

6th International Building Physics Conference, IBPC 2015

Energy performance of an all solid state electrochromic prototype for smart window applications

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Abstract

Electrochromic devices suitable for architectural applications must exhibit acceptable levels in specific performance indicators to carry out useful energy saving functions. These parameters indicate the global response of the window to the solar radiation and completely determine the energetic performance of the glazing. In this paper we present performance data of a home-made all solid state prototype which meets most of the basic requirements. The device is characterized by a visible transmittance modulation between around 68 and 14% (in the full bleaching and colouring states respectively) and demonstrates repeatable behavior after 12 h cyclization.

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Electrochromics; smart windows, solar energy, daylighting, advanced glazing.

1. Introduction

In recent years, considerable interest has been addressed towards advanced glazing, windows being responsible of the highest fraction of energy loss or gain in building facades. Solar heat gain accounts for about 37 % of the total cooling energy consumption of buildings while heat loss through windows represents over 40 % of the total building energy leakages. Nevertheless, highly insulated passive houses are able to fulfil the winter heating energy needs by uniquely exploiting solar heat gains. These few examples show how fenestration components of modern energy

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saving buildings should be conceived to provide improved utilization and control of radiant solar energy by integrating dynamically switchable devices able to change their optical properties as a function of the external climatic conditions. In this framework, electrochromic (EC) windows, characterized by persistent and reversible modulation of their visible and near IR optical transmittance under the action of a low voltage, represents the new frontier of advanced glazing building research [1].

In this paper we present performance data of an home-made all solid state EC prototype based on amorphous tungsten trioxide. The potential of the device for architectural applications is evaluated by measuring the most critical indicators related to energetic performance, namely the optical transmittance and reflectance coefficients, the solar heat gain coefficient, the thermal transmittance and, in addition, the lifetime. The measured values are then compared to the optimal performance requirements for smart window applications, the last data being deduced in this study by literature review.

2. Experimental: the EC device

The home-made EC glazing prototype is a full solid state device of area 12×12 cm² and thickness 8 mm comprising different layers deposited on two glass substrates covered by fluorine doped tin oxide according to the following configuration:

Glass/SnO₂:F/WO₃/PEO-PEGMA:Li/NiOH:Li/SnO₂:F/Glass

- The “active” layer is a tungsten trioxide (WO₃) film deposited by r.f. sputtering from a tungsten trioxide target.
- The “ion storage” layer (NiOH:Li) is a nickel oxide film electrochemically deposited on the conducting glass and subjected to insertion of lithium ions by cyclization in a saturated LiOH 1 N electrolytic solution.
- The middle layer (PEO-PEGMA:Li) is a polymeric electrolyte with lithium dissolved salts acting as a ion conductor directly deposited on both electrodes by a spray gun.

The “active” layer and the “ion storage” material exhibit a complementary electrochromism. When an electric voltage is applied to the electrodes the metallic cations contained in the storage are driven by the electric field through the ion conductor and then are injected into the active material where they combine with the electrons furnished by the external circuit. The consequent change in colour induced by oxidation on the working electrode is the same of that induced by reduction on the counter electrode so that they bleach and colour simultaneously, thus reinforcing the overall colouring effect. The process is reversible and a bleaching process is observed when the EC electrode is positively biased and the ions are released from the coloured material towards the ion conductor. For additional information on the preparation technique and on the structural composition of the sample the reader is addressed to previous studies [2] and references therein included.

3. Results and discussion

This section reports on the experimental methodology and analysis carried out to characterize the energy performance of the prototype.

3.1 Optical transmittance coefficients

The characterization of the optical properties of the device in different switching states involved the measurement of the UV-VIS-NIR (near) normal transmittance spectra by a Perkin-Elmer Lambda 2 spectrophotometer in the 300-1000 nm range and by a Perkin-Elmer system 2000 FT-IR in the 1000-3500 nm range. Results are shown in Fig. 1 where the UV-VIS-NIR (near) normal transmittance spectra for both the fully bleached and fully coloured states is reported. The luminous and solar transmittance coefficients for both the full bleaching and full colouring states are calculated from the transmittance spectrum according to the methodology reported in [3]. Calculation provides the values ($\tau_V=0.68$, $\tau_S=0.51$) for the bleached state and ($\tau_V=0.14$, $\tau_S=0.10$) for the coloured state with a contrast ratio $CR = \tau_V(\text{bleach.}) / \tau_V(\text{color.}) \approx 5:1$. Lower values of the fully coloured transmittance can be obtained by increasing the coloration time, but at the expense of reversible behaviour. Also important for building applications is the residual transmittance regulation in the near infrared region where about 50% percent of the total solar radiation falls.

