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The influence of solar control films on energy and daylighting performance by means of experimental data and preliminary unsteady simulations

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Abstract

Solar control films were investigated as a strategy to improve thermal comfort, lighting conditions, and energy performance in non-residential buildings. The case study follows two adjacent similar offices with large window in the south-west façade of a building in Perugia, investigated by numerical and experimental approaches. The solar control films could strongly reduce the window heat gain (40-60%) and the indoor air temperature (1-1.5°C), whereas the daily average illuminance level was lowered by about 50-60%. Finally the yearly cooling energy demand decreases of about 25% (only South- West façade) and 39% (all the façades), whereas the heating energy demand increases of about 10-15 % thanks to solar control films.

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Keywords: Solar control films; Glazing systems; Windows coatings; Daylighting performance; Energy efficiency; Building retrofitting

1. Introduction

Glass surfaces have an important role in buildings both for daylighting and thermal comfort. Many studies showed that health, comfort, and productivity are improved due to natural light. Nevertheless, heat gains from the windows contribute significantly to the building envelope cooling load and large windows could represent a problem, especially in south façades and in hot climates. In this context, advanced solar control solutions and shading systems are being investigated in order to reduce glare and heat gains and to improve indoor thermal and

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visual comfort conditions in existing buildings. A suitable way to change the lighting and energy properties of existing glazings could be the use of solar control films, especially in moderate or hot climates [1]. The effect of solar window films on building performance was investigated in the Literature by means of building energy simulation tools [2-3], whereas the experimental investigation was limited to two case studies in Hong Kong, taking into account the performance in terms of solar heat gain, daylighting, and electricity consumption reduction [4-5]. In Li et al. [5] a typical air-conditioned cellular office in Hong Kong was investigated, by comparing similar offices with and without solar films: diffuse solar radiation can be reduced by 30% using window film coatings, while the reduction grows up when the direct component is dominant. For a fully air-conditioned open-plan office, it was found that solar film coatings, when coupled to light dimming controls, can reduce the electricity usage and the lighting and cooling energy consumption by 21.2% and 6.9% respectively [4]. Building energy simulation tools were also used to estimate energy savings due to solar control films in a commercial building with large curtain wall areas in Shanghai, China [2] and in a department in México [3]: in the first case a reduction by 44 % of solar heat gain coefficient was found when they are applied on the external side of existing windows. The reduction is only 22% if the films are applied on the internal side; in [3] the yearly energy consumption was reduced up to 16% for a room when the solar control film is applied on a simple glass. Also the Lawrence Berkeley National Laboratories (LBNL), together with GSA's Green Proving Ground (GPG), used building energy simulations in order to evaluate the performance of a spectrally-selective absorbing film installed at the Goodfellow Federal Center in St. Louis, Missouri. Solar-control retrofit films provide significant cooling savings especially in buildings with single-pane clear windows in warm climates with mild winters [6].

The present study aims at developing an experimental and numerical analysis of solar control films performance in highly glazed buildings, taking contemporaneously into account energy consumptions and indoor thermal and visual comfort issues. The effect of the solar control film was evaluated in terms of energy performance, such as heat gain from the windows, thermal performance (air temperature), and lighting performance (i.e. daylight illuminance). The case study features two similar offices in a typical office building with large openings in moderate climate conditions, i.e. the center of Italy: the reference office has conventional glazing systems, whereas in the other one solar control film systems were applied on the glazing. The performance of the two offices was investigated both by experimental survey and simulations: based on the experimental results, an unsteady state model was implemented using EnergyPlus software and the results were compared. Finally, the influence of solar control films on energy performance was evaluated for the whole building thanks to the implemented model.

