability of high performing buildings, optimization and modelling techniques as well as a broad range of building integrated RES (Renewable Energy Sources) and ZEB (Zero Energy Buildings).

In addition to presentations of technical papers, IBPC 2015 also included expert keynote talks, workshops, special sessions for IEA and EU research projects and doctoral student seminars.

Guest Editors/Chairs of IBPC 2015.

Prof. Marco Perino
Chair of IBPC 2015
TEBE Research group
Department of Energy
Politecnico di Torino

Prof. Vincenzo Corrado
Co-chair of IBPC 2015
TEBE Research group
Department of Energy
Politecnico di Torino

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Thermal and optical properties of a thermotropic glass pane: laboratory and in-field characterization

Lorenza Bianco[a], Francesco Goia[b], Valentina Serra[a,]*, Michele Zinzi[c]

[a]TEBE Research Group, Department of Energy, Politecnico di Torino, Torino, Italy
[b]The Research Centre on Zero Emission Buildings, Faculty of Architecture and Fine Art, Norwegian University of Science and Technology, Trondheim, Norway
[c] ENEA—Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Roma, Italy

Abstract

Switchable windows are glazing technologies that exhibit dynamic optical properties and may thus be used to improve the energy performance of buildings. A window system based on a thermotropic glass pane was tested both in the laboratory and by means of an outdoor test cell facility.

In this paper the full optical and thermal characterization of this glazing technology is presented. Experiments and data analysis led to the characterization of the behaviour of the thermotropic glazing both when this technology is used alone (single glass pane) and when it is integrated in a multilayer fenestration (a triple glazed unit).

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Keywords: Switchable windows; thermotropic glass; test cell; optical properties; experimental analysis.

1. Introduction

Thermotropic materials are a particular group of chromogenic substances that exhibit a reversible change in the optical properties depending on the temperature of the layer itself. These materials are usually realized by either a combination of two components that separates above a certain temperature (phase separation) or by particles embedded in a polymeric matrix [1] which change its phase of aggregation (solid to liquid) above a certain temperature (phase

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* Corresponding author. Tel.: +39 0110904431; Fax: +39 0110904499
E-mail address: valentina.serra@polito.it

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transition). In the former case, the switch in the optical properties is obtained by phase separation (the two components do not change the individual optical properties), while in the latter case the principle of functioning is based on a change in the optical properties of the particles (phase transition) [2]. Thermotropic layers based on phase transition are not activated (*off* state) when the thermotropic layer is below the switching temperature, and under such a condition the particles and the matrix present a very similar refractive index. This determines high visual and solar transmission, primarily in direct-to-direct mode. When the thermotropic layer is activated, that is when its temperature is above the switching point, the refractive index of the embedded particles changes due to the phase change (from solid to liquid). This results in an increased scattering in the bulk of the material. Under this state, the layer becomes less transparent, with higher reflectance and absorptance, as well as transmission/reflection primarily in diffuse mode [3].

A new product based on phase transition in protected domains has been developed not long ago and it is nowadays available on the market as a laminated glass [2]. However, in order to achieve compliant thermal transmittance values and comfort requirements, such a technology needs to be integrated in a more complex window system – i.e. a double or a triple glazing unit.

The aim of the research is to characterize the dynamic behavior of such a responsive component both at the technology scale and when it is integrated in a multilayer fenestration system. Moreover, only solar and luminous properties for *on* and *off* state, without any information for the switching phase (which occurs in a relatively wide temperature range and therefore represent a not negligible state of functioning) are available, limiting the possibility to correctly simulate the performance of such a components by means of building performance simulation tools. Optical properties are thus also evaluated in the laboratory for the switching phase, while a full scale (in outdoor test cell) experimental campaign provides information about the thermal and energy behavior of this system in a real-case application.

