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Optical Performance Evaluation of DSSC-integrated Glassblocks for Active Building Façades

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ABSTRACT: *The paper outlines the results of a research, carried out at the University of Palermo, aimed at the assessment of the energy performance of a novel glassblock integrated with 3rd generation Dye-Sensitized Solar Cells (DSSC), which, when installed into panels, allows obtaining translucent building envelopes able to provide high thermal and visual comfort levels while producing clean energy. The paper focuses on the optical analyses of four different configurations of DSSC-integrated glassblocks, carried out by using the optical design software Zemax. The values of optical transmittance, the solar factor and the electric power – calculated for each configuration – are discussed.*
Keywords: *Glassblock, BIPV, Optical analyses, DSSC, Zemax software*

I. Introduction

In the last decades, sustainability applied to building design has been widely recognized as an essential and unavoidable strategy to restrain the use of non-renewable energy sources and to reduce CO2 emission in the atmosphere. In particular, research on innovative components for building envelopes, able to guarantee high levels of thermal comfort and good day-lighting indoor conditions, turns out to be of great interest for the overall enhancement of buildings energy efficiency. At the same time, great efforts have been focused into the integration of renewable energy sources into the building envelope through the use of novel multifunctional products that, when installed as building technical elements or functional layers, are able to produce clean energy while, at the same time, providing different functions that are typical of the building envelope.

For the present work, an innovative product for the building integration of photovoltaics (BIPV) has been considered. The product is an "active" glassblock, which was designed by SBskin. Smart Building Skin s.r.l., Academic Spin-Off of the University of Palermo. The product is fit for the installation of translucent roofs and façades and able to produce clean energy thanks to the integration with 3rd generation Dye-Sensitized Solar Cells (DSSC) [1].

Four different configurations of DSSC-integrated glassblock have been defined and patented [2], also referred to as "Hypotheses" [3]. In particular, the four Hypotheses of DSSC-integrated glassblock are:

- Hypothesis 1, where the DSSC module is placed on the external face of the glassblock, covering a portion of the glazed surface that is framed for the remaining part by a glazed border;
- Hypothesis 2, where the DSSC module is placed on the external face of the glassblock, covering the whole glazed surface;
- Hypothesis 3, where the DSSC module is placed on the internal face of one of the two glass shells that compose the glassblock;
- Hypothesis 4, where the DSSC module is inserted inside glassblock cavity, subdividing it into two chambers; the module, in particular, is inserted through the use of a plastic "thermal belt" that is cold-glued to the glass shells that form the glassblock.

The four configurations differ on the dimensional characteristics of the solar module and on its position inside the glassblock, as it is shown in Figure 1.

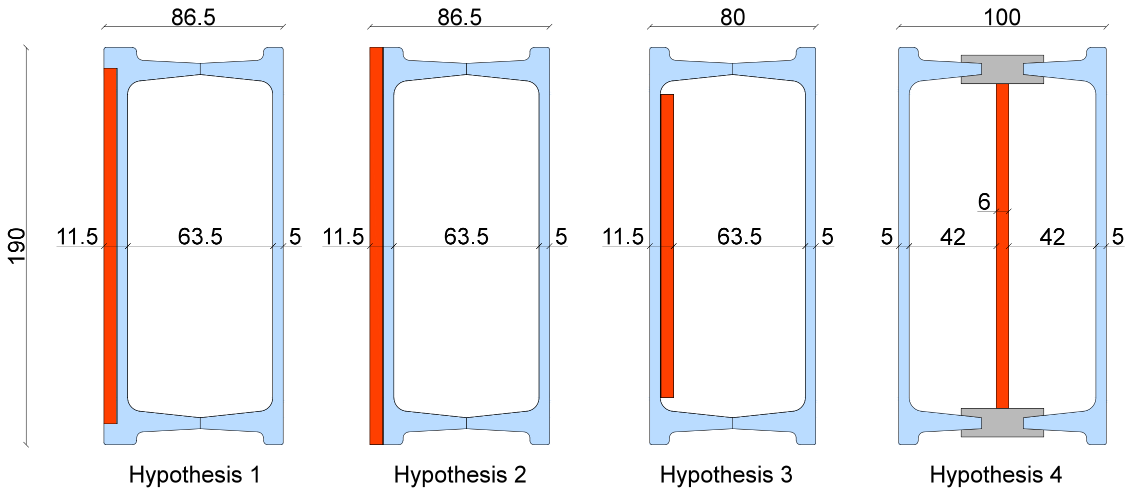


Figure 1. The four patented "Hypotheses" of DSSC-integrated glassblock (dimensions are expressed in mm)

The present paper focuses on the evaluation of the effects of DSSC integration on glassblock optical behavior, taking into account each of the four above-presented hypotheses. The analyses were conducted by using the ray-tracing commercial software Zemax, which simulates the propagation of rays through an optical system and the effects of the presence of different objects (such as simple and aspheric lenses, mirrors, diffractive elements) [4].

