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Development of an Electric-Driven Smart Window Model for Visual Comfort Assessment

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ABSTRACT

Smart windows, especially those electric-driven, represent one of the most advanced technologies for controlling solar radiation. For a correct use, it is necessary to understand their real behaviour through in-situ measurements on full-scale application as well as calibrating and validating visual simulation models capable of predicting their performances. In this paper, the preliminary results of current research activities aimed at developing simulation models of electric-driven full-scale glazing are presented. The research activities started with the assessment of the visible solar transmittance as a function of light incident angle through in-situ measurements; different models, with related values, of the visible solar transmittance were considered. For each simulation model, the corresponding transmittance value was set in the RADIANCE “*trans*” material model and the simulated illuminance values, for a defined acquisition point of a test-facility, were then compared with the experimental data. Finally, for each model, indoor luminance distributions were reported considering a typical office seating position. Preliminary results, based on the in-situ measurements approach, highlighted a sufficient accuracy for one of the models adopted; further analyses are needed in order to upgrade the simulation models available and assess the effective performances of these windows.

KEYWORDS
Electric driven window, Experimental measurements, Visual Comfort, Daylight simulation, Radiance.

INTRODUCTION

The correct use of daylight allows to reduce energy use for lighting in buildings as well as improve visual comfort (Ciampi et al., 2015a; Ciampi et al., 2015b). In this scenario, smart windows, especially those electrically driven, can play an important role in controlling the visual and thermal conditions inside a room. Differently from conventional windows, these new typologies of glazing allow to vary their visible and thermal characteristics by applying an electric field to active layers. With the aim of controlling solar radiation and improving indoor conditions, more and more new electric-driven types of smart materials and systems are being developed. Nevertheless, for the best use of these new technologies, in-situ assessments on full-scale devices are necessary to understand their real behaviour upon varying internal and external conditions as well as to develop simulation models capable of predicting their performance under different operating conditions. For these reasons, experimental and theoretical studies have been performed to evaluate the visual and thermal performances of different full-scale devices as: electrochromic windows (Piccolo et al., 2009), Suspended Particle Device (SPD) (Ghosh et al., 2016) or gasochromic windows (Feng et al., 2016). In this paper, the preliminary results of experimental research aimed at evaluating the visual behaviour and developing simulation models of an Electric-Driven (ED) glazing are presented. The analysed electrically driven glazing can be switched from an opaque white (milky) to a transparent (clear) state in the presence of an electric field. A preliminary and simplified optical characterization of the electric-driven glazing was performed to evaluate the visible solar transmittance as a function of sunlight incident angle, through simultaneous on-site measurement of the vertical illuminance values on the external and internal surfaces of the window; the measurements were collected on a full-scale ED device by using a test facility. Experimental data were then used to calibrate and validate simulation models of the two states of the ED glazing using a RADIANCE “trans” material model as first approach; the calibration/validation was carried out by using models of glazing solar transmittance presented in previous researches. Finally, it has been performed a preliminary comparison among different simulation models for ED glasses in terms of illuminance distributions as well as Discomfort Glare Probability (DGP) inside the facility.