2. Methodology

2.1. The case study

The case study follows a well-insulated multifunctional building (lecture rooms and offices) at the University of Perugia, built 25 years ago in Perugia, center of Italy. Large windows with conventional double glazing system are present both in the south-west and south-east façades [7]. Two adjacent offices (Office A e Office B), with similar dimensions (floor area equal to about 31.5 m^2), were chosen for the study: they are on the 1st floor and they have two large openings (total area of 6.7 m^2) in the south-west façade. In order to solve glare and discomfort problems, especially in springtime, when air-conditioning system is off, and to investigate solar control films performance, they were applied on the window of office B, while office A was used as reference case. The films are manufactured with sputtered technology and they are designed for external applications; the thickness of the film is 75 microns and a medium bronze color was chosen in order to reduce the transmitted solar energy without too much reducing the visible light transmittance (Figure 1).

2.2. Experimental campaign

The experimental campaign, was carried out from April to September 2013, thanks to two environmental monitoring stations and stand-alone programmable probes installed in the two offices [8-9]. In order to compare measured data with simulated data ones, the following parameters were considered: indoor air temperature (1 meter high from the floor), in the center of the rooms; the daylight illuminance on the workplane (0.75 m height from the floor), measured by illuminance meters placed in the centre of the room (point 2) and nearest to the window (2 m far, Point 1). The global solar radiation on a horizontal surface and the outdoor air temperature were measured on the roof of the building and compared to the weather input data in EnergyPlus, in order to evaluate their influence on the results.

2.3. Simulation

The building performance was evaluated by means of EnergyPlus Software. In order to predict hourly diffuse irradiance on a tilted surface (window) or external illuminance, the Perez model was used based on hourly horizontal data from a TMY weather file [10]. The daylighting illuminance was calculated using Timestep Frequency (10 minutes); the daylight illuminance levels in a zone depends on many factors: exterior light sources, location, size, optical properties of fenestration systems, reflectance of interior surfaces and location of reference points. The optical properties of glazings were estimated on the basis of optical measurements carried out using a spectrophotometer [11-12]. The occupancy of two persons was assumed for the offices and 5.5 m^2/person (UNI TS 11300) were considered for the T zones (ground floor zones, lecture rooms) as internal loads. The presence of occupants was considered from 7 am to 7 pm for each workday. The internal electric equipment was considered as 3 W/m^2 for the offices and 1 W/m^2 for the lecture rooms. The considered ventilation rate was 0.011 m^3/s per person for the offices and 0.007 m^3/s per person for the ground floor zones. For the energy demand evaluation, the cooling period was June 1st – September 15th, whereas the heating one was October 15st – April 15th, as dictated by the Italian Law for this zone; room air set-point temperature, based on occupancy schedules, was assumed equal to 20 °C and 26°C respectively in heating and cooling period.

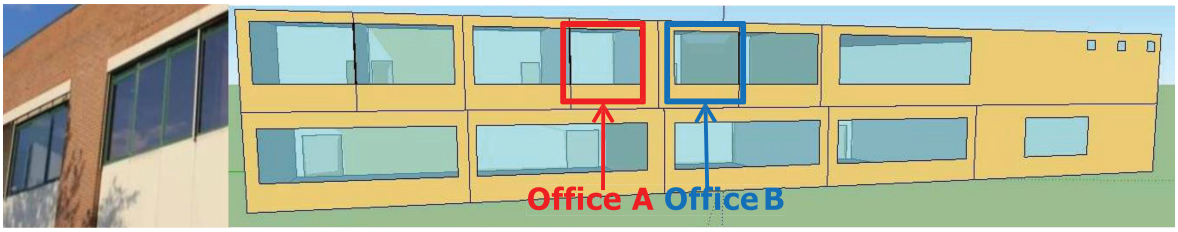


Figure 1. The investigated building (left) and the 3D model implemented in EnergyPlus (right).

3. Results and discussion

3.1. Preliminary simulations and comparison with experimental data

Figure 2 shows the hourly profiles of the indoor air temperatures (a) and the daylight illuminance values in the center of the room (b) measured during the weekend of June 15th -16th, when the HVAC system was off and nobody was inside. Due to the solar control films, the indoor air temperature of the office with solar film coatings is about 2°C lower than air temperature in the reference office, especially in the afternoon (7 pm - 8 pm). The peak daylight illuminance of 1200 lux at 4 pm is reduced to around 400 lux, accounting for a reduction of over 60 %. The reduction is consistent with optical data of solar control films: the measured reduction in visible transmittance of the glazing is about 62 %. For these days, the experimental results were compared with the simulated data, obtained considering yearly simulations carried out with the Typical Meteorological Year (TMY) file.

