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Thermal Performance of an Electric-Driven Smart Window: Experiments in a Full-Scale Test Room and Simulation Model

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ABSTRACT
This paper reports the results of experimental tests and numerical simulations aimed at evaluating the performance of an electric-driven smart window with respect to solar control in buildings. The experimental performances of the electric-driven smart window were evaluated using a south oriented full scale experimental facility designed and realized. The tests were carried out during the summer under real sky conditions upon varying the state of the electric-driven smart window (clear and milky). In the first part of the paper, the experimental results are discussed in terms of surface temperature of glazings as well as indoor air temperature in order to highlight the potential benefits on thermal comfort associated to the application of electric-driven smart windows. In the second part of this paper, the experimental data are compared to the numerical results generated through a simulation model of the electric-driven smart window in order to assess its reliability under different operating scenarios. Finally, the simulation model is used to quantify the potential cooling load reduction deriving from the integration of electric-driven smart windows in an office façade located in Naples (Italy).

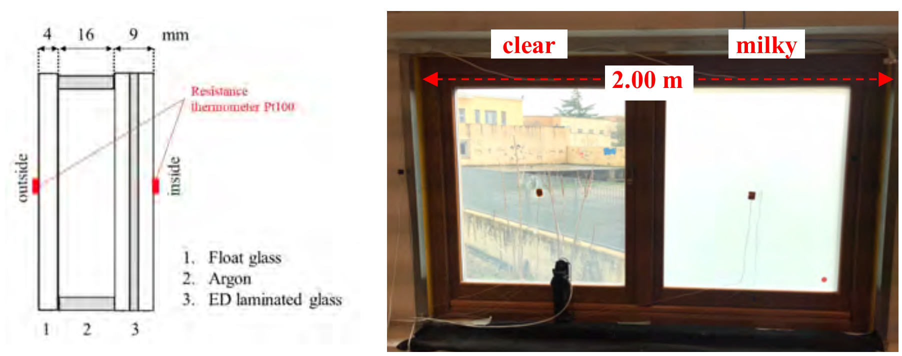
KEYWORDS
Smart windows, Electric-driven smart windows, Thermal comfort, Solar control, TRNSYS

INTRODUCTION
A significant portion of the total worldwide energy demand (around 40%) can be attributed to heating and cooling of the building sector (European Commission, 2015). In this context, the Electric-Driven (ED) smart window technology, especially for the buildings with a large glazed surface, can help to significantly reduce the energy consumption as well as to improve the indoor thermal comfort. Indeed, these new typologies of glazings allow to vary their visible solar transmission and solar factor by applying an electric field. A large number of studies are currently in progress about electric-driven smart windows (Baetens R. et al. 2010, Fernandes et al. 2013, Niklasson and Granqvist 2006, Piccolo 2010, Piccolo et al. 2009, Piccolo and Simone 2009, Sibilio et al. 2017). The literature review reveals the need to perform further experimental analysis to evaluate the on-site performances of these type of smart windows taking into account that: (i) the most analyzed electric-driven smart windows typology has been the electrochromic window, (ii) the visual comfort as well as the electric energy savings for lighting have been the most investigated aspects and (iii) the experimental performances of small-scale smart windows prototypes have been generally investigated. However, it can be noticed that the benefits in terms of reduction of cooling energy demand as well as capability in maintaining the thermal comfort by the application of the smart windows have been rarely investigated.

In this paper, the results of experimental tests and computer simulation modelling aimed at evaluating the thermal performance of a full-scale ED windows with respect to solar control in buildings are reported. The experimental thermal performances of the ED window were evaluated by using a south oriented full-scale experimental station during the summer and under real sky conditions. In the first part of the paper, the experimental results are discussed in terms of surface temperature of glazings as well as indoor air temperature. The ED window is modelled by means of the software (WINDOW 7.5) and then imported into the software (TRNSYS 17). In the second part of the work, the numerical results are compared to the experimental data in order to assess the model reliability. Finally, the ED window model is used to quantify the cooling energy demand reduction deriving from the use of ED windows into an office façade located in Naples (Italy).

