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Visual performance of yellow, orange and red LSCs integrated in a Smart Window

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Abstract

The present work aims to experimentally analyze daylighting performances of the LSC-*Smart Window* developed by a joint R&D collaboration project between Eni (the largest Italian integrated energy company) and the Politecnico di Milano. The LSC-*Smart Window*, designed with the aim of enhancing the use of luminescent solar concentrators in the building sector, will be analyzed in an array of different configurations, realized with LSCs of different colors (specifically: red, orange and yellow) and compared to neutral PMMA plates.

Our *Smart Window* represents an active element in the energy performance of a building, providing a multifunctional contribution in terms of energy saving through dynamic solar control and renewable energy production.

A prototype of the *Smart Window* has been realized and installed in one of Eni's headquarter buildings for its accurate performance analysis.

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Keywords: Luminescent Solar Concentrator; *Smart Window*; Daylighting; Correlated color temperature; Visual comfort

1. Introduction

Nowadays Luminescent Solar Concentrators (LSCs) represent a very promising R&D field in relation to building integration of solar-powered architectural components [1-4]. These components can likely represent an effective way to produce renewable energy, preserving the transparency of the building envelope and exploiting a wide amount of surfaces (such as windows) otherwise neglected.

A major issue in the use of LSCs as window components is their color which, a part from being directly related to the energy-efficiency of their doping components (dyes), affects indoor daylight quality in terms of surface illuminance, spectral and luminance distribution. These characteristics influence at turn the quality perception of indoor spaces and therefore their acceptance by the users [5,6]. Specifically, the application of our LSCs, all characterized by warm colors, is argued to positively change the indoor quality of light, producing favorable effects on visual comfort by enhancing the warm component (especially in climates with prevailing covered sky conditions) [7]. The dyes - responsible for providing the LSC plates' coloration - produce a spectral shift of the incident wavelength generating a greater overlap with the wavelength peak of human photopic vision, improving both the indoor level of illuminance and the luminous efficacy.

In this context, the present work focuses on the experimental assessment of daylighting performances of LSC plates of different warm colors (red, orange and yellow) compared to a neutral PMMA baseline, by means of a physical scale model for *Smart Window*. The latter allows to easily test and compare different types of LSCs with the aim of identifying the real prototype that maximizes visual comfort.

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2. Description of the LSC *Smart Window*

The analyzed *Smart Window* is composed of a fanlight - which integrates 4 LSC modules – enclosed in a clear double glazing with two inward opening doors and of a lower part, composed by a standard neutral glass. The frame is made of thermal break aluminum profiles. The LSC plates integrated in the *Smart Window* are coupled through the edges to a series of high-efficiency silicon PV cells.

The upper and the lower parts of the window above eye level are divided by a horizontal aluminium light shelf, extending from the exterior to the interior of the building (with a part of the shelf protruding inside the window and a part outside). The shelf prevents unwanted direct sunlight from entering the indoor space by reflecting it towards the ceiling (thanks to a high-reflectance coating of its upper surface), thus minimizing glare, boosting light levels spatial distribution and reducing the amount of accumulated heat. The light shelf also serves the purpose of avoiding visual discomfort, thanks to the multiple reflection-diffusion effect which mixes the colored light coming from the fanlight with the clear one passing through the underlying neutral glass. The final result is a natural indoor light characterized by a lower color temperature.

The window is also equipped with metal reflective venetian blinds, placed inside the double glazing, that can be adjusted by rotating the slats from an open to a closed position, achieving different levels of transparency in relation to the sky conditions and the position of the sun, or otherwise that can be folded upward allowing the maximum penetration of radiation. The blinds' movement is driven by electric motors, one for each door, integrated into the double glazing and powered by the PV solar cells positioned along the edges of the four LSC plates. Incorporated batteries are used to store PV electricity and to ensure a proper functioning of the system in every weather condition. An external irradiance sensor - connected to a single board computer with predictive-adaptive control logic [8] – drives the movement of the blinds and optimizes the *Smart Window* set-up in terms of internal comfort and energy saving.

The first prototype, shown in Fig. 1, has been installed in January 2016 in Eni's headquarters in Novara. The choice of red LSC plates was motivated by their ability to maximize PV production, among other existing alternatives [2].

