Applied Energy 225 (2018) 975–985

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy savings due to building integration of innovative solid-state electrochromic devices

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HIGHLIGHTS

- Building integration of a newly designed electrochromic technology was studied.
- Overall yearly energy savings as high as 25% respect to the reference case.
- Visual comfort: 82.7% of hours achieved optimal illuminance conditions on an annual basis.

ARTICLE INFO

Keywords:
Electrochromic
Smart windows
Solid-state
Building-integration
Energy balance
Visual comfort

ABSTRACT

The next generation of adaptive facades includes dynamic electrochromic (EC) windows: they can dynamically modulate the daylight and solar energy entering buildings by application of an external voltage. Windows play a pivotal role in the definition of the energy balance as well as environmental impacts of buildings. Emerging technologies are focused on the optimization of these building components. We carried out an interdisciplinary study dealing with building integration of an innovative chromogenic technology, consisting in a recently designed single substrate solid–state electrochromic device, developed by some of the authors, with excellent figures and a compact device architecture. The practical implications on the building energy balance were analyzed by means of suitable simulations, carried out in Energy Plus. A reference office building was equipped with different glass technologies on the façade (clear glass, solar control, electrochromic glasses) and located in different cities (Rome, London and Aswan) to also include climatic effects in the analysis. The EC technology here presented outperforms all the others, with overall yearly energy savings as high as 40 kW h/m^2 yr (referred to window surface) in the hottest climates, assuming the clear glazings as benchmark. Daylighting performances were significantly improved using innovative solid-state EC devices, both in terms of Useful Daylight Illuminance (UDI) and Discomfort Glare Index (DGI). In the best case, 82.7% of hours achieved optimal illuminance conditions on an annual basis.

1. Introduction

Electrochromic (EC) windows, or “smart windows”, can be considered a “green” nanotechnology [1]. As reviewed by C.G. Granqvist, emerging chromogenic technologies (especially thermochromics and electrochromics) can regulate the throughput of visible light and solar energy in dynamic tintable glazings, yielding better energy efficiency than static solutions [2]. Numerous materials show an EC behavior: the most investigated materials are transition metal oxides, but also organic ECs (conjugated polymers or small molecules) have attracted the attention of several research groups worldwide [3]. EC oxides are typically subdivided into two kinds: cathodic and anodic [4]. Cathodic ECs color under ion insertion and cathodic reduction, whereas the anodic ones activate their optical transition due to ion extraction and anodic oxidation. Anodic and cathodic ECs, for this reason, are said to show a complementary fashion. Tungsten oxide (WO_3) is by far the most known and investigated cathodic EC material, whereas a typical anodic inorganic EC oxide is nickel oxide (NiO). The EC coloration/bleaching process is highly reversible and, for the above mentioned inorganic oxides, is finely explained by means of two simple redox

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https://doi.org/10.1016/j.apenergy.2018.05.034
Received 7 February 2018; Received in revised form 10 April 2018; Accepted 5 May 2018

reactions [5].

The research field of chromogenic materials has catalyzed the attention of several research groups worldwide, since the 80′s. In particular, EC devices [6,7] based on transition metal oxides typically show a multilayered, battery-like architecture [8]. An EC device generally contains transparent conductive substrates, an interposed electrolyte and one or two EC materials. Optical absorption varies when electrons are inserted (extracted, in case of anodic EC materials) into the cathodic EC material from the transparent conductive oxide and charge balancing ions enter from the electrolyte (or exit, respectively, in the case of anodic ECs), simultaneously.

Conventional liquid or gel electrolytes, sandwiched between the two EC materials, represent one of the most critical limitations, since they suffer from poor structural stability, tendency to leak and evaporate, and, then they affect the EC response with irregularities and non-uniform coloration [9–11].

Thus, a substantial effort is in progress, worldwide, to produce innovative solid electrolytes with the aim to overcome these major drawbacks. Solid polymer electrolytes (SPE) are among the most promising materials due to their low processing costs, electrochemical stability, flexibility and easy scalability [12–14]. A clear trend is currently visible in the design of innovative EC devices, aiming at obtaining solid-state devices, in order to achieve higher duration but also architectural simplification and reduction of impacts and costs [15].

Some of the authors [16,17] reported the performances of a newly designed full solid-state EC device fabricated on a single substrate, made of glass as well as flexible plastic, adopting a Nafion electrolyte film as a suitable solid electrolyte, (8 μm thick) sharing its interfaces with an EC WO_3 layer and a highly transparent and conductive RF-sputtered ITO film, deposited at room temperature (RT). Open issues like electrolyte leakage or solvent evaporation, limited durability and inhomogeneous EC transition were addressed with respect to the more complex sandwich-type architecture, typically containing sticky gel or liquid electrolytes. The best device fabricated showed an optical contrast of 49% (at 650 nm), a switching response time of 30 s and, interestingly, a very low electric energy absorption. Such values are among the best found for solid-state EC devices [18–22]. The electro-optical performances of these devices were adopted as an input for the simulation activities reported hereafter.

