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Performance requirements for electrochromic smart window

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ABSTRACT

To accomplish specific energetic and environmental tasks in buildings large area electrochromic windows must exhibit acceptable levels in specific performance indicators. These parameters concern a number of electrical, thermal and optical properties which depend on the structural composition and configuration of the electrochromic device. In this paper a comprehensive and systematic analysis of the optimal performance requirements of electrochromic windows from the perspective of building energy efficiency and indoor comfort has been carried out. A comparison with the performance of a home-made fully solid-state electrochromic device tested in laboratory controlled conditions and of large-area electrochromic glazing currently available in the market is also made. The study points out the actual potential of the electrochromic technology for smart window applications and identifies some desirable performance improvements for optimizing building integration.

1. Introduction

In recent years, considerable interest has been addressed towards advanced glazing, windows being responsible for 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 [1,2] while heat loss through windows represents over 40% of the total building energy leakages [3]. On the other hand, highly insulated passive houses are able to fulfil the winter heating energy needs by uniquely exploiting solar heat gains [4]. These few examples show how fenestration components of modern energy saving buildings should be integrated by advanced solar control devices providing improved utilization and control of radiant solar energy. Traditional devices are, in general, manually or automatically operated mechanical systems (drapes, blinds, shades, louvres, overhangs, etc.) with static optical properties. Therefore, they preclude “adjustments” of the glazing transmittance for performing energy saving or visual comfort tasks. Often, glare control is performed at the expense of useful daylight so that artificial light has to be used in the rooms despite high external light availability. Furthermore, they constitute a substantial architectural constraint because they compromise, partially or totally, the view of the outdoor environment. To overcome these limitations glazing technology research is currently focusing on the development of active smart windows able to change their optical properties for dynamic regulation of the incoming flow of solar light and heat in response to external time-varying weather conditions (temperature, sunlight intensity, sky luminance, etc.) or according to occupants' visual comfort requirements. In this framework, electrochromic (EC) technology for “smart windows” applications represents the new frontier of advanced glazing building research and all studies in this field aim for giving it a primary position among the emerging technologies [5,6]. These active devices are essentially multilayer electrochemical cells characterized by the ability of changing reversibly their optical transmittance under the action of a low electric field, thus providing responsive and dynamic modulation of the thermal and optical properties of the buildings' glazed surfaces. Very promising applications are foreseen in large area smart windows, high-contrast displays, automotive glazing, mirrors, sunglasses, sunroofs and spacecraft. When used as smart windows in architectural applications, potential energy savings are expected to derive from combined cooling load reduction, useful solar heating and enhanced daylighting [7].

The effective utilization of large-area EC devices in buildings applications entails they must exhibit acceptable levels in specific performance indicators to accomplish the required energetic and/or environmental tasks. These performance indicators concern a number of electrical, optical and thermal properties which depend on the structural composition and configuration of the EC device. Parameters commonly selected as relevant performance indicators

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are [8–12]: (1) switching voltage; (2) switching speed; (3) optical memory; (4) optical transmittance coefficients; (5) solar heat gain coefficient; (6) optical reflectance coefficients; (7) thermal transmittance; (8) colour rendering; (9) operating temperature; (10) lifetime.

Although the above basic electrochromic performance parameters have been described in the materials science literature [8–12], a comprehensive and systematic analysis of their performance requirements is still not given to the authors' knowledge. This study reports on a detailed analysis about the general requirements and the specific performances of EC glazing from the perspective of building energy efficiency and indoor comfort. The analysis relies on current standards and literature review (mostly building simulation studies covering a wide range of environmental, architectural and operating conditions). To verify if the resulting performance ranges are matched by the current EC technology they are compared to the performance of a home-made fully solid-state EC device tested in laboratory controlled conditions and of large-area EC glazing prototypes currently available in the market. The aim is to provide a comprehensive analysis which could help in defining the actual potential of EC switchable devices for smart windows applications and, contemporarily, to identify desirable performance improvements for optimize building integration.