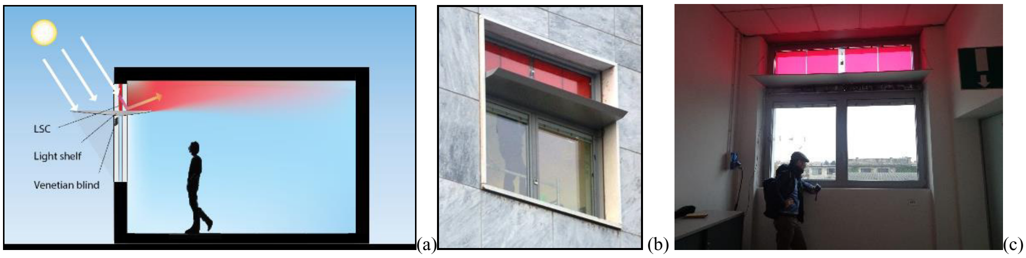

Fig. 1. *Smart Window* concept design (a), external view (b) and internal view (c) of the installed prototype with red LSCs

The *Smart Window* prototype faces a test room of dimensions 4m L × 3m W × 3.5m H, located on the second floor of the building and oriented south/south-east (azimuth 27°).

3. Methodology

As anticipated above, experimental measurements were carried out on a physical scale model fitted to the test room and the *Smart Window* in order to simplify and speed up performance evaluations in relation to different configurations and boundary conditions.

In this sense, general quantitative analysis of natural light operated on scale models constitutes a very effective tool for the characterization of lighting in confined spaces [9] as it does not require the introduction of correction factors, typically used in fluidodynamics or in acustics. The visible portion of electromagnetic radiation spectrum is in fact charachterized by wavelengths much smaller than the size of the scale model. This implies that the conclusions derivable from observations of the scale model are immediately referable to the real case, by easily adapting the parts of the scale model to directly evaluate the influence on specific parameters.

Our paper reports the results in terms of spectral power distribution (SPD), illuminance (E) and correlated color temperature (CCT) of the incoming light into the scale model which reproduces the dimension, the internal surfaces' color and the orientation of the real test room in which the Eni's *Smart Window* is applied.

4. Experimental measures

In the following section, we present and discuss the experimental performances of four different colored fanlights which integrates, respectively, a red, an orange, a yellow LSC and a neutral PMMA plate.

4.1. Experimental setup

Following the methodology previously described, a 1:10 scale model of the *Smart Window* and of the related test room were considered (Fig. 2). The test room was built with hardback polystyrene sheets coated with a colored cardboard, well reproducing the real characteristics of the internal finishes. The *Smart Window* was realized combining a transparent PMMA plate in the lower part (τ_V=0.97) with a colored LSC as fanlight.

The lighting measurements on the scale model were performed with a spectrophotometer Konica Minolta CL-500A (accuracy 2% and repeatability of 0.5%) placed in the middle of the scale room. It should be noted that due to the small size of the scale model, the movable shading system is not modelled, thus according to the real operation of the *Smart Window*, the measurements were performed in a mostly cloudy day considering opened blinds.

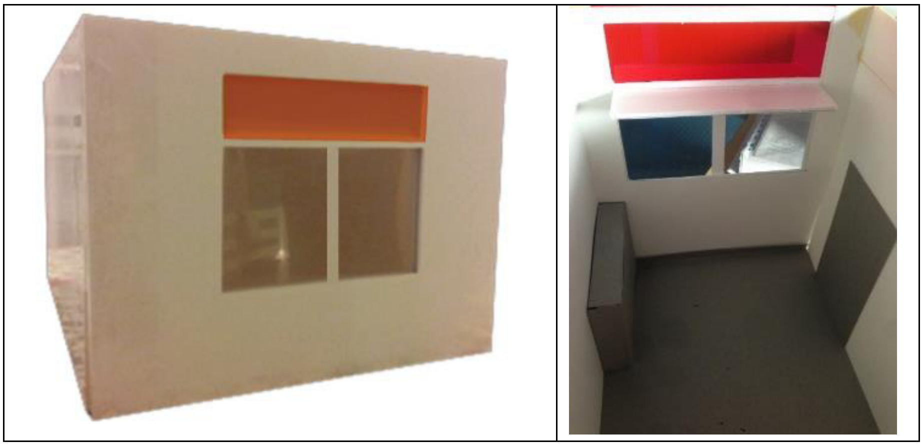

Fig. 2. Scale model of the test room and *Smart Window*

4.2. Performance analysis of several LSC plate integrated in the fanlight, under the same boundary conditions

Using this experimental setup, we characterized and compared - through a detailed analysis of the scale model - the performance of the Smart Window endowed with four different colored fanlights incorporating a red, an orange and a yellow LSC plate, or a neutral PMMA slab. The experimental analysis was carried out on the 8th April 2016 in the test facility of the Politecnico di Milano during a mostly cloudy day, with an external illuminance of 27,656 lux on the horizontal plan. As shown in Fig. 3, the Smart Window with the red fanlight absorbs more electromagnetic waves in the range between 360 nm and 600 nm than the neutral fanlight and transmits/emits a higher spectral power in the range between 600 nm and 720 nm. Nevertheless, since the human eye is more sensitive to radiation wavelenghts close to 555 nm, the level of illuminance measured for the Smart Window with red fanlight is lower by about 23% than that the one measured in the case of neutral fanlight.

