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Thermo-chromic glazing in buildings: a novel methodological framework for a multi-objective performance evaluation

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Abstract

Transparent adaptive façade components can improve the energy performance and the indoor environmental quality of buildings. Nevertheless, their utilization is not widespread, due also to the lack of a robust methodology to comprehensively evaluate their potentialities and find out their most suitable applications. The present paper introduces a novel methodology to characterize the behavior of a transparent adaptive façade component, a thermo-chromic glazing, and predict its effects, through numerical simulations, on energy performance and visual comfort aspects. An experimental characterization on the thermo-chromic glazing was performed to determine its optical properties at the variation of its surface temperature. The component was found to be able to switch its visible transmittance between 0.71 and 0.13, and its solar transmittance between 0.65 and 0.28. The experimental results were used to feed the numerical model created on purpose to describe the adaptive behavior of the component. Finally, a numerical simulation campaign was performed to assess the effects of the thermo-chromic glazing on energy and visual comfort aspects of an enclosed office located in Turin. It was found that the thermo-chromic glazing reduced the overall energy performance compared to a static selective glazing, but it allows improving the visual comfort conditions within the space considered.

Keywords: Thermo-chromic glazing; transparent adaptive façade components; integrated simulation; energy performance; visual comfort; experimental characterisation.

1. Introduction

In the last few years, particular emphasis was given to researches related to advanced glazing for smart building envelopes, which can significantly contribute to the achievement of decarbonization targets. The development of

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transparent façades able to change their thermal/solar/luminous properties according to boundary conditions and user needs, in order to optimize indoor environmental quality and maximize the energy efficiency, is one of the current research direction mainly pursued by designers, manufacturers and scientists [1].

Among the so called adaptive façades (confining the analysis to the material/component scale only), the switchable glazing represents a very promising solution. In more detail, strong research efforts in this field are currently devoted to improve the spectrally selective properties of the glazing, to better manage heat, solar and visual transmission. Within the different dynamic glazing, i.e electro-chromics, gaso-chromics, liquid crystals, suspended particle devices, photo-chromics and thermo-chromics, the last one, based on a color and properties change due to temperature variations, is enjoying ever-increasing popularity. The most relevant drawbacks due to the poor switching efficiency of the conventional VO_2 coatings, onto which thermochromism is based, are being solved by working on different aspects, i.e. film thickness, dopant and microstructure [2, 3, 4, 5, 13]. A widespread implementation in real buildings is therefore approaching [6].

Alongside the innovation at material/component level, parallel researches have to be carried out, aimed on one hand at fully characterizing its performance and on the other hand at providing tools able to manage contemporarily energy and comfort aspects. During actual building operation, an adaptive glazing should meet several requirements, pertaining to different physical domains [7]. Thus, when adopting these dynamic glazing, the capability to provide a clear picture of the overall behavior and performance, through the adoption of the right metrics, indicators and tools, becomes of paramount importance to make the expected energy savings, together with the high comfort level expectations, really achievable.

2. Methodology

The present study proposes i) to determine the optical properties of the thermo-chromic glazing at the variation of its surface temperature and ii) to evaluate the effects of its application on a case study office, in respect to those relative to a traditional selective glazing. The methodology followed to perform this study can be subdivided into two distinct parts: an experimental characterization of the thermo-chromic sample and, starting from the results obtained in the first phase, a numerical analysis of a case study office equipped with the thermo-chromic glazing. The first phase, carried out by means of an integrating sphere at ENEA Casaccia Research Center, allowed an accurate determination of the optical behavior of the thermo-chromic glazing at the variation of its driving factor, i.e. its surface temperature. A numerical model to describe the thermo-chromic behavior was created starting from the outcomes of the first phase. The numerical model was then implemented into a novel simulation tool, under development at Politecnico di Torino, to numerically evaluate the effects of the application of the thermo-chromic glazing to an office case study. The tool used allowed performing a simultaneous evaluation of the effects of the adaptiveness of the thermo-chromic glazing on energy and visual comfort aspects. This was done by managing different simulation software, for different purposes, together in a unique integrated simulation process. The outcomes of this phase were then compared to a reference case, represented by a traditional selective glazing.

In the combination of an experimental campaign and a simulative analysis lies one of the strength of the present work, as it allows creating a numerical model for the behavior of the thermo-chromic glazing starting from accurate data (more accurate than those commonly provided by manufacturers). This aspect becomes even more important when considering that the numerical analysis here performed, being very accurate, requires a heavy computation; feeding thus the numerical model with high resolution input data assures a higher precision in the analytical results.