2. The thermotropic technology

The thermotropic laminated glass tested during the research activity is called SOLARDIM® ECO [4] and it is commercially available. The thermotropic glass pane is constituted by a clear glass pane of 4 mm thickness, a green glass pane of 4 mm, and a 1.5 mm resin layer (the thermotropic layer) placed between the two glass panes (Fig. 1 b sample A). The values declared in the manufacturer's technical datasheet are referred to a resin layer of 1.7 mm and a 2x1 mm clear glass with the change of the optical properties occuring in the temperature range 20°C to 40°C. The visual and solar properties reported in the datasheet (normal-hemispheric mode) are: τ_l *on*=0.35, τ_l *off*=0.69, τ_e *on*=0.41 and τ_e *off*=0.69. The declared glass thermal transmittance is 5.74 W/m^2K, the g-value is 0.78 and 0.59, for mode *off* and *on* respectively.

When assembled in a more complex window system, the thermotropic glass pane was positioned in front of a triple glazing unit (sample B) composed by (from outdoor to indoor):

- 9.5 mm thermotropic laminated glazing
- 8 mm clear glass pane with low-e coating
- 15 mm filled with 90% of Argon
- 8 mm clear glass pane
- 15 mm filled with 90% of Argon.
- 4 mm clear glass pane

The same triple glazed assembly was used to realize a reference fenestration (Sample R) that was simultaneously tested in the same outdoor test cell facility for comparison purpose (Fig. 1 a).

3. Experimental characterisation

The experimental characterisation of the glazing systems was carried out in the laboratory and through an outdoor test facility. Spectrophotometry measurements were done to evaluate the optical properties in the laboratory. In parallel an experimental activity in test cell was performed to measure the performance of the technologies when exposed to real boundary conditions. Laboratory measurements were conducted only on the thermotropic laminated glazing (sample A), while test cell measurements were carried out on the three samples: the thermotropic laminated glazing alone (sample A), the triple glazing unit with the thermotropic (sample B) facing the outdoor environment and the reference triple glazing unit (sample R).

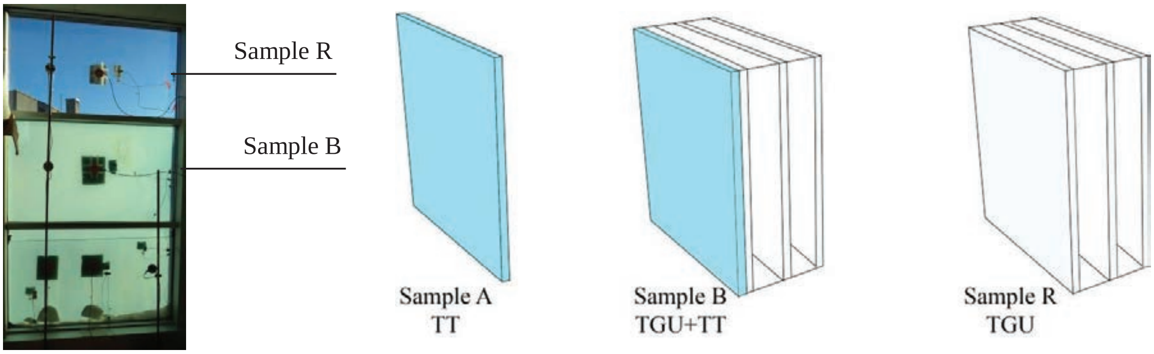


Fig. 1. (a) Internal view of the test cell measurement, Sample B and R mounted in the test cell TWINS, (b) The different samples tested during the experimental campaign.

3.1. Laboratory measurement

The optical characterisation of the thermotropic laminated glazing (sample A) was carried out with an in-house optical bench, consisting of the following components.

- Light source: 300W xenon arc lamp power. The collimated beam can be adjusted by means of lenses and diaphragm, to set the diameter of the required size according to the measurement requirements. A 6 cm diameter was set for this campaign,
- Integrating sphere (75 cm in diameter). The inner surface is made in Spectralon, a high diffusive material with a reflectivity greater than 95% in the whole solar range (300-2500 nm). The sphere is equipped with several ports to perform measurements of the optical properties. A 20 cm sample port was used for this campaign,
- Detection system: two array spectrometers and two detectors – NMOS for the 380-900 nm range (resolution 1.4 nm/pixel) and InGaAs for the 900-1700 nm range (resolution 3.125 nm/pixel).

The spectrophotometers have a measurement error of ± 0.02 (considering a spectral quantity that ranges from 0 to 1). The experimental layout is shown in figure 2.