Simulated air temperatures and experimental data are different by 2 h in phase and EnergyPlus underestimates the maximum temperature values: the maximum difference between simulation and experimental data is about 2 °C (Fig. 2a). Moreover, the differences could be also due to the experimental facility: the measured temperatures were in fact local values, while the simulated ones are volume averaged values. The results daylighting simulations in the central point of the rooms (Fig. 2b) are in reasonable agreement with the experimental ones, even if Energy Plus seems to overestimate the illuminance, according to the Literature [13]; moreover, the real values are lower because of the interior (such as furniture) and exterior (such as trees) obstructions, which were not included in the model. In order to further improve the thermal model, new simulations should be carried out considering a new weather file based on the outdoor air temperatures and the solar radiation measured data, which are very different from the original file (Figure 2c), especially for outdoor air temperatures.

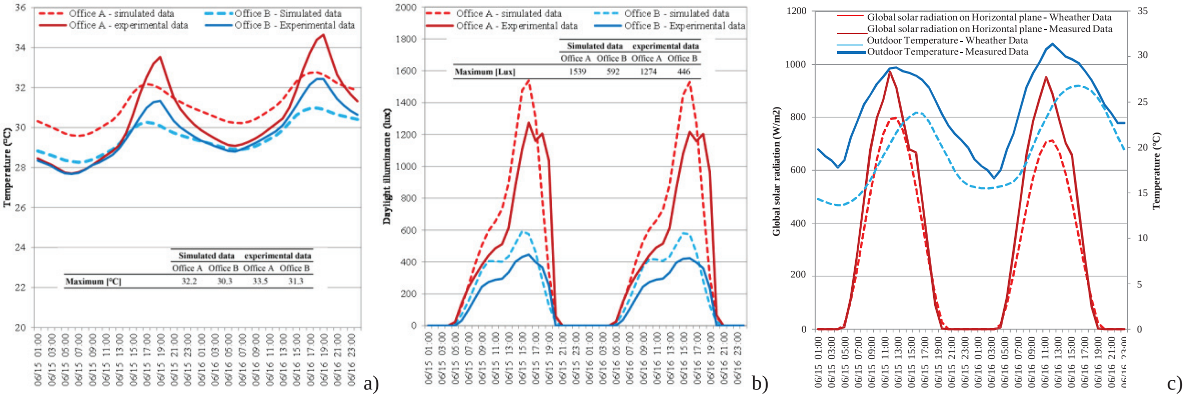


Figure 2. Model validation: comparison between experimental data and simulated data for indoor air temperature (a) and Daylight illuminance (b); comparison between wheatear data (TMY) in EnergyPlus and experimental data (c).

3.2. Energy and indoor thermal comfort analysis

The influence of the solar control films on thermal comfort and energy consumptions was evaluated by means of the thermal model, also considering periods when experimental data were not available. In particular, the window heat gains and losses with and without solar films were evaluated in two periods (winter and summer). The trends are represented in Fig. 3 considering a typical winter week (Fig.3(a)) and a typical summer one (Fig.3(b)). In January the maximum gain in office A is about 700 W, in office B the values are lower than 300 W; in July the maximum gains are about 2000 W and 1300 W respectively in office A and B. In winter the maximum differences between the offices in terms of heat gains vary in 50 – 60% range, in summer the maximum differences are about 40%. The window heat losses are not very different in the two offices (maximum differences of about 3-6% both in winter and in summer). Also the mean air temperatures in both the offices are represented (HVAC system is on during weekdays). As final remark, during spring periods, when HVAC system is off, the mean differences between the air temperatures in the two offices vary in 1-1.5°C range, therefore the comfort conditions in office B are better than in office A.