2. Experimental

The EC device considered for the experimental tests is the same as used by the authors in previous studies [13–15] so only a brief description is given here. For additional information on the preparation technique and on the structural composition of the sample the reader is addressed to the above specified works and to the references therein included.

The home-made EC glazing prototype is a full solid state device of area $12 \times 12\ \text{cm}^2$ and thickness 8 mm comprising different layers deposited on two K-glasses [16] according to the configuration shown in Fig. 1.

- The "active" layer is a tungsten trioxide (WO_3) film deposited by r.f. sputtering from a tungsten trioxide target.
- The "ion storage" layer 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 an ion conductor directly deposited on both electrodes by a spray gun.

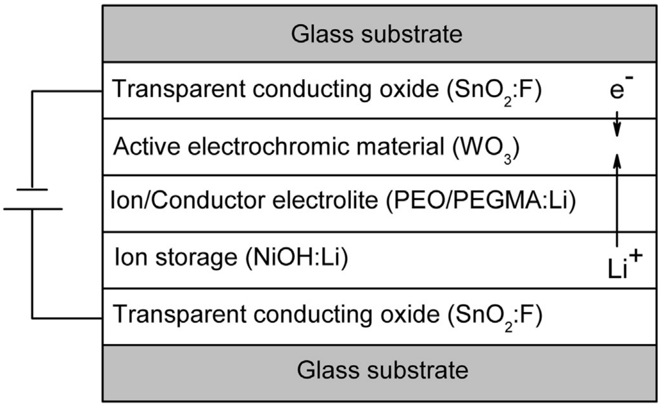

Fig. 1. Multilayer structure of the EC device.

The "active" layer (WO_3) and the "ion storage" material (NiOH:Li) exhibit a complementary electrochromism. When an electric voltage is applied to the electrodes – negative on the working electrode (cathode) and positive on the counter electrode (anode) – 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.

The detection of the electrical characteristics of the prototype was performed using galvanostatic equipments and a PAR 263A potentiostat. The characterization of the optical properties in different switching states involved the measurement of the UV–vis–NIR (near) normal transmittance spectra by 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. The same instruments equipped with a specular reflectance accessory have been employed for (near) normal spectral reflectance measurements (in the visible and infrared solar range).

When evaluating the experimental measurements on the small-area sample it must be remarked that they are only partially representative of and applicable to large-area EC glazing, since most of the performance parameters are size-dependent. So, the performance tests carried out on the home-made device have to be appreciated as a function of this major limitation. Anyway, to overcome this shortcoming the performance data of large area EC glazing currently available on the market are also considered in this study.

3. Results and discussion

In this section a complete survey on the EC window performance requirements is carried out. For each parameter, optimal range values are indicated and compared to the ones measured for the prototype under investigation and to the ones characterizing large-area EC glazing currently available in the market. As for the first set data, in each section the experimental methodology and the equipment employed for their acquisition is described in detail. Uncertainties affecting the spectroscopic measurements are about ~1% while, based on the reproducibility of data, a maximum error of 5% is estimated for the other measurements. As for the second set of data, in this paper reference is made to the review articles of Baetens et al. [5] (see Table A2) and Jelle et al. [17] (see Table B).

3.1. Switching voltage

An applied switching voltage is needed to start the coloration process, i.e., the charge migration in the constituent layers of EC devices. The potential level depends on the electronic conductivity and ionic diffusivity of the component substrates. A low voltage drop along the electrode surfaces is generally obtained by using transparent electronic conductors of low sheet resistivity ($<20\ \Omega/\square$) [18] while high ionic diffusivity rates ($>10^{-4}\ \text{S cm}^{-1}$) are generally obtained by employing high porosity WO_3 amorphous films with dissolved conducting materials like gold nanoparticles [19]. These characteristics are essential for achieving low switching voltages as well as for increasing the commutation velocity of the device between its extreme switching states, the so called "switching speed" (see next section).