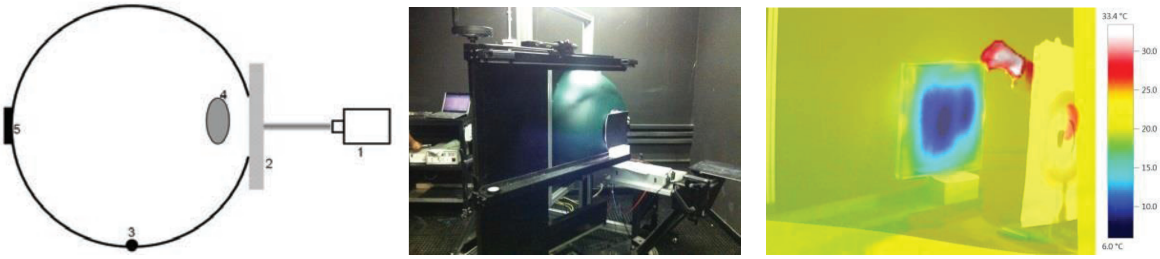


Figure 2. Optical bench apparatus in transmittance modes (left). Main parts: 1-light source; 2-sample port (transmittance port) with holder; 3-opticfibre connected to the detection system; 4-auxiliary port; 5-reflectance port. Optical bench in reflectance mode (middle). Infrared thermal image of the sample A during the measurement (right)

According to the test procedure, the measured (beam-hemispherical) quantities were: solar (τ_e) and visual (τ_l) trasmittance at different incidence angles (0°, 30°, 45°, 60°); solar (ρ_e) and visual (ρ_l) reflectance at near-normal incidence, measured versus a Spectralon white reference. Being the experimental set-up of single beam type,

transmittance and reflectance measurements were corrected with the auxiliary port method [5].
Measurements were carried out at different sample temperature and the surface temperature was controlled by thermal images acquired by Testo 875-2i with a ±2°C accuracy (Fig. 2 right). First, a calibration of the thermal apparatus was carried out and the emissivity of the thermographic camera was set according to the surface temperature of the sample measured by means of a contact sensor (thermocouple). Samples were tested in the range of 11 °C to 46 °C (surface temperature).

Solar and light reflectance ρ were calculated starting from spectral data following the methodology presented in ISO 9050:2003 [6] and the same procedure was applied for the transmittance (τ). Solar transmittance and reflectance were calculated in the 380-1700 nm range, instead of 380-2500nm range, because of the limitation of the measurement setup. The observation range is equal to 93% of the whole solar power, according to the procedures defined in ISO 9050:2003 [6], and thus well representative of the entire solar spectrum.

3.2. Test cell measurement

Parallel to the lab measurements, an experimental campaign was conducted by means of an outdoor test cell facility. The thermotropic glazing integrated in a triple glazing unit (Fig. 1 sample B) was mounted on the south exposed façade of the test cell [2] which has a controlled indoor air temperature (tolerance ±1 °C). The measurements were carried out during different seasons by means of temperature sensors (thermocouples), heat flux meters and pyranometers connected to a data logger for continuous data acquisition. Since October 2014 the sample B was disassembled and the measurements were conducted only on the laminated thermotropic pane (Sample A).

Data analysis was performed to calculate the equivalent thermal transmittance (*U*-value*) of the different samples through a linear regression method. Moreover, external and internal pyranometers allowed solar transmission (τ_e) to be calculated as the ratio between the transmitted and the impinging solar radiation. An equivalent solar factor was evaluated according to the equation presented in (1). The measurement in test cell did not allow the *g-value* to be directly determined due to dynamic temperature profile of the outdoor environment and of the geometrical aspects of solar radiation (beam angle, diffuse vs. direct irradiance). However, it is worth highlight that this method limits the assessment of the *g*-value* as a daily average, therefore including on, off state and transition phase.

$$g* = \frac{E_{24,t�} - E_{24,\Delta t}}{E_{24,i�}} \qquad (1)$$

Being:

$E_{24,t�}$ Daily total energy gain (or loss) through the technology (short-wave and long-wave radiation) [Wh/m^2];
$E_{24,\Delta t}$ Daily energy gain (or loss) through the technology due to the indoor-outdoor thermal gradient [Wh/m^2];

$E_{24,i�}$ Daily solar irradiation on the technology’s external surface [Wh/m^2].