Contrast ratios at the most equal to 10:1 are required when the EC glazing has to perform energetic tasks (minimization of heating/cooling loads and artificial lighting energy consumption) regardless of visual comfort requirements. Most computational studies [4, 5] show, in fact, that EC windows with CR ranging between 5:1 and 10:1 are able to provide significant energy saving compared to conventional glazing. Reduction in energy consumption of the order of 30÷50% of the total heating, cooling and lighting building energy use has resulted from building simulations in cooling dominated climates. The energy saving diminishes in heating dominated climates or when the EC glazing is operated by control strategies trading off between energy-based and comfort-based issues [4]. Dynamic ranges higher than 10:1 don't automatically lead to an increase in energy saving. This is because the minimum achievable solar heat gain coefficient (SHGC) is not significantly reduced when CR falls below 10:1 [6]. On the other hand, for very low values of the visible transmittance, the cooling load reduction benefits are generally exceeded by the increase in lighting requirements.

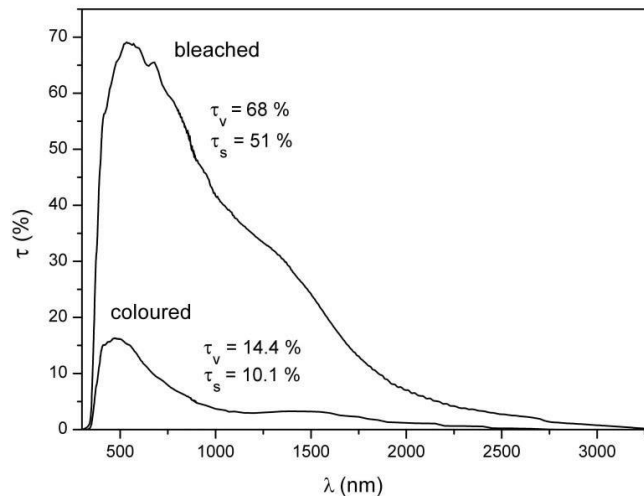


Fig. 1. Optical transmittance spectra of the EC device in the full bleaching and full colouring states

From these arguments we can conclude that the prototype exhibits modulation ranges suited to accomplish almost all the energy tasks required in buildings. Higher values of the full bleaching transmittance, anyway, would be desirable to enhance daylight utilization in the winter season and heating dominated climates.

3.2 Solar heat gain coefficient

For most WO_3 based EC devices the physical mechanisms subtending the change in optical transmittance in response to the applied voltage is light absorption so only a small fraction of the impinging solar radiation is reflected off. This entails that the internal surface of a single-pane EC window – when switched to low transmittance states – releases a great fraction of the absorbed radiation towards the indoor environment via convective and radiative heat transfer. So, in order to correctly estimate the real potential of EC devices in performing energetic tasks, the solar heat gain coefficient (SHGC) should be taken as relevant parameter. The highly absorbing behaviour of most EC devices diminishes obviously their effective dynamic transmittance control on solar radiation and the associated energy performance in buildings. The technical solution routinely practiced to overcome this problem is to dispose the EC multi-layer coating on the inside surface (surface 2 counting from the outside) of a double-glazed insulating window [6]. A low-emissivity coating on the inner pane (surface 3) will further increase the rejection of the absorbed heat to the outside.

To simulate realistic glazing behaviour the prototype has been assembled with an ordinary 4 mm thick clear float glass (without coating) to form the outer pane (pane 1) a small-size double glazing unit (DGU) of area $12 \times 12 \text{ cm}^2$ and with about 10 mm air gap (see Fig. 2 a). The DGU has been then integrated in a test-cell equipped with

photosensors and temperature sensors which allowed to monitor the microclimate parameters influencing the heat transfer with the local outside environment. The SHGC is calculated by applying energy balance to the test cell while using the monitored parameters as an input (for details see ref. [2]). The experimental results (acquired in summer-time under real sky conditions) are shown in Fig. 2 (b) where the SHGC is plotted as a function of the sunlight incidence angle for the EC glazing switched to the full bleaching (open circles) and full colouring (full circles) state. The values obtained for the SHGC coefficient in the full bleaching and full colouring states are 0.53 and 0.12, respectively.