2.1. Material and sample

The Vanadium Oxide VO_2 thermochromic material is embedded in the interlayer of a laminated glass unit composed of: double layer of 3 mm of float glass; approximately 1 mm of polymeric interlayer integrating the nanostructured functional material. The characterized thermochromic laminate sample has a size of 400 mm by 400 mm. For the numerical analysis the LGU was combined has the outermost laminate of an IGU as discussed in Section 3.1.

Fig. 1. Different states of TC glass, 400 x 400 mm sample under direct solar radiation.

2.2. Experimental characterization

The optical characterization of the thermo-chromic sample was carried out with an in-built spectrophotometer, able to perform measurements on complex samples, which conventional instruments are not suitable for. The experimental set-up consists of the following components:

- The light source is a 300 Watt xenon arc-lamp with adjustable power, which covers the whole visible spectrum and 94% of the solar spectrum, as defined in the relevant standard [8]. The size of the collimated beam can be modulated through a system of lenses and diaphragms according to the measurement requirements and sample geometric complexity. The light beam diameter was set to 60 mm for this measurement campaign.
- The spectrophotometer is equipped to an integrating sphere with a 75 cm diameter. The sphere external shell is made of aluminum, while the internal surface is made of Spectralon, a white material with reflectivity greater than 95% in the whole solar range. The sphere is equipped with several ports to perform transmittance and reflectance measurements with the auxiliary port method, needed for single beam-type spectrophotometers. The sample port diameter can be varied according to sample characteristics, a 200 cm port was used for this test.
- The detection system consists of three array spectrometers and three detectors to analyze different spectral bands: NMOS for the 250–1000 nm range (dispersion 1.4 nm/pixel) and InGaAs for the 900–1700 nm range (dispersion 3.125 nm/pixel). In the post elaboration, spectral data are re-built with 1 nm as spectral resolution. The signal (radiant power) in the sphere is transmitted to the detection system via optic fibers.

The measurement procedures used in the present study are the following:

- the transmission coefficient is measured as the ratio between the radiation transmitted by the specimen mounted on the sample port and the energy directly entering the sphere by the same port without specimen;
- in the reflection mode, the light beam entering the sphere hits the sample with an 8 deg. angle of incidence. The reflection coefficient is measured as the ratio between the radiation reflected by the specimen and that of a calibrated white target, both mounted in turn on the sample port. Full measurement procedure is explained in [9].

The instrument error is estimated to be 0.02 for the different measurement modes.

Measurements were carried out at (near) normal incidence for different surface temperature values. The sample was heated-up by direct exposure to solar radiation and the surface temperature was monitored during each measurement through thermo-graphic analyses. Since the optical transition of such systems may vary in cooling and heating, it is stated that the test was carried out in heating mode.

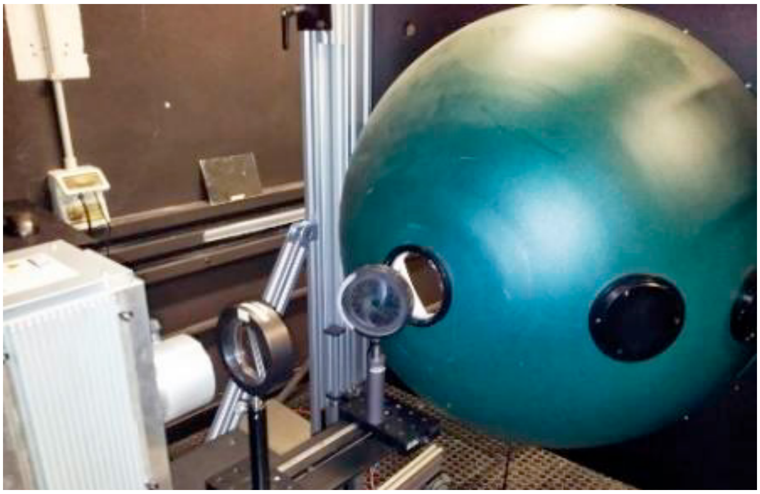

Fig. 2. Spectrophotometer with large integrating sphere and light source used to characterise the thermochromic sample.