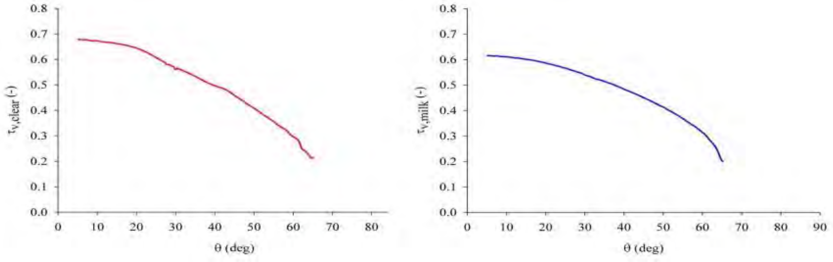
TEST FACILITY AND MEASUREMENTS SET UP

In order to allow for experimental studies to assess the in-situ visual performances of full-scale smart windows, an experimental station was designed and set-up at the Department of Engineering of the University of Sannio (Ascione et al., 2016; Sibilio et al., 2016). The station consists of a steel structure placed on a turntable, with external size of 6.00 m x 6.00 m and height of 5.50 m. The facility is equipped with a double-hang wood frame window with a total size of 2.000 m x 1.200 m, a ratio between glass area and total window area equal to 0.59; each hang has a glazing with size of 0.785 m x 0.900 m. In this paper, the first results of the in-situ visual characterization of the two full-scale double ED glazings, manufactured by Gesimat (GESIMAT), were presented. The ED glazing was composed, from outside to inside, of a 4 mm uncoated float glass, a 16 mm gap filled with Argon and an electric-driven layer between two 4 mm uncoated glasses. According to the technical data declared by the manufacturer, the ED glazing is switched from milky to clear state by applying an electric field of about 115 V, within about 1 s. In the clear state, ED glazing was characterized by a visible solar transmittance (τ_{vis}) equal to 72.5%, a thermal transmittance (U_g) equal to 2.5 W/m^2K, a solar factor (g) equal to 0.72 and a power demand of about 10 W/m^2. In the milky state, the ED glazing was characterized by a visible solar transmittance (τ_{vis}) equal to 60.7%, a thermal transmittance (U_g) equal to 2.5 W/m^2K and a solar factor (g) equal to 0.67. The in-situ visual characterization was carried out in two steps: (1) evaluation of the visible solar transmittance as a function of light incident angle and (2) evaluation of vertical internal daylight illuminance on a specific measurement point.

Evaluation of the visible solar transmittance as a function of light incident angle

The first set-up was realized to evaluate the variations of visible solar transmittance as a function of the sunlight incident angle. With this aim, the vertical illuminance values on the external surface of the window E_v^{ext} and just behind the internal surface of each ED glazing E_v^{int} were acquired during different days with completely clear sky conditions. In this step, measurements were performed with i) window west oriented and ii) left ED glazing in clear and right ED glazing in milky state. The illuminance values were acquired every 20 s by three Konica Minolta T-10 (accuracy of ± 2 %) when direct sun light strikes on lux-meters, from around 2 pm (incident angle of direct light about 65°) to the sunset (incident angle about 5°).

Figure 2a shows the experimental visible solar transmittance values, calculated as $E_v^{\text{int}} / E_v^{ext}$ for clear state, while Figure 2b shows those for milky state.

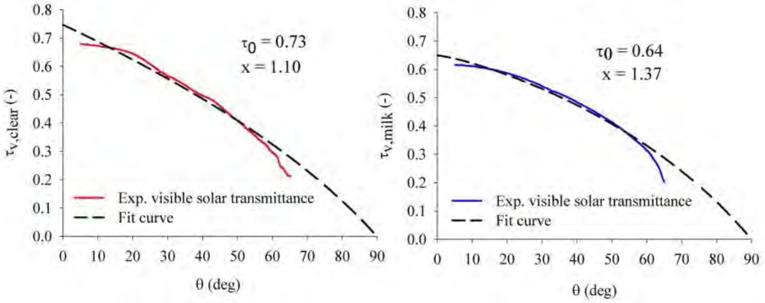


a) b)

Figure 1. Experimental visible solar transmittance values as a function of the sunlight incident angle for a) clear and b) milky state.

The experimental data were then compared with 3 simulation models:

1) **#1 (τ_{maker})**: value of the visible transmittance constant for different sunlight incident angles and equal to the value declared by manufacturer;
2) **#2 ($\tau_{dif\text{-}dif,fit}$)**: value of the visible transmittance constant for different sunlight incident angles and equal to the diffuse-diffuse transmittance $\tau_{dif\text{-}dif,fit}$ of the glazing, defined as $\tau_{dif-dif,fit} = \int_0^{\pi/2} \tau_v(\theta)\sin(2\theta)d\theta$ where θ is the incident angle and $\tau_v(\theta)$ is the empirical angular function $\tau_v(\theta) = \tau_0 \cdot (1 - \tan^x(\theta/2))$ (Reinhart and Andersen, 2006); these models are reported as dash lines in Figure 2a for clear and Figure 2b for milky state. The calculated values of $\tau_{dif\text{-}dif,fit}$ are equal to 43.8% for clear and 42.7% for milky state;
3) **#3 (τ_{fit})**: value of the visible transmittance variable with the sunlight incident angle and equal to value predicted by the empirical angular function $\tau_v(\theta) = \tau_0 \cdot (1 - \tan^x(\theta/2))$ (dash lines in Figure 2a and Figure 2b).



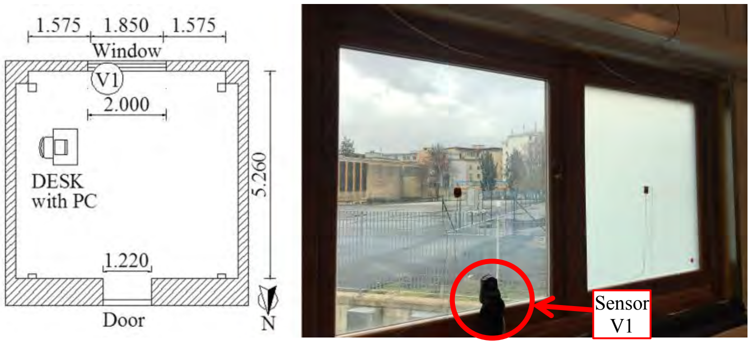
a) b)

Figure 2. Curve fitting for a) clear and b) milky state (model #2 and #3).