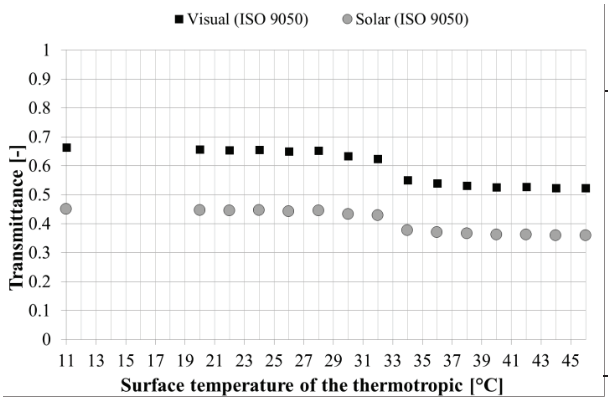
4. Results and discussion

4.1. Laboratory measurement

When the thermotropic laminated glazing is in active state (translucent), which means above the transition temperature, it shows an increase in the solar and visual reflectivity due to back-scattering effect, and a consequent reduction in transmittance. In Fig. 4 and Tab. 1 τ_l and τ_e are plotted against the sample’s surface temperature, monitored by means of infrared thermal imaging.

During *off* state (clear), corresponding to a surface temperature between 11 °C and 28 °C, visible and solar transmittance present a constant value of 0.65 and 0.45 respectively. It is important to point out that the thermotropic material presents a slightly translucent aspect (i.e. part of the transmitted radiation is scattered) even when in *off* state, which determines a reduction of the transparency. The switching phase occurs in the range between 28°C and 34°C of the surface temperature, but the highest reduction of τ_l and τ_e is observed between 32 °C and 34 °C. During the *on* state (translucent), when the surface temperature is higher than 34 °C, τ_l further decreased from 0.55 to 0.52, while τ_e decreased from 0.38 to 0.36. Visual and solar properties are lowered, when switching from fully transparent to fully translucent state, by 21% and 20 % respectively. These results are not in line with data available from the technical data sheet of the product, which report a greater difference between visual and solar properties when in different state, probably due to the different sample features and measurement equipment.

In Tab. 2 a) the integral values of the solar, visible and near infrared transmittance at different incident angles for the *off* state are reported. Reflectance values are given in Tab. 2 b), where state *off* values correspond to a sample surface temperature of 11/13 °C while state *on* refers to a sample temperature of 45 °C. As expected, it is possible to notice that, when the material is in *on* state, transmittance decreases while reflectance and absorptance increase.



Surface temperature [°C]	τ_e [-]	τ_l [-]	Surface temperature [°C]	τ_e [-]	τ_l [-]
46	0.36	0.52	30	0.43	0.63
44	0.36	0.52	28	0.45	0.65
42	0.36	0.53	26	0.44	0.65
40	0.36	0.53	24	0.45	0.65
38	0.37	0.53	22	0.45	0.65
36	0.37	0.54	20	0.45	0.66
34	0.38	0.55	11	0.45	0.66
32	0.43	0.62			

Fig. 4. Solar and visible transmittance at the varying of the sample

Table 1. Solar and visible transmittance for different sample surface temperature. temperature.

Table 2 a). Angular characterisation for a sample state *off*, on the solar, visual and nir spectra transmittance, for different beam angles, according to ISO 9050:2003 (left). b) the solar, visual and nir spectra transmittance, transmittance, reflectance and absorptance, for state *off* and *on*.

