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Set-up and calibration by experimental data of a numerical model for the estimation of solar factor and U$_g$-value of building integrated photovoltaic systems

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Abstract

The acronym BIPV (Building Integrated Photovoltaics) refers to the installation of photovoltaic systems which, in addition to convert solar energy into electrical energy, have a high level of architectonical integration with the built environment, becoming a real architectural cladding to be installed over the buildings in place of traditional envelope systems. Many typologies of BIPV have been developed, however their thermal characteristics such as g and Ug-value are not well evaluated and require more detailed analyses considering that they could replace large extension of traditional building envelope. A first approach to address this problem is proposed in this work. A mathematical model based on a finite differences scheme for the estimation of the thermal parameters g and Ug-value has been developed and tuned using experimental value measured on sample BIPV with a Hot Plate and a Solar Calorimeter. The results of the model show that the introduction of solar cells in a laminated glass or in a double glass leads to a reduction of energy parameters modifying winter and summer energy balance of the building system.

Keywords: BIPV; Glazing systems; Solar factor; Ug-value; Energy modeling.

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1. Introduction

In recent years the application of photovoltaic modules on buildings has rapidly grown. This is due to an increased interest from owners, technicians and policy makers related to environmental issues and the design of near zero energy buildings. The policy makers allocated many economic incentives to improve the diffusion of systems for production of green energy integrate in buildings [1, 2].

In particular, technologies related to Building Integrated Photovoltaics (BIPV), which allows both the production of energy and an excellent integration with the building façades, have had considerable development. In parallel to the diffusion of such technologies, new research themes related to the thermal and optical characterization of BIPV modules have been explored. In particular have not yet been consolidated the values of the main parameters of optical and thermal characterization of these transparent elements which are: thermal transmittance U [W m^{-2}K^{-1}], solar factor g [-],visible transmission τ_v. [-], solar transmission τ_e. [-], emissivity ε [-], absorption α [-] and energy reflection ρ [-]. These parameters are essential to properly characterize the BIPV components and to compare these new components with standard transparent systems which don't produce energy.

This work aims to fill some gaps in the field of BIPV component characterization. In detail, the above described parameters are characterized through laboratory test in the Fistec Laboratory of the IUAV University of Venezia (I), the ENEA UTEE-ERT Laboratory in Roma Casaccia, in the SSV laboratory in Murano (VE), and in the Fraunhofer Institut für Solare Energiesysteme ISE in Freiburg (Germany). In addition to the experimental characterization of optical and thermal parameters, a finite volume analytical method was developed, allowing to deal more solid simulation of the BIPV glazing systems.

2. Materials

In order to accurately characterize the thermal properties of the BIPV's elements, an experimental campaign on samples of BIPV was carried on. The values obtained by the measurements are used to calibrate a numerical model. The test specimens used in the experimentation are selected in order to represent most common typologies in the current building market [3]. They were double glazing systems in which the first external layer is a laminated glass with photovoltaic cells inside the interlayer. The second glazing system is a laminated glass with low-e coating; between the two laminated glasses an air cavity of thickness 12 mm is located. The total thickness of the double glazing system was 29.8 mm. The stratigraphy of the glazing system analyzed is described in table 1.

The photovoltaics cells are polycrystalline square cells which sizes are 156 mm x 156 mm, the nominal power: 4.3 W, and the efficiency $\eta_{cell} = 0.15$. Through the experimentation are obtained the Ug-value and the g of these samples.

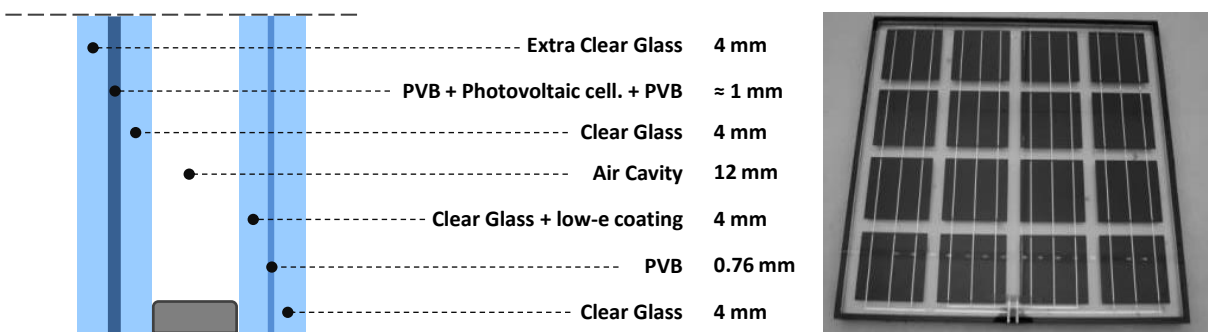|	
Extra Clear Glass	**4 mm**
PVB + Photovoltaic cell. + PVB	**≈ 1 mm**
Clear Glass	**4 mm**
Air Cavity	**12 mm**
Clear Glass + low-e coating	**4 mm**
PVB	**0.76 mm**
Clear Glass	**4 mm**

