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Evaluation of energy, thermal, and daylighting performance of solar control films for a case study in moderate climate

Elisa Moretti*, Elisa Belloni

Department of Engineering, University of Perugia, Via Duranti 93, 06125 Perugia, Italy

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ABSTRACT

Solar control films could be a suitable way to reduce cooling energy consumptions and to reduce discomfort conditions in existing glazed buildings, but their performance is often evaluated by numerical analysis only. In this paper, an integrated thermal-energy and lighting characterization of solar control films performance was carried out by full-scale experimental setup and numerical analysis: two similar offices, with and without solar control films, in a multifunctional building in moderate climate were investigated. Solar control films strongly reduced the incoming solar radiation (about 60%), not depending on the external solar radiation. During springtime, window films allowed a reduction of about 2–3 °C of the indoor air temperature, during sunny days; they influenced also the globe thermometer temperature: with window coatings, it is almost equal to air temperature, whereas with conventional windows, it is about 2 °C higher, especially in the afternoon, due to the contribution of glass surface temperature (which is 10 °C higher). Furthermore, the contribution of artificial light increases, especially on cloudy days, because the daily average illuminance level was lowered by about 59%. Finally, preliminary simulations showed that the cooling energy demand decreases of about 29% thanks to solar control films, but at the same time the energy demand for heating increases of about 15%.

1. Introduction

In the most cases non-residential buildings have been built with very high window-to-wall ratios, due to esthetic reasons and in order to encourage daylighting for energy savings and visual comfort. Daylighting plays a significant role in designing energy-efficient buildings and involves relevant benefits both in terms of saving electricity consumptions and in improving visual comfort for the occupants, also allowing a productivity increase [1]. Nevertheless, heat gain from the windows contributes significantly to the building envelope cooling load and large windows could originate glare problems, especially in south-facing facades [2]. The impact of glazing properties on thermal and visual comfort has been widely studied through numerical analysis and field measurements [3–8]. Shading systems are shown to reduce glare issues and cooling loads, equally they contribute to higher heating demands, as well as to artificial lighting. Automatically controlled shading systems can reduce energy demand of south-facing windows, but they should not be installed without a thorough case-by-case investigation: increased energy demand was found if an improper shading strategy was chosen [9–12].

In this context, advanced solar control solutions are being investigated in order to reduce glare, heat gains and to improve indoor thermal and visual comfort conditions [13]. Smart windows technologies for solar control in new buildings, such as dynamic shading systems, sustainable glazed water films, gasochromic, liquid crystal, electrophoretic or suspended-particle devices, and electrochromic windows are the most promising solutions [14]. In many situations, existing buildings have to be retrofitted by changing the envelope thermal properties, choosing the best solutions at lower costs. A suitable way to change the properties of glass windows is to use solar control films, which could be applied to existing glazings in order to modify their lighting and thermal properties, especially in moderate or hot climates [15].

Solar control films are designed to reduce solar heat gains through the glass in existing buildings, by absorbing or reflecting the incoming solar radiation; a wide review on the technology was presented by Lampert [16]. The films deeply modify optical and thermal properties of the glasses, reducing both the solar factor and the light transmittance [17–21]; Gueymard and Du Pont [22]

* Corresponding author.
E-mail address: elisa.moretti@unipg.it (E. Moretti).

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Nomenclature

AM	in the morning
DI	daylight illuminance (lux)
I_{cl}	thermal insulation of clothing (clo)
M	metabolic rate (met)
PM	in the afternoon
PMV	Predicted Mean Vote (−)
PPD	Predicted Percentage of Dissatisfied (%)
Office A	office without solar control films
Office B	office with solar control films
T_a	air temperature (°C)
T_g	globe thermometer temperature (°C)
α_e	solar direct absorptance (−)
ρ_e	solar direct reflectance (−)
τ_e	solar direct transmittance (−)
τ_v	light transmittance (−)

performed an analysis on 37 different glass systems: single, double and triple glass units, showing the influence of solar control films on some of these solutions.

The effect of solar window films on building performance is deeply investigated in the Literature also by means of building energy simulation tools. In Yin et al. [23] the energy savings from applying solar control films in a commercial building with large curtain wall areas in Shanghai, China, was studied by eQUEST software. The results showed that the solar window films allowed a decreasing of shading coefficient and solar heat gain coefficient by 44% when applied to the external side of existing windows; whereas the reduction was 22% if the films were applied to the internal side. The influence of solar films in an apartment in México was investigated by Chávez-Galan and Almanza [24], using the Energy-10 software. The yearly energy consumption is reduced up to 16% for a room with a solar control film applied to a simple glass.