The results can be read on the so-called "detector", an absorbing film that records the power of the light rays remaining after having crossed the previous layers.

Optical and solar transmittance, solar factor, shading coefficient – as defined in the standard UNI EN 410:2011, Determination of luminous and solar characteristics of glazing [5] – and electric power have been analyzed.

Different configurations of DSSC-integrated glassblock were analyzed and compared [6] in order to identify the highest performing hypothesis in terms of both optical and electrical responses.

II. Numerical Analyses On Different DSSC-Integrated Glassblock Configurations

In order to define the optical model of the DSSC-integrated glassblock, it was necessary to determine the optical properties of each material composing the system. In particular, the spectral transmittance $T(\lambda)$, reflectance $R(\lambda)$ and absorptance $A(\lambda)$ as well as the corresponding refractive index n and extinction coefficient k of each layer of the system were defined, taking into account a wavelength ranging from 280 to 2500 nm, as indicated by the reference standard EN 410:2011.

The DSSC assembled at the Ecole Polytechnique Fédérale de Lausanne (EPFL) and deeply discussed by Wenger & al. 2010 [7] was used in the simulations. Since the optical DSSC characteristics data are only described in the wavelength range 400-1400 nm, it was necessary to extrapolate the data in the remaining part of the solar spectrum wavelength range. In particular, the values of absorption, reflection and transmission of the different DSSC layers were considered constant in the 280-400 nm and 1400-2500 nm ranges equal to the value corresponding to 400 nm and 1400 nm, respectively. These assumptions do not affect the results in a significant way, since the amount of energy corresponding to the interpolated ranges is about the 10% of the total energy of the whole solar spectrum.

For the purpose of this study, the solar cell, which is a sandwich composed of seven different layers, was simulated as a unique optical equivalent material, whose spectral properties result from the combination of the properties of constituent layers.

All the optical properties have been obtained from published scientific papers and from product catalogues of different companies. Then a series of wavelength ranges was selected, input data were weighted according to the considered ranges and finally inserted in the software.

It must be noted that, apart from the spectral refractive index of each material, Zemax does not require as input data any of the above-mentioned optical properties. The latter are instead needed to obtain, by simply applying the appropriate laws of Optics [8], the parameter indicated by the software as $T^*(\lambda)$ correlating reflectance and transmittance. Having defined $T^*(\lambda)$, it was weighted according the selected wavelength ranges and finally input in the software.

The characteristics of the light source used for Zemax simulations are given by the standard EN 410:2011, which provides the spectral distribution of the solar radiation for each wavelength interval[1].

In reference to the Air Mass Index[2] , the solar spectrum considered is A.M. 1.5, normally used to compare the characteristics parameters for different commercial PV modules. The value of Direct Normal Irradiance (DNI) is about 900 W/m^2.

A preliminary numerical test of Zemax model accuracy was obtained by calculating the solar transmittance of a 6 mm thick float glass sheet (according the EN 410:2011) and comparing the numerical result to the theoretical solution deducted from the direct application of analytic equations. The computation confirmed that the Zemax model was correctly tuned.

In a first stage of the research, the simulations on the four hypotheses were run by considering the DSSC-integrated glassblock positioned with its external surfaces perpendicular to the direction of sunrays.
In order to assess the DSSC-integrated glassblock behavior, the new model for the simulations included:

- a 5 mm thick glass layer (representing one of the two glass shells forming the glassblock);
- a 6.125 mm thick DSSC module (as in Wenger et al. 2011);
- POM-C elements, used for the "thermal belt" (Hypothesis 4) and the profiles needed for the assembly of glassblocks into panels.

Each hypothesis of PV integration has been simulated in two sets of configurations:

- the first one (indicated as 1_1, 2_1, 3_1, 4_1), is only characterized by the glass shells, the DSSC module and, in the case of Hypothesis 4, the thermal belt;
- the second one (indicated as 1_2, 2_2, 3_2, 4_2), also takes into account glassblock support structure made of POM-C profiles.