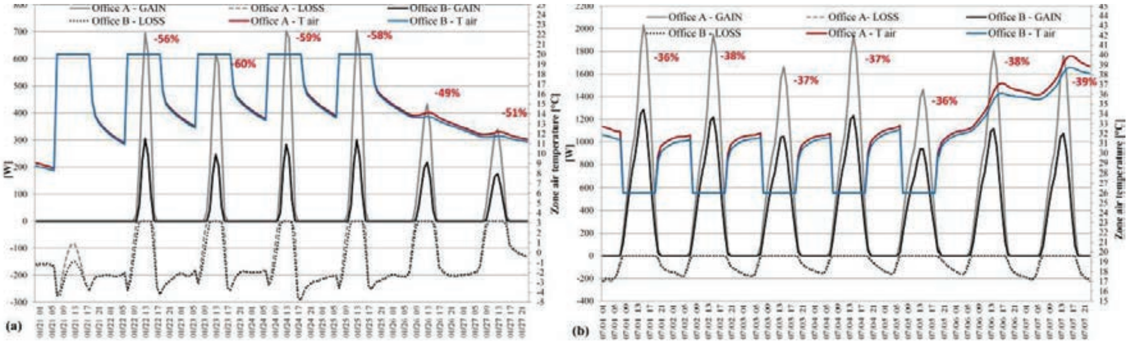


Figure 3. Window heat gain and loss in Office A and B: (a) typical winter week, (b) typical summer week.

Finally, the annual energy demand was evaluated by considering three different scenarios (Fig.4): (1) all the windows have simple double glazing systems; (2) only the windows in South-West façade have exterior solar control films; (3) the solar control films were applied to all the glazing façades of the building. In Perugia, the yearly heating energy demand of the building is about 29 kWh/m^2 and the cooling energy demand is 17 kWh/m^2 considering double glazing systems applied to the entire building (scenario (1)). Thanks to the application of the solar control films systems, the cooling energy demand decreases of about 25% and 39% respectively considering scenarios (2) and (3). Nevertheless the heating energy demand increases of about 10-15%. On the contrary, in Rome the annual cooling energy demand of the building is higher than heating energy demand (20 kWh/m^2 for cooling and 16 kWh/m^2 for heating); the cooling energy demand decreases of about 38% (scenario (3)) but the heating consumptions of the building grows more than the increase obtained for Perugia (about 33%).

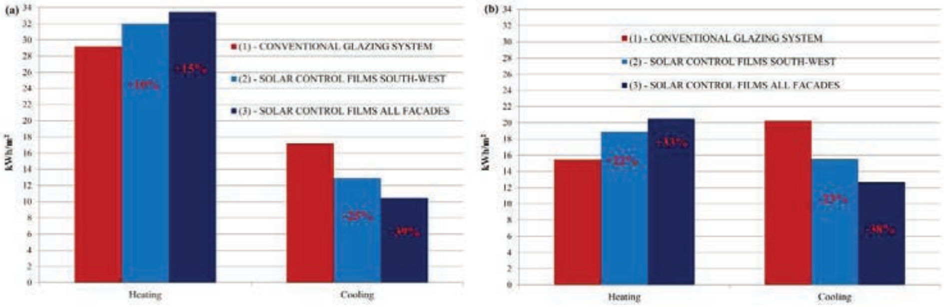


Figure 4. Annual energy demand (kWh/m^2): (a) Perugia, (b) Rome.

3.3. Daylighting analysis

Figure 5 shows the daily estimated daylight illuminance profiles at the central point (Point 2) and at a point nearest to the window (Point 1) for a typical winter week (a) and a typical summer one (b). It can be observed that, during the winter, the daylight illuminance values are lower (the peak value is about 600 lux at point 2) and the reduction due to solar films is about 50%; at point 1, the reduction is of the same order of magnitude in cloudy days, dominated by diffuse solar radiation (January 21st, January 26th and 27th), whereas the peak values are similar in sunny days (about 2000 lux). In the summer, using the solar control films, the reduction in illuminance is quite constant in both points and it is about 60%, both for sunny and cloudy days (when diffuse radiation is dominant).