On the contrary, the Smart Windows which integrate yellow and orange luminescent components absorb more radiation in the wavelengths between 400 nm and 540 nm and transmit/emit a larger amount in the range between 540 nm and 720 nm, particularly functional for the perception of the luminous flux, with respect to the Smart Window with neutral fanlight. In Fig.3 the external spectral power distribution is shown, together with that measured inside the model of the test room, applying 4 different colored fanlights.

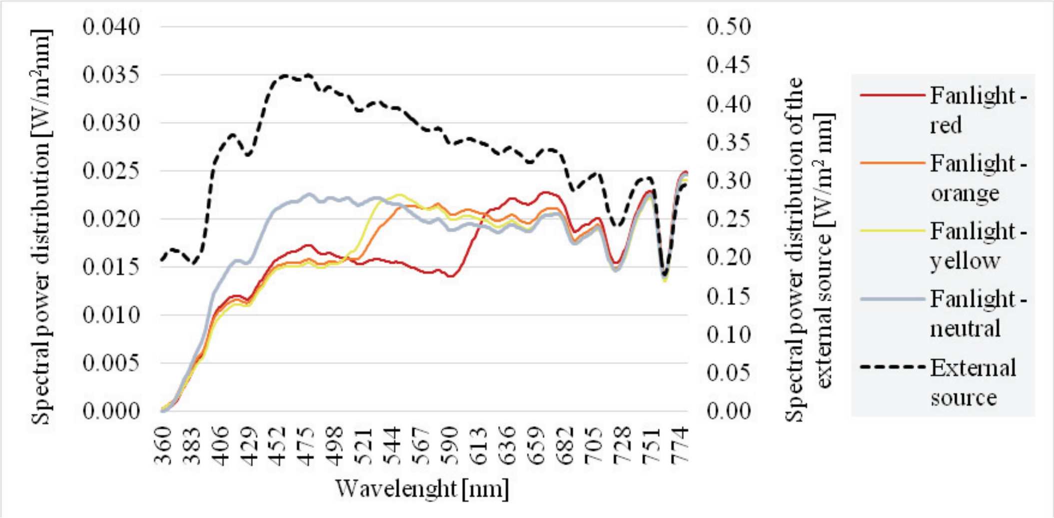

Fig. 3. Spectral power distribution for 4 different colored fanlight

To better understand the achivable benefits related to the application of the LSC fanlight, Tab. 1 summarizes the experimental results obtained on the scale model in overcast sky conditions.

Table 1 – Summary results of the experimental tests in the scale model (made on April 8, 2016; overcast sky)

Parameter	Unit	Source	Fanlight neutral	Fanlight red	Fanlight orange	Fanlight yellow
Illuminance (E)	lux	27,656	1,507	1,167	1,432	1,470
Luminous efficacy (K)	lm/W	192	195	170	202	209
Chromaticity coordinates (x, y)	-	0.3182	0.3270	0.3504	0.3660	0.3621
	-	0.3309	0.3443	0.3364	0.3682	0.3778
Correlated color temperature (CCT)	K	6,201	5,738	4,353	4,164	4,252

It is possible to observe that, even though the neutral fanlight esnures a higher illuminance than that measured with the LSC fanlights, yellow and orange LSC modules are characterized by a higher luminous efficacy (K) with respect to the neutral slab - respectively of 7% and 4% - due to the spectral shift operated by the LSC dyes. It should be pointed out that the luminous efficacy is defined as the ratio between the luminous flux [lm] and the radiant spectral flux [W]. In this respect, the yellow and the orange LSC modules, as shown in Fig. 4, can produce a greater visual effect than the outgoing power from the component. In contrast, the Smart Window integrating the red LSC absorbs most of the radiation wavelengths where the human eye is more sensitive and thus gives rise to a lower luminous efficacy .