In order to calculate the transmittance both in the visible and solar ranges (respectively T_{vis} and T_t), as well as g value (g) and Shading Coefficient (SC), the detector was placed beyond the whole glassblock.
In particular, the detector provides the value of transmitted power across each glassblock configuration. By dividing this value by the power striking on glassblock external surface, the transmittance of the object is obtained, as in Equation (1):

$$T_t = \frac{\sum_{\lambda=300nm}^{2500} S_\lambda \times T(\lambda) \times \Delta(\lambda)}{\sum_{\lambda=300nm}^{2500} S_\lambda \times \Delta(\lambda)} \quad (1)$$

where: $S_\lambda$is the relative spectral distribution of the solar radiation, $T(\lambda)$is the spectral transmittance of the device and □. □..is the wavelength interval.

In order to evaluate the transparency of the object as perceived by human eye, the value of transmittance was also calculated in the visible spectrum for wavelengths ranging from 380 to 780 nm. In this case, however, a different spectral distribution was used, i.e. the relative spectral distribution in the given range, multiplied by spectral luminous efficiency $V(\lambda)$[3], as indicated in EN 410:2011.
The transmitted solar power, recorded by the detector beyond the glassblock, also allowed to calculate the solar factor (g) and the shading coefficient, which were obtained starting from their definitions in accordance to the standard EN 410:2011.

For the assessment of the electric power, the detector was placed right before the DSSC layer, in order to read the power on the sun-facing surface of the solar device. The DSSC analyzed by Wenger & al. (2010) is characterized by an efficiency of 10%, but for the calculation of the electric power, this value – that is referred to a lab cell – had to be reduced, in order to take into account the decrease in the conversion efficiency occurring when scaling lab cells to commercial modules. In particular, 7% DSSC module efficiency was assumed for the calculations, according to the literature data [9]. Simulations were carried out considering the whole surface of the DSSC module as active, while the actual active area of DSSC typical striped configuration (capable to maximize the conversion efficiency) is smaller due to the presence of edges and spaces between the cells. In particular, a 72.5% active area was assumed in the simulations, considering as a reference the geometry of the commercial DSSC module produced by Solaronix SA [10]. Further analytic studies and laboratory tests will be carried out to verify the validity of the numerical approach comparing the results of this study to the real behavior of prototypes. The optical model presented in this work is based on a set of

[1] Solar radiation is a measure of the irradiance produced by the Sun in the form of electromagnetic radiation.
[2] The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere.
[3] The spectral luminous efficiency V(λ) takes into account the different responses of human eye to different wavelengths.

conservative assumptions and is intended to qualitative identify the highest efficient configuration of DSSC-integrated glassblock between the different hypotheses studied.
The electric power of the module was calculated by the following equation:

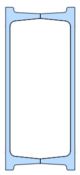
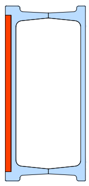
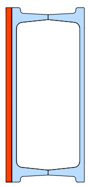
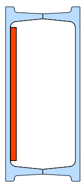
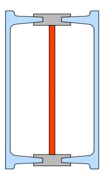
$$P = \mu \times I_o \times sen(\alpha) \times S \quad (2)$$

where: μ is the photovoltaic conversion efficiency, which was assumed equal to 7%; I_o is the Global Horizontal Irradiance at Standard Test Conditions (1000 W/m^2); α is the angle of incidence of the solar rays with respect to the cell plane which, in this case, is considered equal to 0° [11]; S is the active area, obtained by multiplying the glassblock area (0.0361 m^2) by the DSSC module percentage area per glassblock (A). The A value differs from one hypothesis to the other, whereas the active area, as above underlined, is constant and assumed equal to 72.5%, as mentioned above.

III. Results

The results of the analyses on the four hypotheses are shown in Table 1, where the DSSC module percentage area per glassblock (A) is indicated for each hypothesis. The following simulation outputs are reported: optical transmittance in the solar spectrum (Tt) and in the visible spectrum (Tv), solar factor (g value), shading coefficient (SC) and peak electric power (P) expressed in Watt (Wp). Results of the simulations on standard glassblock, before the solar cell integration, are reported too, in order to give an idea of starting product performance.

