Solar Energy Materials & Solar Cells 116 (2013) 14–26

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

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

An empirical study of a full-scale polymer thermochromic window and its implications on material science development objectives

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ARTICLE INFO

Article history:
Received 7 December 2012
Received in revised form
26 March 2013
Accepted 29 March 2013
Available online 4 May 2013

Keywords:
Thermochromic
Windows
Solar control
Building energy efficiency

ABSTRACT

Large-area polymer thermochromic (TC) laminated windows were evaluated in a full-scale testbed office. The TC interlayer film exhibited thermochromism through a ligand exchange process, producing a change in solar absorption primarily in the visible range while maintaining transparent, undistorted views through the material. The film had a broad switching temperature range and when combined to make an insulating window unit had center-of-glass properties of Tsol = 0.12–0.03, Tvis = 0.28–0.03 for a glass temperature range of 24–75 °C. Field test measurements enabled characterization of switching as a function of incident solar irradiance and outdoor air temperature, illustrating how radiation influences glass temperature and thus effectively lowers the critical switching temperature of TC devices. This was further supported by EnergyPlus building energy simulations. Both empirical and simulation data were used to illustrate how the ideal critical switching temperature or temperature range for TC devices should be based on zone heat balance, not ambient air temperature. Annual energy use data are given to illustrate the energy savings potential of this type of thermochromic. Based on observations in the field, a broad switching temperature range was found to be useful in ensuring a uniform appearance when incident irradiance is non-uniform across the facade. As indicated in prior research, a high visible transmittance in both the switched and unswitched state is also desirable to enable reduction of lighting energy use and enhance indoor environmental quality.

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1. Introduction

Thermochromic (TC) materials transition from a clear cold state to tinted hot state at a critical temperature or range of temperatures that is inherent to the fundamental chemistry and makeup of the material. Unlike thermotropic materials which are translucent when switched, thermochromics maintain a transparent view irrespective of its switched state. These materials have been and continue to be developed for window and skylight applications as a means of passively controlling solar heat gains in buildings. The concept is to transmit solar radiation through the cold, untinted window in the winter to reduce heating energy use requirements and absorb then reject radiation with the hot, tinted, low-e window in the summer to reduce cooling energy use requirements. Windows are responsible for about 30% of US building heating and cooling energy use with an annual impact of 4.1 Quads (Quad = 1×10^{15} Btu) of primary energy use in the US [1]. Control of solar heat gains in this manner has the potential to reduce building energy use and peak electric demand, assuming that the switching response of the thermochromic matches the typical heating and cooling demand profiles of residential and commercial buildings.

Thermochromic windows are starting to emerge on the market but very little is known about how these devices affect the energy performance and indoor environmental quality in buildings. As with any innovative technology, consumers require information in order to determine how the technology works and whether the technology provides sufficient benefits that would justify the incremental cost of the thermochromic above a conventional window. The thermochromic window has been argued to be competitive to electrochromic (EC) windows because it can provide dynamic control without the added cost and complexity of thin film electrochromic coatings: electrochromic windows require dc power and an automatic control system to capture energy efficiency benefits. Thermochromic glazings and films (for laminate applications) require neither power nor controls and would be applicable to the new and replacement windows market.

Proving energy efficiency claims at the proof-of-concept stage is hindered by a number of technical barriers. The spectral properties of TC prototypes must be fully characterized under a range of thermal conditions, so the prototype must be sufficiently stable and durable. Simulation tools must be modified to accept these data in order to model building

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0927-0248/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.solmat.2013.03.043

energy performance. Field verification by way of calorimetry, mockups in outdoor testbed facilities, or installations in occupied buildings require large-area prototypes, so the prototype must be at minimum in the fabrication stage of maturity. As such, material scientists have been and are continuing to formulate new TC devices based on limited guidance as to what the optimal solar-optical properties and critical switching temperatures should be for building energy-efficiency applications.

There are two classes of thermochromic materials: inorganic and polymer based thermochromics, both of which have seen significant developments occur on the material science front recently as a result of exploiting nanoparticle composites for spectrally selective absorption [2]. Both types have been extensively reviewed in the literature [3–5], providing information on the current status of material science developments, switching characteristics of the various material formulations, and an assessment of market maturity. Near-term polymer thermochromics exhibit absorption but remain transparent in the tinted phase, where absorption is primarily in the visible (VIS) range (wavelengths between 380–780 nm). Recently, significant R&D effort is being expended to achieve modulation in the near-infrared (NIR) portion of the spectrum (750–2500 nm) while maintaining sufficient transmittance in the visible range. Li et al. [4] summarizes the material science development objectives for inorganic VO_2-based thermochromic materials, which applies in general to organic TC materials as well even though the mechanisms for thermochromism may differ:

1) Lower the critical temperature, τ_c, at which the TC transitions between semiconducting (untinted) to metallic (tinted) states from ~68 °C for bulk VO_2 to a comfort temperature of ~25 °C,
2) Broaden the modulation of solar transmission (ΔT_{sol}), and
3) Achieve a high visible transmittance in the unswitched state.