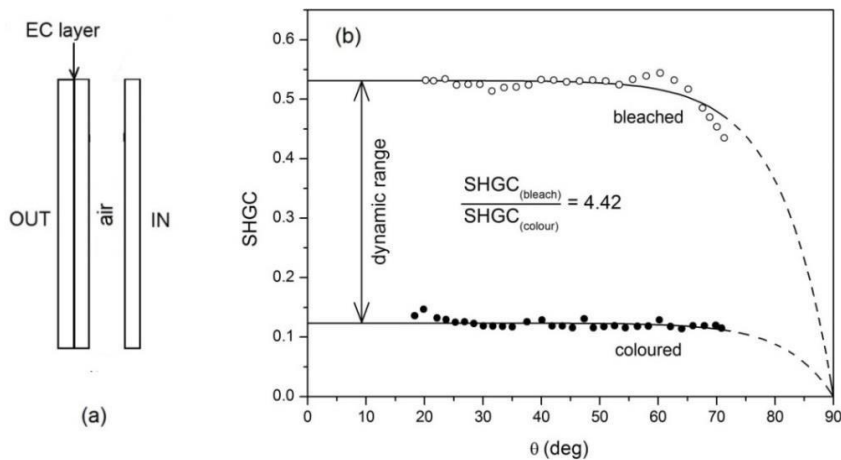


Fig. 2. (a) The schematic of the DGU assembled for tests. (b) The angle dependence of the solar heat gain coefficient for the EC-DGU fully bleached (open circles) and fully coloured (full circles).

Electrochromic glazing should be able to switch to SHGC values as high as 0.6 (typical of high-solar gain low-e glazing) when heating is required while it should be able to attain SHGC values as low as 0.2 (typical of spectrally selective low solar gain low-e glazing) when cooling is required [7]. Building simulation studies [8] show that the general criteria $SHGC_{(bleach)}/SHGC_{(color)} > 3$ should provide at minimum 10% saving in building energy demand compared to low-e glazing. For the home-made prototype the resulting value of the ratio $SHGC_{(bleach)}/SHGC_{(color)}$ is 4.42 which is well above the minimum required level ($=3$) for energy saving purposes.

3.3 Optical reflectance and absorption coefficients

Superior energy performance should be clearly expected from EC glazing if it was able to reflect the near-infrared (NIR) fraction of the solar radiation in its darkened state instead of absorbing it or, more exactly, if the switching in this spectral range would occur mainly through modulation of the NIR reflectance coefficient (ρ_{nir}). This would allow to reduce the fraction of absorbed light (causing long term degradation of devices), thus reducing secondary heat gain

The same instruments used for optical transmittance measurements have been employed for (near) normal spectral reflectance measurements (in the visible and infrared solar range) by equipping them with a specular reflectance accessory. The reflectance and absorption spectra of the investigated device are reported in Fig. 3 for the fully coloured and fully bleached states. The values of the luminous (ρ_V) and solar (ρ_S) reflectance coefficients, calculated from these spectra according to the methodology reported in [3], are ($\rho_V=0.010$, $\rho_S=0.010$) for the bleached state and ($\rho_V=0.075$, $\rho_S=0.083$) for the coloured state.

Recent studies point out how EC devices with high modulation range of the ρ_{nir} coefficient could realize energy saving for most climates also in the winter season, whereas conventional absorbing EC glazing are poorly efficient [9, 10]. Selkowitz [11] calculated that a reflecting EC coating give always rise to a lower SHGC compared to its absorbing counterpart for a double glazing unit with the EC layer coated on surface 2 or 3. The “ideal smart window” [10] should have $\rho_{nir}=0$ in the fully bleached state and $\rho_{nir}=1$ in the fully coloured state. But research

conducted in this area (mainly investigating the reflective properties of crystalline WO_3 in the NIR region [12]) let suppose the ρ_{nir} modulation range 0.1 - 0.7 as a more realistic target.

Referring to these arguments, a poor modulation of the reflectance coefficient of the investigated prototype is registered while the spectral absorption coefficient $\alpha(\lambda)$, calculated from the measured $\tau(\lambda)$ and $\rho(\lambda)$ functions as $\alpha(\lambda) = 1 - \tau(\lambda) - \rho(\lambda)$ (shown in the insert of the same figure), evidences its highly absorptive behavior.