Later, as first approach, the ED glazing was modelled through the RADIANCE "*trans*" material. The "*trans*" material model considers the glass as a perfect Lambertian diffuser and assumes the solar visible transmittance constant for different light incident angles. The two states of ED glasses were simulated setting the amount of light transmitted as totally direct for clear and totally diffuse for milky state.

Evaluation of vertical internal daylight illuminance on a specific measurement point

The external daylight availability as well as the internal illuminance daylight distributions were acquired at the same time, with the test room south oriented. The measurements were collected on sunny days from 9:00 to 18:00 local time with a time step of 1 hour, on 12th, 13th and 18th July in the milky state and on 11th, 15th and 16th July in the clear state. The external daylight availability was evaluated acquiring the horizontal global and diffuse illuminance values on the roof of the facility, by using two illuminance-meters LP PHOT 03 (DELTA-OHM), with accuracy <4%. For the horizontal diffuse illuminance, a black painted shadow-ring, with a diameter of 0.574 m and thickness equal to 0.052 m were used. The simulation results were compared with the experimental data acquired by an illuminance-meters Konica Minolta T-10 placed in vertical position just behind the glass (V1, as reported in the Figure 3a). Figure 3b shows the window equipped with the ED glasses in the clear (left pane) and milky (right pane) states. In this paper, only the sensor V1 was considered because it was not affected by internal light reflections, allowing to evaluate the behaviour of the glazing alone.



a) b)

Figure 3. a) Layout of the room with position of the sensor and b) the ED device in the two states.

RESULTS AND DISCUSSION

Figure 4 the comparison among the experimental illuminance values acquired behind the ED device (measurement point V1), the simulation results obtained setting the visible transmittance equal to τ_{maker}, $\tau_{dif\text{-}dif,fit}$ and τ_{fit} as well as the external horizontal global illuminance values. In the figure, the connecting lines between the dots are only guidelines for the eye to connect data points. The values are plotted as a function of both the hour of the day and the light incident angle. The Figure 4 shows that:

- whatever the glazing state is, the simulation performed using τ_{maker} overestimates the experimental data, while τ_{fit} underestimates the experimental data;
- for both the clear and milky state, the simulations performed using $\tau_{dif\text{-}dif,fit}$ allow to achieve the best prediction of experimental data;
- whatever the glazing state is, the simulation performed using $\tau_{dif\text{-}dif,fit}$ overestimates the experimental data in the morning, while underestimates the measured values in the afternoon;
- the average relative percentage error values with respect to the measurements are equal to about 73.0% for τ_{maker}, -2.6% for $\tau_{dif\text{-}dif,fit}$ and -59.0% for τ_{fit} in clear state, while in the milky state are equal to about 59.0%, -2.0% and -52.0%, respectively;
- for $\tau_{dif\text{-}dif,fit}$ in the clear state, the smallest illuminance difference between the experimental and simulated data is observed on 16th July at 16:00 (with values of about 5287 lux and

5243 lux, respectively); in milky state, it is observed on 12th July at 17:00, (with values of about 4900 lux and 4861 lux, respectively).

In Figure 5, the simulated luminance distributions inside the facility, using the three simulation models described above, were reported. With the aim of reproducing a typical seating position, the luminance distributions, with associated DGP values, were calculated from a point placed at the eye level of a person considered as seated at the desk, facing and looking at the screen of a notebook computer (Figure 3a). The simulations were carried out at midday of a conventional sunny sky with sun.