Angle	τ_e [-]	τ_l [-]	τ_n [-]
0°	0.45	0.67	0.27
30°	0.42	0.63	0.24
45°	0.38	0.58	0.22
60°	0.33	0.50	0.18

	τ_e [-]	τ_l [-]	τ_n [-]	ρ_e [-]	ρ_l [-]	ρ_n [-]	α_e [-]	α_l [-]	α_n [-]
state *off* (11-13°C)	0.45	0.66	0.26	0.07	0.10	0.05	0.48	0.24	0.69
state *on* (45°C)	0.36	0.52	0.23	0.10	0.16	0.05	0.54	0.32	0.72

4.2. Test cell measurement

As far as the test cell campaign is concerned, the assessment of the thermal behavior of the thermotropic technology (sample A) and the component with the thermotropic (sample B) is carried out by comparing the performance of the two glazing systems against that of the reference triple glazed unit (which does not integrate any termotropic layer). Thermal transmittance values were calculated and result equal to 0.78 W/m^{2}K and 0.90 W/m^{2}K, respectively for the triple glazed unit with thermotropic glazing (sample B) and without thermotropic layer (sample R), respectively. The thermal transmittance of the laminated thermotropic glazing alone is clearly higher than those of sample B and R. A U-value of 4.3 W/m^{2}K was measured for the laminated thermotropic glass alone. Thermal transmittance values were used to assess the g*-values, that are presented in Tab. 3. The thermotropic technology is able to reduce by 37% the solar heat gain; when the thermotropic technology is applied to a TGU, the solar coefficient of the system decreases from 0.47 to 0.18. However, it must be stated again that this value corresponds to a daily average and thus cannot fully describe the dynamic behavior of the system. Regarding the solar transmission, a comparison between the data collected for sample A, B and R was performed during two mid-season days (October and April) representative of a state *off* configuration. The direct solar transmission (τ_e) of sample B is in the range of 0.14, while for sample A and R is 0.33 and 0.45, respectively.

Data from a hot summer day with high solar radiation were also analyzed in order to better characterize the *on* state of sample B. By looking at the trend of the solar transmission in Fig. 5, it is possible to notice that the values vary between 0.13 and 0.21. From 09.00 to 11.00 the surface temperature of the glazing is in the switching phase, but the trend of the τ_e does not show any relevant reduction. Just a small decrease in the solar transmission values for the sample B can be noticed, but a similar trend is registered for the reference sample R. This can be explained considering measurement inaccuracy due to unwanted partial shadows over the internal pyranometer.

It is possible to state that the switching effect and the dynamic property of the thermotropic glass pane, when applied in a TGU, are not evident due to the combined effect of all the glazed layers of the system.

	Sample A	Sample B	Sample R
	TT	TGU+TT	TGU
g*	[-]	[-]	[-]
	0.63	0.18	0.47
τ_e	[-]	[-]	[-]
	0.33	0.14	0.45
U*	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]
	4.30	0.78	0.90

Table 3. g*-value and U-value for the three samples (state *off*).

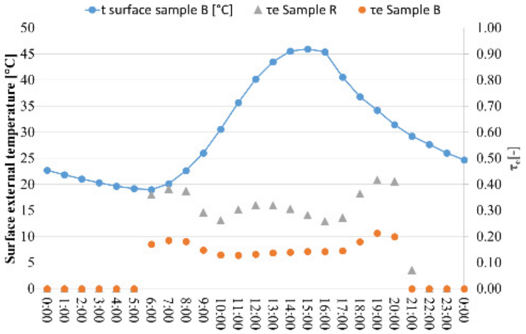


Fig. 5. Solar transmission coefficient of Samples B and R and surface temperature of Sample B.

5. Conclusion

A thermotropic laminated glass has been investigated both at component (single laminated glass) and at system (assembled in a triple glazed unit) level. Laboratory and test cell measurements have been carried out in order to characterize the thermal and optical properties of the samples at the varying of the surface temperature.

In this paper, the characterisation of the optical properties of the technology at different temperature levels, and assess the switching phase interval (between 28 °C and 34 °C) is presented. The reduction of the solar and visual transmittance between the *off* and the *on* state is revealed to be around 20%. Angular characterisation is presented for the state *off* of the technology.

Data collected by means of test cell monitoring have been analysed in order to assess the equivalent solar factor (g*), U-value and direct solar transmittance for the *off* state configuration of the technology. The *on* state configuration was analysed as well but just a small decrease in the solar transmission values for the sample B compared to sample R was noticed.

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