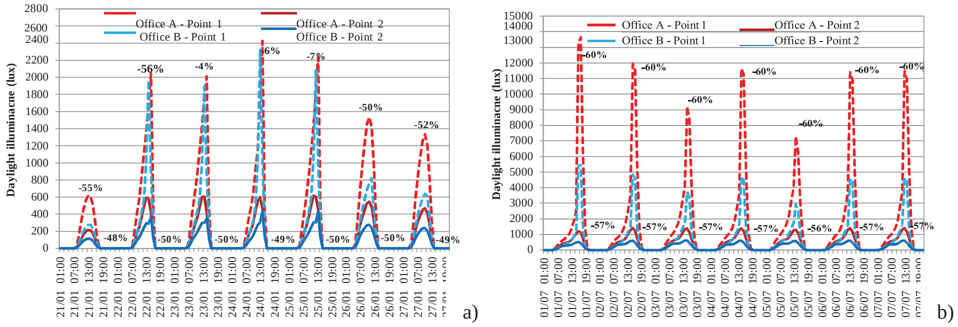
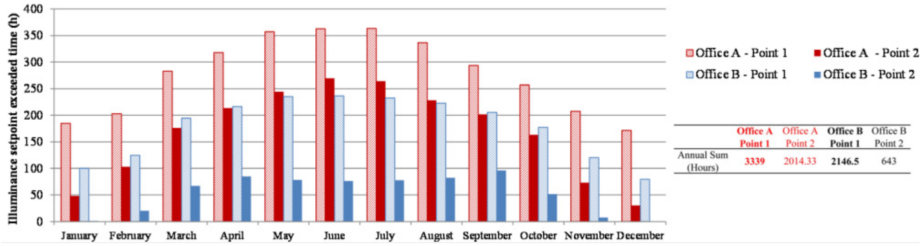


Figure 5. Daylight illuminance in Office A and B: (a) typical winter week, (b) typical summer week.

Next to the window, the peak daylight illuminance is higher than 10000 lux during sunny days, with very important glare problems; due to solar control films, the values decrease to about 4000 lux, accounting for a reduction of over 60 %. In office A, the daylight illuminance on the working plane is higher than the recommended value (500 lux) for a large amount of time during the year (Fig.6, about 2000 hours, about 46 % of the total occupancy period), whereas with solar control films artificial light is needed in order to reach the designed value (the daylighting illuminance is higher than 500 lux for about 650 hours, about 15 % of the total occupancy period).



	Office A Point 1	Office A Point 2	**Office B Point 1**	Office B Point 2
Annual Sum (Hours)	**3339**	2014.33	**2146.5**	643

Figure 6. Daylighting illuminance setpoint (500 lux) exceeded time (hours): monthly and yearly values for Office A and Office B.

4. Conclusions

Solar control films could be a good strategy to reduce cooling energy consumptions and to reduce glare problems in existing non-residential buildings with large windows, but their performance is often evaluated by numerical analysis, without any comparison with experimental data. In the present work, the performance of two very similar offices with and without solar control films on the window glass was evaluated by means of experimental data and a thermal model implemented in EnergyPlus. Thermal-energy analysis showed the solar control films capability to reduce the indoor air temperature (when the HVAC system is off a reduction of about 2°C was observed) and the window heat gains: the maximum reduction is about 50-60% in winter and 40% in summer. A reduction in daylight illuminance availability was also found: the illuminance level was reduced by about 50- 60% both during sunny and cloudy days. Preliminary simulations show that the annual cooling demand decreases thanks to the use of the solar control films: the reduction is about 40% both in Perugia and in Rome. Nevertheless the heating energy demand increases of about 15% in Perugia and 33% in Rome, due to the less solar gain with solar control films. Future studies will focus on the final model validation, taking into account also the HVAC system, and the evaluation of the lighting electricity consumptions, depending on the daylighting availability. Many other places will be simulated, in order to evaluate the influence of solar control films in different climate conditions.

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