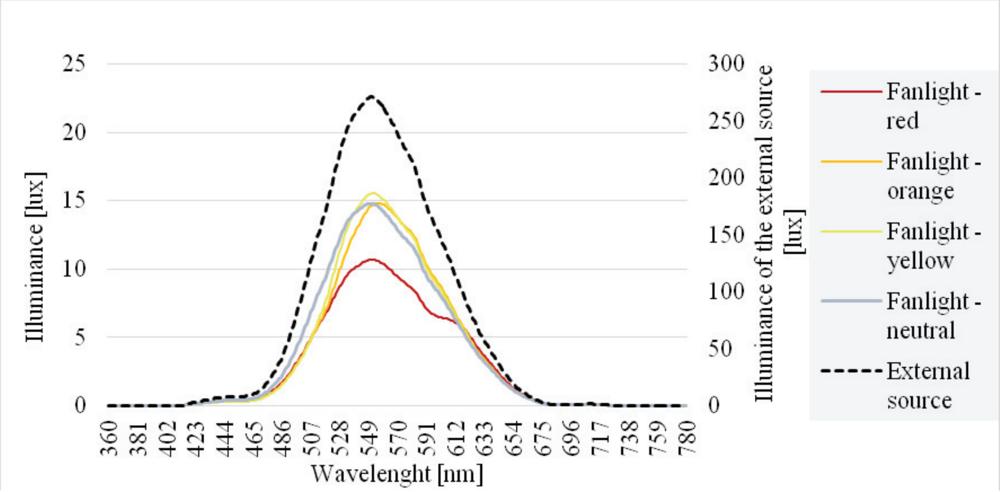

Fig. 4. Illuminance distribution for 4 different colored fanlight

In general, the most significant advantage related to colored LSC fanlights can be ascribed to the decrease of correlated color temperature (CCT) which enhances perceptual and visual comfort. In facts the CCT can be decreased from 5,738 K (neutral fanlight) to 4,353 K, 4,164 K and 4,252 K respectively with the red, orange and yellow LSCs. We may therefore conclude that the integration of LSC plates makes light warmer producing a pleasant and stimulating atmosphere.

5. Conclusion

The present work allowed to assess daylighting performances of a series of innovative *Smart Windows* developed by Eni and the Politecnico di Milano, based on configurations realized with LSC plates characterized by different colors. The analyzed active component – the window's fanlight - has the potential to reduce the buildings energy requirements and to improve their indoor levels of comfort. In detail, a comparative experimental analysis carried out on different LSC plates integrated in the fanlight, demonstrates that the application of yellow and orange colored elements allows to increase the luminous efficiency of the incident radiation due to a spectral downshift which is most favorable for the human eye and at the same time to reduce the color temperature of the environment changing the perception of indoor space and improving visual comfort. On the contrary, red LSC plates - although allowing to further reduce the color temperature of incoming light - decreases luminouse efficacy, when compared to a neutral plate. Our study therefore concludes that yellow LSC fanlights are the most suitable in buildings applications in terms of improved visual comfort. In a following paper, we plan to address further issues related to color rendition.

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References

[1] Van Sark W G J H M, “Luminescent solar concentrators - A low cost photovoltaics alternative”, *Renewable Energy* 2013; **49:**207-210.

[2] Aste N, Tagliabue L C, Del Pero C, Testa D, Fusco R. Performance analysis of a large-area luminescent solar concentrator module. *Renewable Energy* 2015: **76:** 330-337.

[3] Aste N, Tagliabue L C, Palladino P, Testa D. Integration of a luminescent solar concentrator: Effects on daylight, correlated color temperature, illuminance level and color rendering index. *Solar Energy* 2015;**114**: 174-182.

[4] Aste N, Del Pero C, Tagliabue L C, Leonforte F, Testa D, Fusco R. Performance monitoring and building integration assessment of innovative LSC components. Clean Electrical Power (ICCEP), 2015 International Conference on. IEEE.

[5] Myong SY, Jeon SW. Efficient outdoor performance of esthetic bifacial a-Si: H semi-transparent PV modules. *Applied Energy* 2016;**164**: 312-320.

[6] SEAC. BIPV Report 2013: State of the art in Building Integrated Photovoltaics. http://www.seac.cc/fileadmin/seac/user/doc/SEAC_BIPV_Report_2013.pdf. 2012

[7] Valdez P, Mehrabian A, Effects of color on emotions, *Journal of Experimental Psychology* 1994; **123:**394–409.

[8] Aste N, Adhikari RS and Del Pero C. An algorithm for designing dynamic solar shading system. *Energy Procedia* 2012; **30**: 1079-1089.

[9] Cesarano A, Bellia L, Sibilio S, Elementi di illuminazione naturale, Appunti dalle lezioni del Corso di Illuminotecnica, Acustica e Climatizzazione nell'Edilizia, de Costanzo Editori; Napoli; 1996. (Italian)

Biography

Niccolò Aste is an Associate Professor of the Dept. of Architecture, Built Environment and Construction Engineering. Graduated.

He has been actively engaged in several National and International research activities related to energy efficiency of the built environment and to the exploitation of renewable energy sources.