2.3. Numerical analysis

The measured optical properties were used to create a numerical model describing the behavior of the component at the variation of its surface temperature. The numerical model was then implemented in a Building Performance Simulation Tool to perform a simultaneous evaluation of the effects of the adaptiveness of the thermo-chromic glazing on energy and visual comfort aspects. This was done by managing together a daylight simulation software (DAYSIM, which in turn uses Radiance computation engine) [10] and an energy simulation software (EnergyPlus) [11]. The case study chosen was an enclosed office, located in Turin, 3.6 large, 4.5 m deep and 2.7 m high. One of the short walls, South-oriented, was equipped with a window 3.3 m large and 1.5 m high, for a Window-to-Wall Ratio (WWR) of 50%. The wall equipped with the window had an average thermal transmittance of 0.77 W/m^{2}K, while all the other surfaces were considered as adiabatic. The window was alternatively equipped with the thermo-chromic glazing and with a selective glazing, as reference case, with the same visible transmittance as that of the thermo-chromic glazing in its clearer state. Glazing performance indicators for the thermochromic and selective glazing are summarized in the Section 3.2.

The energy aspects were evaluated by means of the Energy Performance Index (EP), representing the annual primary energy demand per unit of floor area. The global average efficiency of the heating system is 0.9, while for the cooling system the SEER is 3.1. For cooling and lighting energy uses 2.17 is considered as the conversion factor for electric energy to primary energy, while 1 is adopted for heating energy uses as per local national context of the numerical study). The global EP was calculated as sum of the energy performances relative to heating (EP_h), cooling (EP_c) and lighting (EP_l).

Visual Comfort aspects were evaluated by means of the Useful Daylight Illuminance (UDI) [12], a Climate-Based Dynamic Metric that quantifies the percentage of occupied time of the year in which daylight is above, below and between an upper and a lower threshold value. These thresholds, respectively of 2500 lx and 100 lx, represent the limits of the range in which daylight is considered useful, i.e. neither too strong, which would cause a glare sensation to the user, nor too poor to perform a visual task. UDI was evaluated for a grid of sensors located at 0.75 m above the floor and at 0.50 m from each wall. For the sake of brevity the present paper focuses on the outcomes of the analyses presented rather than describing in detail the methodology followed.

3. Results

3.1. Experimental results

Preliminary measurements were carried out on the two faces of the sample, to check if the different layers of sample may affect the optic response; as no differences were found the measurement campaign was carried out with side 1 of the sample on the outdoor, as indicated by the manufacturer. The transmittance results are presented in figure 3 for the following temperature values: 15, 30, 45 and 60°C. It can be observed that the material has a higher switching behavior in the visible range (380-780 nm) than in the near-infrared region (780-1700 nm).

This different response is better highlighted in figure 4, where the evolution of broad-band parameters is calculated for measurements carried out every 5°C between extreme surface temperatures (15-70°). The visible transmittance ranges between 0.71 and 0.13, with a switching factor of 5.5; the switching factor decreases to 2.3 for the solar transmittance in the same temperature range, due to the fact that the switching factor in the near-infrared range is 1.3. In absolute figures, the solar transmittance ranges between 0.65 in the cold state and 0.28 in the hot state. Reflectance measurements were also carried out for the different temperature levels, and this quantity showed not to be significantly affected by the thermal conditions. Visible and solar reflectance are both 0.07 in the cold state, while the values decrease to respectively 0.06 and 0.05 in the hot state. According to these results, the absorptance values can be calculated, which account for: 0.22 and 0.28 respectively in the visible and solar ranges in the cold state, raising to 0.81 and 0.67 in the hot state.

The laminate overall optical properties obtained are summarized in Table 1 in the following section.

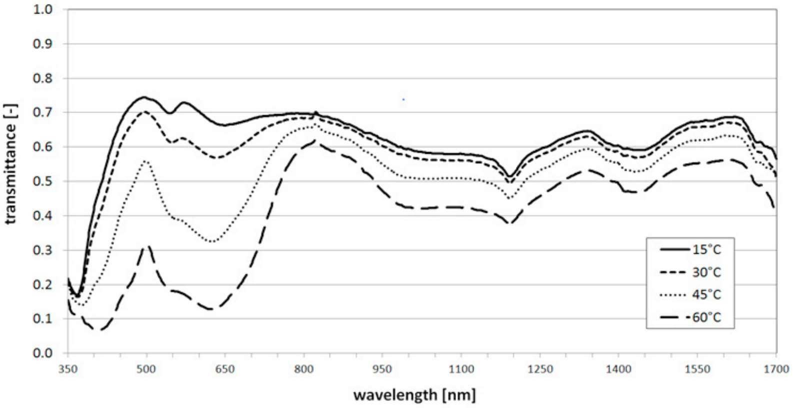

Fig. 3. Spectral transmittance for different surface temperatures of the sample.