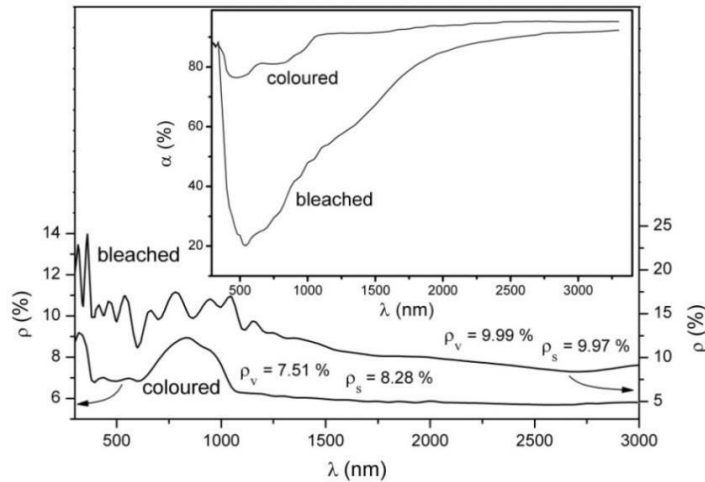


Fig. 3. Optical reflectance spectra of the EC device in the full bleaching and full colouring states. In the insert the absorption spectra calculated as $1 - \tau(\lambda) - \rho(\lambda)$ is shown.

3.4 Thermal transmittance

Insulating glass units including EC layers must obviously meet the thermal insulation requirements generally stated for modern windows. As for the thermal transmittance of the DGU integrating the home-made prototype described in the previous section (see Fig. 2 a), application of the methodology reported in [13] provides the value $2.2 \text{ W m}^{-2} \text{ K}^{-1}$. This value is higher than the ones suggested by recent European building regulations which state that the U -values of modern fenestration should be restricted to $1.2 \text{ W m}^{-2} \text{ K}^{-1}$ [1]. In the near future a progressive decrease of the maximum allowable limits is to be expected under the impulse of the energy-saving and environmental related world governments' policies. U -values lower than $1 \text{ W m}^{-2} \text{ K}^{-1}$ are actually met by commercial EC products in triple-glass arrangements with additional low-e coatings and Ar or Kr fill [1].

3.5 Lifetime

Although not strictly related to the energy performance of EC devices, the lifetime or durability is a crucial requirement for the commercial viability of EC windows. This criteria refers to the ability of an EC device to undergo cyclic commutations reversibly (or with only minor degradation) and to be stable (to have a quite constant performance) against the operating and environmental stresses acting on it when in place for operation. Assuming that the expected lifetime of EC glazing is 20-30 years (as for conventional windows) and that the number of average die commutations is reasonably 3-5 (in dependence of the dominant sky conditions and/or user preferences), it turns out that the sustainable cycling performance of an EC device should vary from 25000 to 50000 cycles.

A preliminary test of the long-term stability of the investigated device was performed operating it at ambient temperature under cyclization by a trapezoidal waveform potential ranging from -2.5 up to 2.5 V with a scan rate of 20 mV/s and a vertex delay time of 100 s. The resulting time dependence of the optical transmittance monitored at 500 nm is shown in Fig. 4. As it is clearly visible, after about 12 h (corresponding to about 60 cycles) the shape of the curves and the switching speed result approximately unchanged, the only noticeable difference being a slightly smaller contrast ratio. We can conclude, therefore, that the investigated prototype exhibits a relatively good stability

under controlled laboratory conditions over 12 h cyclization

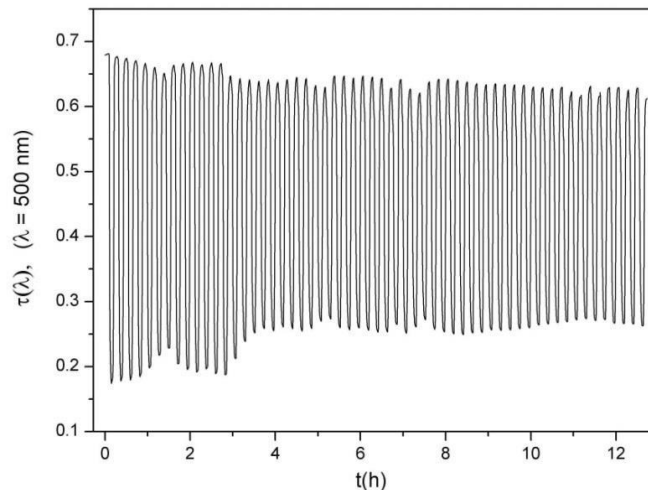


Fig. 4. Transmittance behaviour at 500 nm under trapezoidal voltage cyclization.

4. Conclusions

In this paper, the most critical performance parameters of an home-made EC device have been experimentally determined and analyzed from the perspective of architectural applications. Based on the present study, it turns out that the prototype meet (and in some cases exceed) most of these specifications. Some desirable improvements concern, anyway, higher visible transmittances in the bleached state and enhanced reflectance modulation in the NIR spectral range.

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