Table 1. Summary of the results

Hypotheses		A (%)	Tt (%)	Tv (%)	g (%)	SC	P (Wp)
DSSC		100.00	36.66	12.30	53.00	0.609	1.83
		-	43.74	49.93	59.05	0.686	-
		-	38.76	43.76	54.07	0.621	-
	1_1	80.06	17.06	9.16	27.97	0.321	1.47
	1_2	78.40	15.93	7.89	25.84	0.297	1.47
	2_1	93.78	16.22	7.74	26.99	0.310	1.72
	2_2	91.84	14.69	6.58	25.26	0.290	1.72
	3_1	57.44	19.85	14.45	31.06	0.357	0.84
	3_2	56.25	17.90	12.88	28.60	0.329	0.84
	4_1	65.70	12.80	5.18	27.77	0.319	0.55
	4_2	64.33	11.28	4.00	27.98	0.322	0.57

Normally, glassblock manufacturers provide solar and visible transmittance as well as g value, only by referring to glassblock vision area, i.e. the part of the product that is characterized by a sequence of flat glass surfaces. Hence, the provided transmittance and g values are slightly higher than the values that are obtained by considering the whole product performance. In the present work, it has been decided to take into account the whole product performance, in order to be able to differentiate the hypotheses among each other and account for glassblock glazed border as well as panel support structure.

As it is possible to see in Table 1, the optical performance of the different hypotheses, which depend mainly on the optical characteristics of the used DSSC module, are not significantly different from one another: for example, solar transmittance ranges from about 11% to 20%.

Visible transmittance ranges from about 4% to 14%. Hypothesis 3 is the most transparent: this is due to the lowest module area percentage of this configuration, which means that highly transparent glass occupies the largest area per glassblock among the hypotheses. Hypothesis 4, despite not having the highest module area percentage, is instead the least transparent due to the presence of the thermal belt in POM-C, which is opaque to light. For the same reason, in configurations 1_2, 2_2, 3_2 and 4_2, the presence of POM-C, used for the profiles constituting the support structure of the panel and for the thermal belt, determines a decrease in the optical performance.

It must also be noted that, in the different hypotheses of DSSC-integrated glassblock, an increase of about 15-20 percentage points of the visible transmittance values shown in Table 1 may be estimated, due to presence of inactive and highly transparent spaces between the cells.

Moreover, the module used in these analyses is provided with low values of solar and visible transmittance, but DSSC may also reach notably higher values in terms of transmittance [12], with corresponding but not proportional decrease in PV efficiency. Such results in terms of solar transmittance may be reached in other PV technologies, only by distancing the cells or hole drilling the PV material, thus sensibly reducing the active area and, subsequently, the electric production.

The analysis of the results shows also that there are not significant differences among the four configurations, either for solar factor and shading coefficient values.

The highest values of solar factor and shading coefficient are registered for Hypothesis 3, where the DSSC module is positioned on the internal face of glassblock shell. However, as it has already been said, in this configuration the area of the DSSC module is smaller and subsequently also the electric power, equal to 0.85 Wp, is lower than the values found for the configurations 1 and 2.Therefore, among the four configurations, Hypothesis 2 can be considered the best option in an overall consideration of T, G and SC values and estimated electric power: indeed, the latter is equal to 1.72 Wp and it is the highest among the hypotheses, since here the module is placed on the external side of the product, closest to sun rays, as well as characterized by the widest module area percentage. However, technological reasons (e.g. related to product resistance to atmospheric agents and degradation) may justify preferring the Hypothesis 3. In this sense, further studies on prototypes – which are currently in progress – are fundamental for the choice of the best solution.

IV. CONCLUSION

To sum up, the analyses on such innovative glassblock, integrated with 3rd generation of photovoltaic modules (specifically DSSC), provided detailed information about the highest performing configuration among those designed and demonstrated the validity of this subcomponent for the construction of translucent panels for active building envelopes.

Different results can be obtained by using more or less transparent DSSC modules or by modifying the active area of the module, in order to reach a wider range of solutions, which can allow the integrated glassblock adapting to diversified climate contexts and requirements.

Indeed, a great variety of results, in terms of energy production, thermal, optical and, last but not least, aesthetic performance, can be achieved using DSC modules with different values of transparency and colours as input for the simulations. Other works have already investigated the interactions between transparency and efficiency of DSC and the overall efficiency of a building when DSC is applied as a window system [13, 14].

In parallel, further analyses are being carried out, by using the software Comsol Multiphysics [15], in order to assess the U value of the presented four hypotheses and of novel thermally optimized configurations, and for a more complete definition of the energy performance of this product [16].

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