Noh-Pat et al. developed a mathematical model for the natural convection of air on the vertical canal in a double glazing unit, in order to investigate the effects of a solar control film. The heat gain through windows can be reduced by 55% by applying solar control films on the external side of traditional glazings [25].

As important remark, the performance of a solar control film and the its benefits strongly depend on the climate conditions: Xamán et al. [26] investigated a double pane window with SnS–CuxS film by a numerical model, both in cold and warm climates. The authors found that the use of a solar film is highly recommended for warm climates, allowing a reduction of 52% in terms of energy gained, whereas for cold climates the amount of energy gain through the system reduces of about 10%. Furthermore, the performance of an office room on top of a building with four windows configurations was studied by Gijón-Rivera et al. [27] in two extreme weather conditions: Mexico City and Ottawa. The study was also carried out by using integrated CFD and BES (Building Energy Simulation) models, only for Mexico City [28]: supplying heat transfer coefficients obtained from CFD to the BES models, a more accurate energy analysis could be carried out for the room. In general, the results showed that double glazings with solar films are adequate for both climates, even if the performance was better for Ottawa than for Mexico City, where a conventional double glazing would allow a similar result at lower costs. Considering the total energy loads for cooling and heating, the best window configuration was the double glazing with film in Ottawa and the conventional double glazing in Mexico City. Also the Lawrence Berkeley National Laboratories (LBNL), together with GSA's Green Proving Ground (GPG), evaluated the performance of a spectrally-selective absorbing film by means of building energy simulations. Solar-control retrofit films provided significant cooling savings, especially in buildings with single-pane clear windows in warm climates with mild winters (such as Missouri) [29].

Field measurements of energy and lighting performance of solar control films in subtropical Hong Kong were carried out by Li et al. (2004, 2008). Firstly, the influence on solar heat gain, daylight illuminance, and electricity consumption in typical air-conditioned cellular offices was investigated by in situ measurements, comparing similar offices with and without solar films [30]. The results indicated that diffuse solar radiation can be reduced by 30% using window film coatings, while the reduction increases when the direct component is dominant [30]. Moreover, the electricity energy savings due to solar films was estimated considering a simple case study: a reduction due to the solar control films equal to 55 Wh/m^2 was found.

Li et al. investigated the effects on lighting and cooling energy performance of solar control films for a fully air-conditioned, open-plan office, also taking into account the contribution of lighting control systems. It was found that solar film coatings, when coupled with light dimming controls, can reduce the electricity usage and the lighting and cooling energy consumption by 21.2% and 6.9%, respectively [31].

The effect of window solar controls on thermal and visual performance was also investigated by field monitoring in a test building facility in Malaysia, also characterized by a warm humid climate [32]. Three kind of solar control films were applied to a simple clear glass (6 mm). Results highlighted that the surface temperature of windows are strongly influenced by the solar energy absorption property of the glazing, whereas the indoor air temperature are mainly influenced by the solar energy transmittance. Solar control films with the lower solar transmittance (lower than 8%) allowed the best performance in terms of difference between indoor and outdoor temperatures (for instance at 12 PM it is about 2 °C), but they didn't provide sufficient daylight illuminance levels in the examined test building [32].

It can be concluded that several studies have been developed to estimate how solar control films influence energy consumption and peak demand using building energy simulation [23–29], whereas the experimental investigation is limited to few case studies in warm humid climate (for instance Hong Kong and Malaysia), only taking into account the performance in terms of solar heat gain, temperature difference between indoor and outdoor, and daylighting reduction [30–32].

The present study develops an in-field experimental and numerical integrated analysis of solar control films performance in highly glazed buildings in moderate climate: the multipurpose approach takes simultaneously energy, lighting and indoor thermal comfort issues into account. The effect of the solar control film was evaluated in terms of energy performance, such as incoming solar radiation, thermal performance (air temperature, globe thermometer temperature, window surface temperature), and lighting performance (i.e. daylight illuminance). Moreover, Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) were also calculated as thermal comfort performance indices [33].

The analysis was carried out through in-situ continuous monitoring of two similar offices, by comparing traditional glazing systems and solar control film systems in a typical office building with a high glazing surface in moderate climate conditions, i.e. the centre of Italy. Based on the experimental results, an unsteady state model of the building was implemented using EnergyPlus software in order to evaluate the impact of solar control films on yearly energy demand.