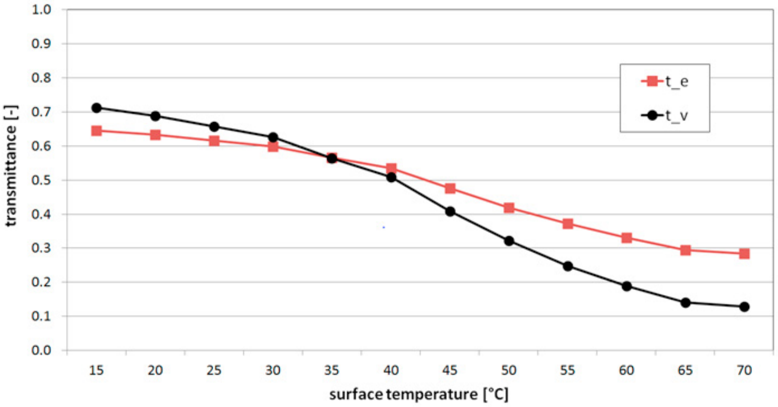

Fig. 4. Visible and solar transmittance for different surface temperatures.

3.2. Numerical results

3.2.1. Glazing Performance

In order to understand what could be the performance achievable by the thermochromic glazing in comparison to traditional glazing, in the numerical analysis a TC glazing unit (TCG) is compared to a standard reference double glazing unit with Selective Coating (SG), both composed by: an external laminate, 16 mm Argon cavity and a 6 mm clear inner pane of glass. For the sake of comparison the only difference between the two glazing unit (TCG and SG) lies in the external laminate, in one case (TCG) composed by the TC laminate, and in the other (SG) composed by a clear glass laminate with a selective coating on the outer surface of the cavity. The model of the compared glazing units is created by means of WINDOW software [14] and imported within Energyplus [11], which uses the validated model *Window calculation module* [15].

In table 1 the integral optical characteristics (visible and solar) of the thermochromic laminate are summarized, as measured according to Section 3.1, moreover the characteristic of the external laminate of the DGU are included for comparison. In table 2 the overall characteristic of the compared glazings are summarized, where it is shown that the dynamic range of the thermochromic glazing is relatively limited, 0.11 range for the g-value and 0.25 range for the visible transmission between the clearest and darkest state.

Table 1. Optical properties of the thermo-chromic glazing (in its cold and hot state) and selective glazing considered.

External laminate properties	τ_{vis} (-)	τ_{sol} (-)	ρ_{vis} (-)	ρ_{sol} (-)	α_{vis} (-)	α_{sol} (-)
Thermo-chromic laminate (cold state)	0.65	0.39	0.05	0.03	0.3	0.58
Thermo-chromic laminate (hot state)	0.37	0.25	0.04	0.03	0.59	0.72
Glass with selective coating	0.65	0.38	0.16	0.41	0.19	0.21

Table 2. Optical properties of the thermo-chromic glazing (in its cold and hot state) and selective glazing considered.

IGU properties	T_{vis}	g-value	U-value (W/m^2K)
TCG (cold state)	0.58	0.45	2.5
TCG (hot state)	0.33	0.34	2.5
DGU	0.59	0.39	2.5

3.2.2. Energy Performance

Figure 5.a shows the results relative to the annual energy performance of the office case study equipped with the thermo-chromic glazing (TCG) and with the selective glazing (SG). It is possible to observe how, for the latitude and climate of Turin, the office equipped with the thermo-chromic glazing shows a slightly worse energy performance than that equipped with the selective glazing, with an increase of 3.14 $kWh/m^2 \cdot year$. Table 3 summarizes the energy performances relative to heating, cooling and lighting obtained for the two glazing technologies analyzed. It is possible to observe how the application of the thermo-chromic glazing is able to significantly reduce the EP_h (-20.6%) and its effects on the EP_l are negligible (+0.6%), but it significantly increases the EP_c (+23.2%).

Table 3. Energy performance relative to heating, cooling and lighting for the two glazing technologies analyzed.