FULL-SCALE TEST-ROOM

The experimental facility is a full-scale outdoor test-room (Ascione F. et al. 2016) designed and set-up at the Department of Engineering of the University of Sannio, Benevento (latitude: 41°7' N; longitude: 14°47' E). The test room has a floor area of 36.0 m^2 (6.0 m × 6.0 m) with a height of 5.5 m. The test-room is able to rotate 360° on the horizontal thanks to a motorized steel support that allows to modify the orientation. The envelope of the experimental station consists of three removable vertical test walls (U=0.43 W/m^2), one unremovable vertical technical wall (U=0.05 W/m^2), a floor (U=0.05 W/m^2) and a roof (U=0.06 W/m^2) (Ascione F. et al. 2016). The total size of the window is 2.00 m × 1.20 m; two ED double glazings (each with size of 0.785 m × 0.900 m), produced by (GESIMAT), were installed. This typology of electric-driven smart window consists of three layers as reported in Figure 1a. In particular, the ED glazing is a polymer with dispersed Liquid Crystal (LC) between two float glass substrates. This third layer allows the ED window to switch quickly (1 second) from transparent to opaque state, and vice versa. The switching is possible thanks to a potential difference across the glazing; in particular, when the voltage is equal to 0 V the smart window is opaque (milky), while when the voltage is equal to 115 V the ED window is transparent (clear). Figure 1b reports an indoor view of the ED window installed in the test-room with the left window pane in the clear state and the one on the right in the milky state.



a) b)

Figure 1. a) Schematic layout of the ED double glazed unit, b) indoor view of the ED window installed in the test-room.

In clear state, ED glazing is 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 milk state, the ED glazing is characterized by τ_{vis} equal to 60.7%, U_g equal to 2.5 W/m^2K and g equal to 0.67.

The outdoor boundary conditions were monitored by means of a weather station. In particular, the test-room is well equipped (Ascione F. et al. 2016) in order to measure the following parameters: air temperature, relative humidity, rainfall, wind-speed, wind-direction, diffuse and global solar radiations. The technical specifications of the outdoor sensors are reported in (Ascione F. et al. 2016). In addition, external daylight availability is evaluated by measuring the horizontal global and diffuse illuminance values on the roof of the test-room by means of two illuminance-meters LP PHOT 03 of (DELTA-OHM) and with an accuracy < 4 %. In order to highlight the potential benefit on thermal comfort associated to the use of the ED windows, the surface temperature of glazings as well as the indoor air temperature are also measured. The temperatures are monitored by using a resistance thermometer Pt100 with a range of -40÷80 °C and an accuracy equal to ±0.1 °C at 0 °C. The sensors on the surface of glazings are installed with appropriate shielding to consider the effect of direct solar radiation. Each parameter is logged every 10 seconds by means of a Fluke NetDAQ Data Logger.

SIMULATION MODELS

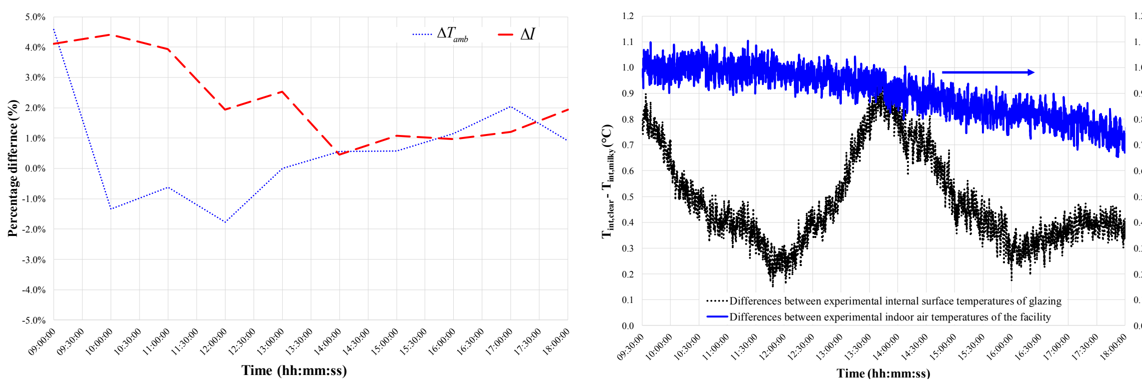
The whole ED window was modelled by means of the software WINDOW 7.5, considering the schematic layout of the ED double glazed unit reported in Figure 1a. In particular, two different window models were realized, one for the ED window in the clear state and another one for the ED window in the milky state. The output file of the software WINDOW 7.5 was then used in software platform TRNSYS 17 by means of the Type 56 to compare the experimental thermal performances with those obtained through simulations. However, in order to take into account the thermo-physical characteristics of the building envelope of the facility (Ascione F. et al. 2016), the test-room was firstly modelled in TRNSYS 17.
A simulation time step equal to 10 seconds was used. During the simulations, the same outdoor boundary conditions measured during the experimental tests were considered.
Finally, the two simulation models of ED window were used to quantify the cooling energy demand reduction associated to a typical office building located in Naples by replacing the conventional double-glazing windows with the same thermal transmittance.