Fig. 1. BIPV test specimen: characteristics and general view.

3. Experimental

3.1. Experimental determination of the thermal conductance of BIPV samples.

The thermal conductance of a 800 mm x 800 mm BIPV specimen has been measured with guarded Hot Plate through the methods described in the EN 674 standard [4, 5]. This measurement apparatus is composed by a hot plate and two cold plates. Between these plates two identical samples are inserted. The thermal flow, from which the thermal conductivity is calculated, is measured from twenty thermocouples placed in every side of the test samples.

The mean temperature between hot and cold sides of the samples is $10 \pm 0,5$ °C. The difference between the mean of the temperature measured on the hot and cold side of the sample is $15 \pm 0,5$ °C. With these boundary conditions the measured thermal conductance of the BIPV specimen is 2.26 W m^{-2}K^{-1} while the U_g value is equal to 1.64 W m^{-2}K^{-1} considering the external and internal heat transfer coefficients respectively equal to 23 ± 3 W m^{-2} K^{-1} and 8 ± 1 W m^{-2}K^{-1}.

3.2. Experimental determination of the g value of the BIPV samples.

The experimental evaluation of the solar factor *g* has been performed at the laboratory TOPLAB (Thermal Optical Testing Laboratory) of the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg (D).

A sample size of 995 mm x 995 mm of the same type of glazing with solar cells previously presented has been tested with the Solar calorimeter GKAL3 equipped with solar simulator [6].

The air velocity and the geometry of the measurement apparatus are set in order to obtain the surface heat transfer coefficients h_e equal to 23 ± 3 W m^{-2}K^{-1} and the internal one h_i is equal to 8 ± 1 W m^{-2}K^{-1}. The temperature of the measuring chamber was maintained at 27 °C. The samples were mounted with air-tight sealing material in front of the absorber of the calorimeter. Lateral heat losses were minimized with an insulating frame of polystyrene (see Figure 2).
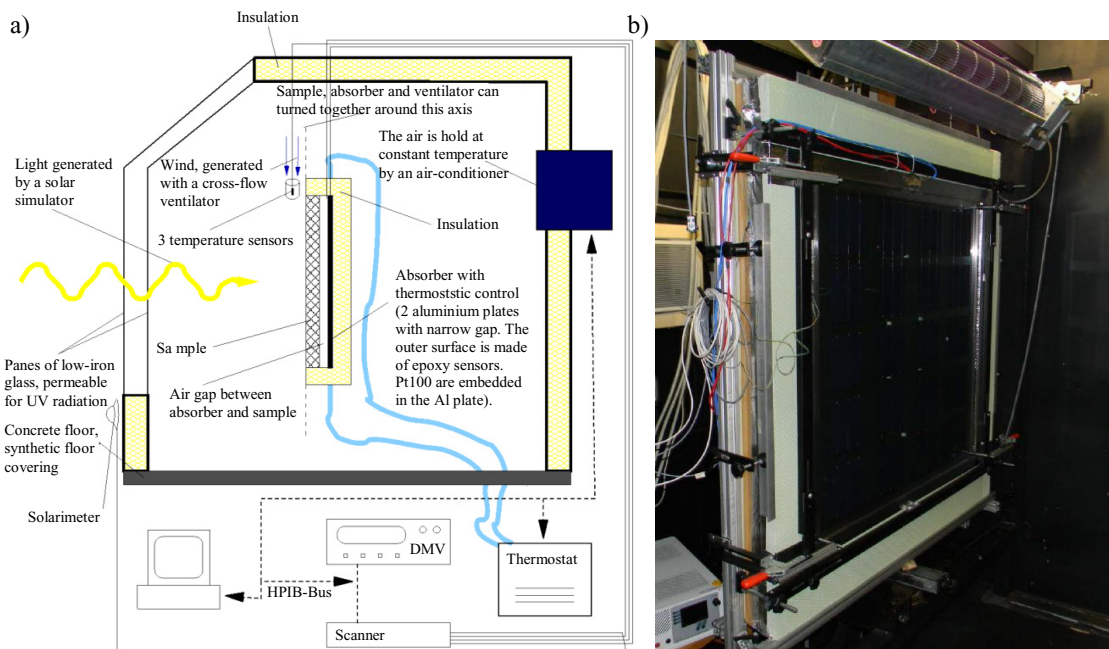