Simulation studies and prior field measurements have been used to evaluate the energy savings potential of this technology and to provide guidance to the material science community as to which properties increase energy efficiency [6–8]. Saeli et al. [7] used the EnergyPlus building energy simulation program to evaluate the energy savings potential of actual and ideal thermochromic films in a daylit office zone, showing that coatings with broad NIR switching and a low critical switching temperature (20 °C) produced significant energy savings in warmer climates compared to conventional glass.

This study provides a detailed investigation of the field performance of polymer based, ligand exchange thermochromic windows for internal load dominated commercial building applications. The film transitions from an untinted clear to dark tinted phase over a range of critical temperatures between approximately 24–75 °C. The film can be produced using roll-to-roll processing techniques in large areas and is designed to be used as an interlayer in a laminate configuration within a low-e insulating glass unit (IGU). The thermochromic switches primarily within the visible portion of the solar spectrum.

A large-area thermochromic window was installed in a full-scale office testbed. Detailed measurements were made to characterize switching performance under variable outdoor conditions. Measured and simulated data were related to the perimeter zone heat balance and energy use for an internal load dominated office zone to illustrate how TC properties affect heating, ventilation, and air-conditioning (HVAC) energy use. Observations were made in the field concerning the appearance of the TC window when the incident irradiation was non-uniform and of its ability to control discomfort glare. Some additional observations were made relating the properties of this specific thermochromic to the three material science development objectives delineated above.

2. Outdoor field measurements

2.1. Field test set-up

A polymer thermochromic film was evaluated in this study. The chemistry of the ligand exchange thermochromic film that was tested is described in [5] as "the rearrangement of ligands around metal ions which cause the formation of metal complexes that increase visible light absorbance with increased temperature". In the patent literature [9], developers describe the thermochromic in detail, where example 294 is similar in composition to what was tested (i.e., slight deviations occurred in amount of materials and type of substrate film used to improve durability and performance). Composition 294 was the only film tested and simulated in this study and is described in the patent as: "thermochromic layers with the following compositions (Table 1) were prepared by extrusion. A 0.03 cm thick layer with composition A was placed on one side of a separator that was 0.0076 cm thick layer of poly(ester terephthalate) which was excited on both sides by glow-discharge and labeled as Southwall "HB3/75 Glow 2-sided" available from Southwall Technologies Inc. of Palo Alto, Calif. Two layers with composition B, totaling 0.09 cm thick, were placed on the other side of the separator. The polymer layer stack was placed between sheets of clear, plain, soda-lime float glass and a laminate was formed in a heated vacuum bag".

Spectral normal transmittance and reflectance of Composition 294 laminated between two sheets of 3 mm, clear glazing were measured using a spectrophotometer (Perkin Elmer Lambda 950) [10]. No hysteresis was noted upon heating and cooling the sample. As shown in Fig. 1, the TC exhibited switching in primarily the visible portion of the spectrum. The Optics 5 software tool [11] was used to determine the spectral properties of the TC interlayer alone and then used with the Window 7 tool [12] to determine the optical properties of the windows evaluated in this study.

A dual-pane clear TC window (TC2) and tinted TC window (TC3) were constructed for the field test, where the former was used in the upper portion of the window wall and the latter was used in the lower portion of the window wall. The clear TC2 window (1.35 × 0.79 m) consisted of two glazing layers: an outboard TC polymer film laminated between two layers of clear glass and an inboard advanced spectrally-selective, low-emittance ($e = 0.035$) glass. The spectral properties for the two glazing layers combined are shown in Fig. 2. The tinted TC3 window (1.35 × 1.73 m) also consisted of two layers, but the outboard TC film was laminated between a pane of spectrally selective tinted glass and a pane of clear glass with the inboard layer unchanged (also shown in Fig. 2). The general makeup of the window unit (substrate materials, low-e coating, gas fill,

Table 1
Composition of the thermochromic film #294 used in this study.

Composition A	Composition B
0.1 m $(TBA)_2NiI_4$	0.2 m $(TBA)_2NiBr_4$
0.11 m 4-(3-PhPr)Pyr	0.4 m 1-butylimidazole
0.3 m TBAI	0.2 m TBABr
0.005 m Ph_3P	0.5 m NPG
0.07 m TMOLP	in Butvar® B-90
1 wt% Tinuvin® 405	
in Butvar® B-90	