	SG [kWh/m^2y]	**TCG** [kWh/m^2y]	**Percent variation** [%]
EP Heating	7.36	5.85	-20.6%
EP Cooling	19.56	24.09	+23.2%
EP Lighting	27.38	27.54	+0.6%

3.2.3. Visual Comfort

Figure 5.b shows the outcomes relative to the annual visual comfort conditions of the office case study equipped with the thermo-chromic glazing (TCG) and with the selective glazing (SG). The results show that the application of the thermo-chromic glazing is able to improve the visual comfort conditions, in respect to those obtained for the selective glazing. In more detail, it is possible to observe that the case study equipped with the thermo-chromic glazing, in respect to the one equipped with the selective glazing, shows:

- nearly an equal value of the UDI$_{\leq 100\ lx}$, (+0.1%), which accounts for the moments of the year in which daylight is too poor;
- a higher value of UDI$_{100\text{-}2500\ lx}$, (+7.9%), which accounts for the moments of the year in which daylight is suitable to perform a visual task;
- a lower value of UDI$_{>2500\ lx}$, (-8.0%), which accounts for the moments of the year in which daylight is too strong, potentially creating hence a glare sensation to the users.

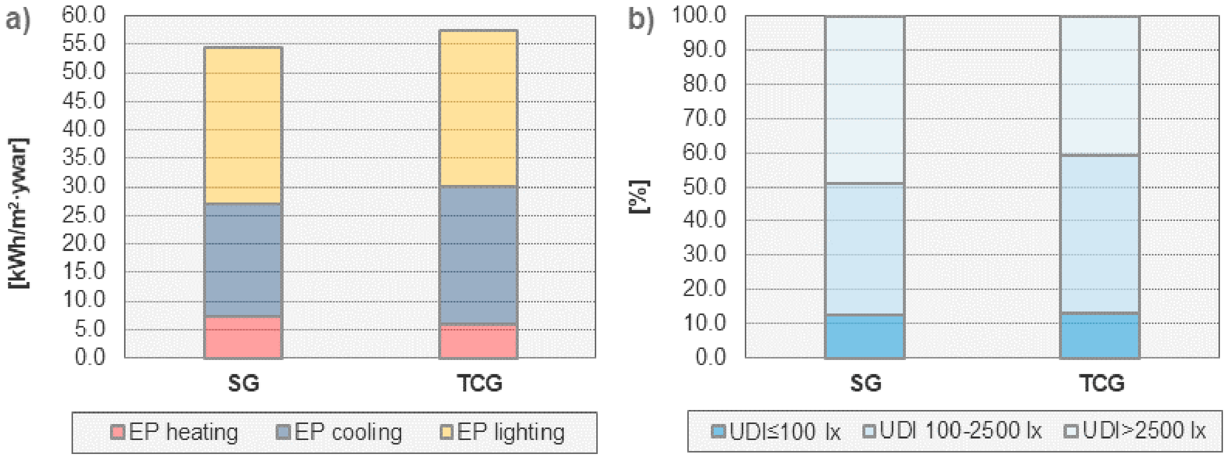

Fig. 5. Numerical outcomes relative to: a) Energy performance and b) Useful Daylight Illuminance.

4. Discussion

From the outcomes of the present study, a different behavior of the thermo-chromic glazing in terms of energy performance and visual comfort can be observed. On the energy performance side, the application of a thermo-chromic glazing shows to be inconvenient for the latitude and case study selected. In fact, the energy use relative to the thermo-chromic glazing is lower than the one relative to the selective glazing, due to higher cooling energy use. This is due to the fact that, when the glazing switches to its darker states, the glass surface temperatures are higher compared to the selective glazing. This is caused by an increased absorption of solar radiation by the thermo-chromic functional layer (from 0.28 to 0.67, as visible in Section 3.1), increasing the secondary heat flow transferred to the indoor environment. This results in a higher cooling need and potentially higher overheating risk. Nevertheless, during winter this has a positive impact, slightly reducing the heating energy demand and increasing radiant temperatures.

On the visual comfort side instead, the thermo-chromic glazing is able to improve the visual comfort conditions in respect to those obtained for the selective glazing, as far as daylight availability (UDI$_{100\text{-}2500\ lx}$) and glare risk (UDI$_{>2500\ lx}$) are concerned. This happens mainly because, as in summer the thermo-chromic glazing is able to reach a darker state (due to a higher outdoor air temperature), it reduces the incoming solar radiation, resulting in an illuminance on the horizontal plane which could increase the glare risk [12]. In winter instead the thermo-chromic glazing, not being able to reach its darker state (due to a lower outdoor air temperature and/or high switching temperature of its thermo-chromic functional layer), allows the same daylight penetration as the selective glazing. This is beneficial as in winter there are generally poorer daylight conditions (in terms of duration and intensity).