RESULTS AND DISCUSSION

Experimental results

Measurements were carried out for about 1 month during the summer of 2017 from 29th June up to 20th July (for a total of 22 days) from 9:00 up to 18:00 by using the above-described facility located in Benevento (latitude: 41°7' N; longitude: 14°47' E). The experimental tests were carried out under real sky conditions with the ED window south orientated. The ED window was manually switched from clear to milky state and vice versa. During the experimental tests the indoor air temperature was monitored, but not controlled, in order to estimate the influence of solar gains upon varying the state of the ED window. Taking into account that only one test-room was available, a first comparison between the boundary conditions during the days with the ED window in clear state and those with the ED window in milky state was carried out. This comparison is mandatory, in order to verify that the experimental tests for both states were conducted in the same outdoor condition. This comparison was performed in terms of percentage difference of external air temperature (ΔT_{amb}), percentage difference of global solar radiation on the horizontal (ΔI) and wind velocity. The comparative test was considered acceptable in the cases of the difference in the outdoor environmental variables never exceeded 5%. Figure 2a reports the values of ΔT_{amb} and ΔI as a function of the hour of the day for July 8th (clear ED window) versus July 12th (milky ED window). No significant differences in terms of wind velocity were observed for this two days. This figure highlights how the values of both ΔT_{amb} and ΔI_{mean} never exceeded

5%; in particular, ΔT_{amb} ranges between -1.77% and 4.58%, while the values of ΔI range from a minimum of 0.46% up to a maximum of 4.41%. This means that the same outdoor conditions for both July 8th and July 12th can be assumed. With respect to these two days, the measured values of the internal surface temperature of the glazing (T_{int}) and the measured values of the indoor air temperature (T_{indoor}) are reported in Figure 2b. In particular, Figure2b shows, on left axis, the difference between the internal surface temperature of the glazing with the ED transparent window ($T_{int,clear}$) and the internal surface temperature of the glazing with the ED opaque window ($T_{int,milky}$) and, on right axis, the difference between the measured values of the indoor air temperature with the ED transparent window ($T_{indoor,clear}$) and the measured values of the indoor air temperature with the ED opaque window ($T_{indoor,milky}$), both as a function of the time. This figure highlights how the differences are always positive: this means that (i) the values of the internal surface temperature of the glazing associated to the clear window are greater than those of the milky window and (ii) using the ED window in the clear state, the indoor air temperature is greater than that one of the ED window in the milky state. In particular it can be noticed how using the ED window in the milky state during the summer the indoor air temperature can be reduced by a value between 0.65°C and 1.10°C.



a) b)

Figure 2. a) Values of ΔT_{amb} and ΔI, b) differences between $T_{int,clear}$ and $T_{int,milky}$ as well as between $T_{indoor,clear}$ and $T_{indoor,milky}$ as a function of the time.

Numerical results

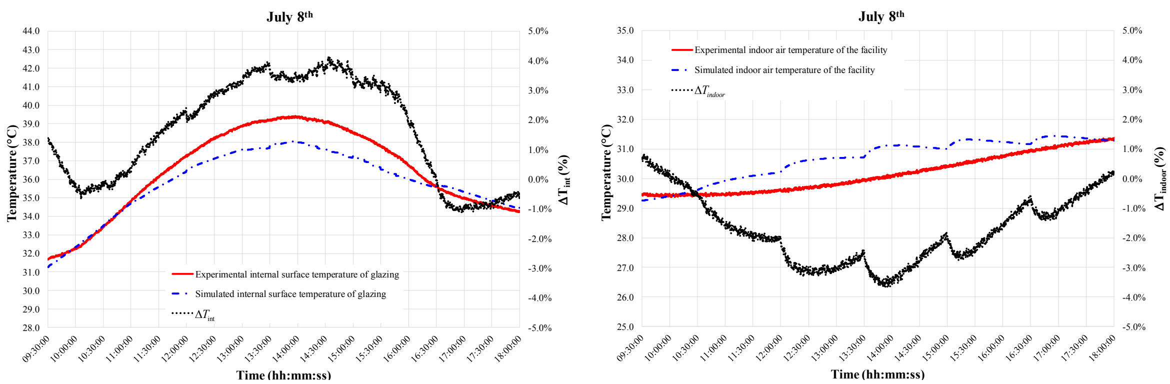
The simulation results were compared to the experimental data in order to assess the model reliability. The comparison was performed in terms of internal surface temperature of the glazing as well as indoor air temperature for both July 8th (ED window in clear state) as well as July 12th (ED window in milky state). In order to verify the accuracy of the modelled ED window, the following percentage differences were calculated:

$$\Delta T_{int} = \frac{T_{int,exp} - T_{int,sim}}{T_{int,exp}} \quad (1)$$

$$\Delta T_{indoor} = \frac{T_{indoor,exp} - T_{indoor,sim}}{T_{indoor,exp}} \quad (2)$$