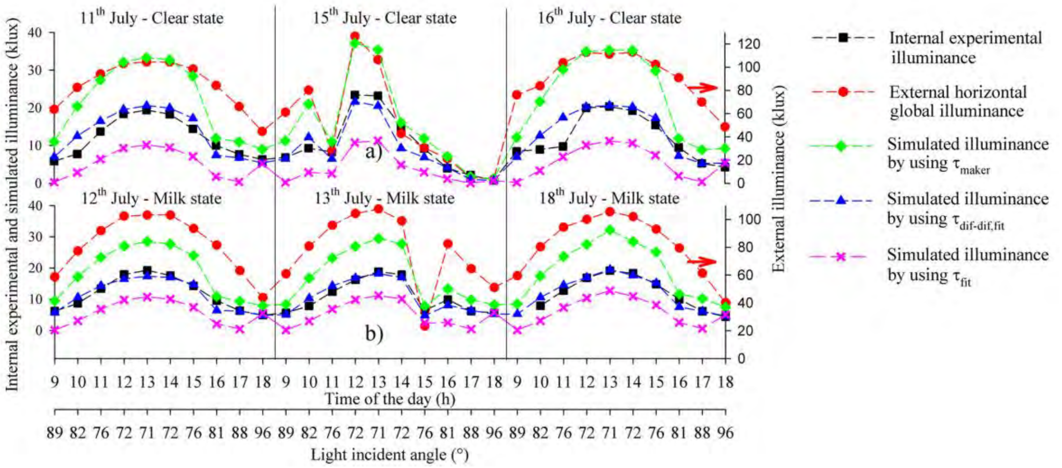


Figure 4. Measured and simulated illuminance values on the measuring point V1 for a) clear and b) milky states as well as the external horizontal global illuminance values.

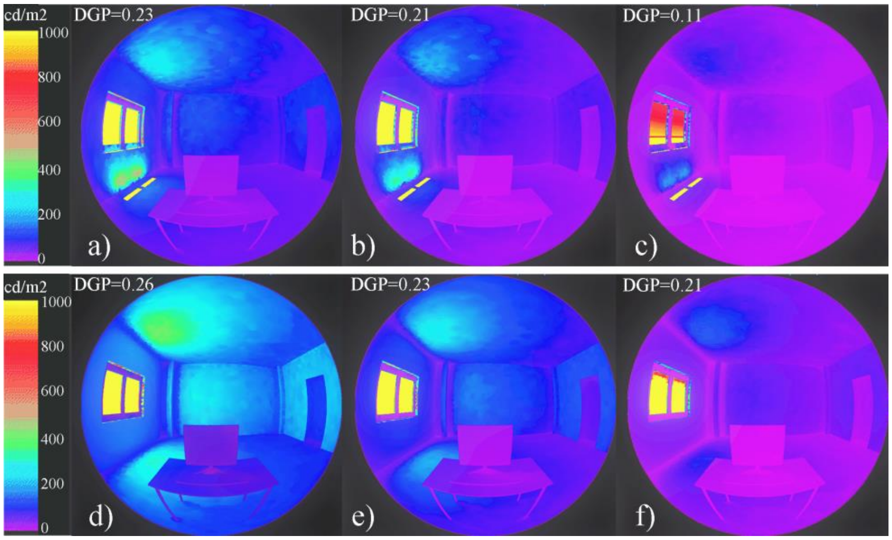


Figure 5. Simulated daylight luminance distributions for a) τ_{maker}, b) $\tau_{dif\text{-}dif,fit}$ and c) τ_{fit} in clear state as well as d) τ_{maker}, e) $\tau_{dif\text{-}dif,fit}$ and f) τ_{fit} in milky state.

The preliminary investigation allows to provide some models for the simulation of the ED glasses and define, among them, the more accurate one for utilization within software for indoor daylighting analysis. The research, even if performed with a preliminary approach based upon on-site measures, highlighted differences in outcome among the different considered models of ED windows. In particular it should be noted that the data provided by the manufacturer do not always provide an accurate assessment of the transmission of sunlight and its value nearby the window. The same results were obtained considering the model τ_{fit} that always underestimate experimental data. Through preliminary on-site measurements it was defined a more reliable sunlight visible transmittance factor that took into account the influence of the incidence angle of solar radiation. The availability of models with a good accuracy represent the starting point to perform detailed analyses for evaluating the ability of these ED glasses to reduce energy consumption and improve visual and thermal comfort in comparison with more conventional design solutions. In addition, for these types of glasses there are other issues to consider, such as: (i) the way in which the light is transmitted inside the room and (ii) the fact that the milky state prevents exterior view. An example of these last effects can be viewed in Figure 5, where ED milky state prevents reflections of direct sunlight on internal surfaces but at the same time lead to higher DGP values with respect to the clear state. Finally, it is important to highlight that the progress in the use of innovative materials raises the issue to have reliable simulation models able to correctly describe their behaviour.

CONCLUSIONS

In this paper, the preliminary results of research activities aimed at calibrating and validating visual simulation models for ED glazing were presented. The RADIANCE "*trans*" material model was used as a first approach to simulate the behavior of the two states of the ED glazing. Starting from the manufacturer data and in-situ measurements, three different values of the visible solar transmittance, for each ED state, were deduced to be set in the "*trans*" material model. The results of the three simulation models show that the simulation model #2 is the best way to predict the experimental data, for both the clear and milky states. The results also suggest that internal daylight distribution, in addition to the weather conditions, is strongly correlated to the simulation models applied for the same smart glazing. In the next research step the ability of other simulation models will be considered to provide a suitable tool for predicting the real performance of these systems.

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