It is quite intuitive to envisage the manifold advantages due to building integration of smart glazings in the architectural envelope, nevertheless only a few attempts have been published so far, aiming at a precise report of attainable energy savings on real buildings, on a yearly basis together with the benefits in terms of visual comfort. The dynamic modulation of the energy throughput of glazings has different, interdependent fallouts. First of all, dynamic tintable glazings affect energy consumption in summer, cutting out a large part of undesired solar gains; they also influence visual comfort indoor by maximizing the use of daylighting and, as a consequence, they reduce the use of artificial lighting. According to Lampert [23], the optical switching technology for glazings bears several advantages: they require powering only upon switching, with small voltages; they show durable memory (up to 48 h) and they are quite prone to large-area fabrication.

More recently, DeForest et al. [24] adopted the EnergyPlus software platform to simulate annual energy performance of a dual-band EC glazing in three building types and several US climate regions. They estimated the savings potential of such windows, capable of achieving annual primary energy savings between 6 kW h/ft^2 yr and 30 kW h/ft^2 yr per window area, reducing heating, cooling, and lighting demand, if integrated on windows, with a value strictly depending not only on the device characteristics but also on climatic conditions.

In a previous work [25], they also presented a simulation study of the energy and CO_2 benefits of a transparent, near-infrared switching EC glazing for building applications. They found that the U.S. savings from near-infrared switching EC deployment could be 167 TWh/yr, to show the technical potential a high performance near-infrared EC glazing could have if deployed throughout the U.S. building stock. As predictable, they found that the conventional EC windows outperformed the near-infrared switching EC glazing in "cooling dominated" climates, like the Mediterranean area. DeForest et al. [26] reported the performance of an early prototype EC window controller showing that for a south-facing large-area window, daily lighting energy use savings (between 6:00 and 18:00 h) could reach 8–23% if EC windows were used instead of 50% transmissive windows. Visual comfort and energy implications of EC windows with overhangs were also investigated in hot and cold climates, finding significant reductions of average annual daylight glare index (DGI) and relevant energy savings (10%) with high WWRs. Peak electric demand can be reduced by 14–16% for large-area windows in either climate [27].

Lee et al. [10] reported results from a full-scale demonstration of building-integrated large-area ECs, with a window-to-exterior-wall ratio (WWR) of 0.40. Their lighting, illuminance, and control operations data suggested that EC windows provide greater energy efficiency and improve environmental quality, if compared to conventional window systems generally adopted in buildings. Automated control of EC windows and correct setting of dimmable lighting systems were also investigated in a conference room in Washington, where lighting energy saving reached 91%, compared to the existing lighting system. The authors used Energy Plus platform to estimate annual energy savings (48%) and peak demand savings (35%) [28].

A visual comfort assessment of EC devices smartly activated by means of photogenerated driving force, namely photovoltachromic devices, was carried out by some of the authors [29]. Starting from real devices electro-optical figures of merit, they found that light penetration in office buildings showed that the integration of photovoltachromic devices in traditional windows could dramatically increase indoor visual comfort (useful daylight illuminance increased up to 71.8% and daylight glare probability down to 12%).

Tavares et al. [30] focused on the energy savings attainable using EC windows as an alternative to shading devices to control solar gain in buildings located in Mediterranean climates. They carried out an energy performance simulation of buildings, comparing three glazing options: single glass, conventional double glazing and EC glazing. They found energy savings of 20.28 and 36.94 kW h/m^2 yr per windows surface in the east/west facades, and a simple payback of 10 years, concluding that the EC glasses are an energy-efficient solution for use in buildings, also in case of refurbishment.

Aldawould [31] compared EC glazings to fixed shading devices in hot dry climate, modeling a typical office building by means of the software DesignBuilder: EC glazing provided the best performance in reducing solar heat gains compared to other tested shading conditions.

Syrrakou et al. [32] carried out an eco-efficiency analysis on an EC prototype and showed that, with the right premises (reduction of the purchase cost to 200 €/m^2 lifetime increase above 15 years), cost and environmental efficiency could be achieved at the same time. They stated that EC glazings theoretically reduce the building energy requirements by 52%, in cooling dominated areas.

2. Methods

2.1. Solid-state ECs: Fabrication methods and characterization of devices

The energetic implications deriving from the building integration of a monolithic solid-state EC fabricated by some of the authors [33] were investigated in the paper. The EC devices (later on referred as CNR-EC) were fabricated on a single substrate, made of glass or flexible plastics, with a simplified architecture based on substrate/ITO/WO_3/Nafion/ITO configuration, in which a Nafion film (with a thickness of 8 μm) tightly shares its interfaces with the WO_3 layer and the highly transparent and conductive RF-sputtered ITO film [10]. Fig. 1 reports a cross section of the device, obtained by scanning electron image.

The whole process was carried out at room temperature (RT)