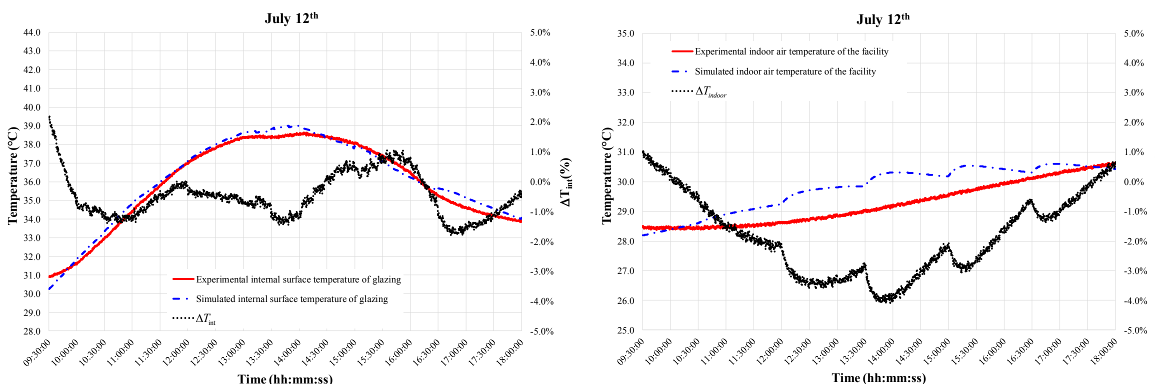
where $T_{int,exp}$ and $T_{int,sim}$ are the experimental and simulated internal surface temperature of the glazing, respectively; $T_{indoor,exp}$ and $T_{indoor,sim}$ are the experimental and simulated indoor air temperature of the test-room, respectively.

Figures 3a and 3b compare the simulation results with the experimental data in terms of T_{int} and T_{indoor} as a function of the time for the clear state (July 8th). These figures highlight how the modelled clear ED window predicts quite well the measured values. In particular, the values of ΔT_{int} range from -1.13% to 4.14%, while the values ΔT_{indoor} during July 8th range from -3.67% to 0.82%. Figures 4a and 4b compare the simulation results with the experimental data in terms of T_{int} and T_{indoor} as a function of the time for the milky state (July 12th). These figures highlight a good model reliability. In particular, the values of ΔT_{int} range from -1.79% to 2.19%, while the values of ΔT_{indoor} range between -4.14% and 1.08%.



a) b)

Figure 3. Comparison between simulation results and experimental data in terms of: a) internal surface temperature of the glazing, b) indoor air temperature.



a) b)

Figure 4. Comparison between simulation results and experimental data in terms of: a) internal surface temperature of the glazing, b) indoor air temperature.

Finally, the two simulation models of ED window were used to quantify the cooling energy demand reduction associated to a typical office building located in Naples (latitude = 40°51′46″80 N; longitude = 14°16′36″12 E) by replacing the conventional double-glazing windows with the same thermal transmittance. In particular, an office building with 200 m^2 as floor area and 600 m^3 as volume with a total window area ($A_{w,total}$) of 36.02 m^2 ($A_{w,South}$=27.02 m^2, $A_{w,East}$= 4.5 m^2, $A_{w,West}$= 4.5 m^2) was modelled in TRNSYS 17 by means of the Type 56. Thermal transmittance of the building envelope has been equated to the threshold values specified by the Italian Law (Italian Decree 2015). A preliminary ON/OFF control logic for the ED window was used; in particular two hours before and two hours after the maximum global solar radiation on the horizontal (from 10:00 up to 14:00) the ED window was switched in milky state, while it was switched in clear state in the rest part of the day. The cooling plant was considered ON from 8:00–18:00 in weekdays with an indoor target temperature equal to 26°C. Performing a simulation during the summer time (from June 1st to August 31st) with a simulation time step equal to 1 minute, a cooling energy demand reduction of about 26% was achieved.

CONCLUSIONS

In this paper the results of experimental tests and computer simulation modelling aimed at evaluating the thermal performance of a full-scale ED window with respect to solar control in buildings were reported. The experimental analysis showed how switching the ED window to the milky state can reduce the indoor air temperature of about 1°C. The ED window was modelled by means of the software WINDOW 7.5 and the comparison between numerical and experimental data showed a good reliability of the developed ED model.

Finally, a cooling energy demand reduction deriving from the integration of ED windows in a typical office façade located in Naples of about 26% was assessed by means of the software TRNSYS 17. In future works, the modelled ED smart window will be used to study and predict the performance of these windows under different operating scenarios.

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