Globally the lighting energy use does not vary according to the glazing adopted, as the UDI fell-short ($UDI_{\leqslant 100\,lx}$) is practically unchanged, in fact the lighting system control is designed to ensure a target of 500 lux on the work-plane.

5. Conclusions

An optical characterization of a thermo-chromic glazing was carried out for different surface temperatures and it was found to present a different switching range, for the same temperature variation, for visible and solar transmittance. For the former the switching factor was found to be 5.5, while for the latter it was 2.3. The reason for this difference lies in the fact that the switching factor for the near-infrared range is extremely low (1.3), which in turn influences the overall solar transmittance, but not the visible transmittance.

The outcomes of the optical characterization were used to feed a numerical model created ad hoc to describe the behavior of the thermo-chromic glazing. This one was used, within a novel building performance simulation tool, to simultaneously evaluate the effects of the thermo-chromic glazing on energy and visual comfort aspects for an enclosed office located in Turin. It was found that the application of this component, for such a case study, is not a suitable choice for the energy performance, as this one is slightly worse than the one relative to a selective glazing. In fact the thermo-chromic glazing, in such a temperate climates, could have advantages to reduce space heating, while reducing potential glare at the same time, although might introduce higher cooling energy needs and potential overheating. On the other hand, the use of the thermo-chromic glazing improves visual comfort conditions, compared to the selective glazing, as it is able to reduce the amount of hours in which daylight is too strong to perform office visual task during summer.

This methodological framework and multi-objective analysis can allow a further investigation on the integration of thermo-chromic glazing in buildings, and in particular the implications of material characteristics not only on the building energy use, but also on visual and thermal comfort. The effects on all these aspects of the application of thermo-chromic glazing in buildings will be extensively investigated considering also different climates, different orientations and spaces with different geometric features.

References

[1] Perino M., Serra,V., Switching from static to adaptable and dynamic building envelopes: A paradigm shift for the energy efficiency in buildings, Journal of Façade Design and Engineering, 2015, 3:2, 143-163

[2] Kamalisarvestani, M. Saidur R., Mekhilef S., Javadi F.S., Performance, materials and coating technologies of thermochromic thin films on smart windows, Renewable and Sustainable Energy Reviews, Volume 26, 2013, 353-364

[3] Gagaoudakis E., Aperathitis E., Michail G., Panagopoulou M., Katerinopoulou D., Binas V., Raptis Y.S., Kiriakidis G., Low-temperature rf sputtered VO_2 thin films as thermochromic coatings for smart glazing system, Solar Energy, 2018, 165, 115-121.

[4] Top, I., Binions, R., Warwick, M.E.A., Dunnill, C.W., Holdynski, M., Abrahams, I., VO2/TiO2 bilayer films for energy efficient windows with multifunctional properties, Journal of Materials Chemistry 2018, 6 (16), 4485-4493.

[5] Warwick, M.E.A., Ridley, I., Binions, R., Variation of thermochromic glazing systems transition temperature, hysteresis gradient and width effect on energy efficiency, Buildings, 201 (2), art. no. 22,

[6] Granqvist, C.G., Recent progress in thermochromics and electrochromics: A brief survey, Thin Solid Films, 2016, 614, 90-96

[7] Favoino, F., Fiorito, F., Cannavale, A., Ranzi, G., Overend, M., Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates, Applied Energy, 2016, 178, pp. 943-961

[8] ISO 9050. Glass in building-determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors; 2003.

[9] Maccari A, Montecchi M, Treppo F, Zinzi M. CATRAM: an apparatus for the optical characterization of advanced transparent materials. Applied Optics, 1998;37:5156-5161.

[10] http://daysim.ning.com/, accessed Sept 2018.

[11] https://energyplus.net/, accessed Sept 2018.

[12] Nabil A, Mardaljevic J. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. Lighting Research & Technology, 2005;37(1):51-59.

[13] Granqvist CG. Electrochromics and thermochromics: towards a new paradigm for energy efficient buildings. In5th International Conference on Functional Materials and Devices (ICFMD), AUG 04-06, 2015, Johor Bahru, MALAYSIA 2016 (Vol. 3, pp. S2-S11).

[14] LBL, WINDOW software, https://windows.lbl.gov/tools/window/software-download, accessed Sept 2018.

[15] Winkelmann FC. Modeling windows in EnergyPlus. Proceedings IBPSA Building Simulation. 2001 Aug 13.

[16] https://www.berlin-innovation.de/uploads/tx_innodb/product_information_gesimat.pdf, accessed Sept 2018