Fig. 2.(a) Cross-section through the measurement chamber and the calorimeter; (b) Photo of the sample mounted in the measurement facility.

The boundary conditions used during the tests are described in standard EN 410 [7]. The measurements are performed with normally incident radiation (angle of incidence 0°).

The irradiance on the sample is about 540 W m^{-2}. The measurements were performed with two different load conditions for the PV cells, once without an electric load (open circuit) and once with the PV cells maintained by an electronically controlled ballast at the point of maximum power generation (MPP Maximum Power Point tracking). In addition to the sample previously described, another BIPV system with simpler stratigraphy has been characterized. This one was a single laminated glass with photovoltaic cells in the interlayer (see figure 3a).The results are reported in table 1.

Table 1. Experimental *g* values

sample ID	PV load condition	indoor glass surface temperature	*g*
Laminated	Open circuit	42°C	0.45 ± 0.04
Laminated	MPP tracking	39°C	0.43 ± 0.04
Double glazing	Open circuit	31°C	0.28 ± 0.03
Double glazing	MPP tracking	30°C	0.27 ± 0.03

4. Modeling and calculation

4.1. Analytical determination of the thermal conductance of BIPV samples

The thermal conductance of a glazing system can be calculated by the analytical methods described in the EN 673 [8]. This method uses the physical characteristics of each layer to determine the thermal characteristics of the entire glazing system. The physical characteristics implemented in the numerical model in order to obtain the thermal transmittance of double glazing system with photovoltaic cells, are the thermal resistance of the float glasses, the surface emissivity and the physical and fluid-dynamics properties of the gas in the cavity.

The total thermal resistance of a double glazing system is given by the sum of the thermal resistance of the glass panes, and the thermal conductance of the air cavity. Using the same boundary conditions for the hot plate measurements the thermal conductance of the BIPV test specimen results 2.193 W m^{-2} K^{-1} while the U_g value is 1.60 W m^{-2} K^{-1}.

4.2. Analytical determination of the g value of the BIPV samples

In order to estimate the optical and thermal properties of elements of different BIPV typology a finite difference model has been developed [9]. This analytical approach has been applied on the two kinds of stratigraphy of BIPV system measured on the Fraunhofer laboratory. As first step, the numerical model has been applied on the simpler stratigraphy: a laminated glass in which a layer of photovoltaic cells is inserted. As second step, the model is applied to the other test specimen: a double glazing system which stratigraphy is described in figure 1 and Figure 3b. Each node is identified by a number as proposed in the numerical model.
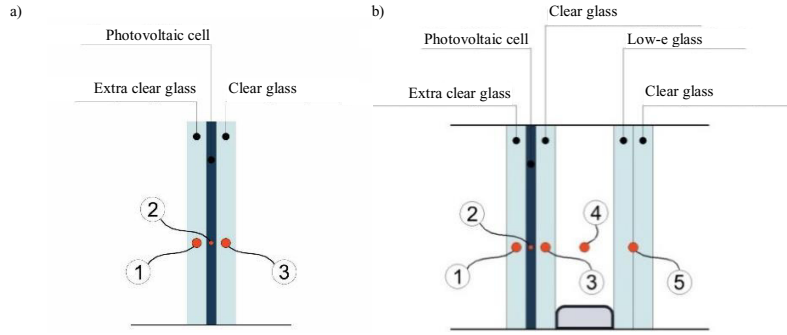
Fig. 3. (a) single laminated glass BIPV sample section; (b) double laminated glass BIPV sample section

Each node of the model is a finite volume of material; the heat balance has been carried out using the electrical analogy of a RC circuit and considering the interaction of four components on the node itself: shortwave radiation component (from 0.3 μm to 2.5 μm), longwave radiation component (from 3 μm to 100 μm), conduction and convection thermal exchanges components.

All the optical parameters used in the numerical method are obtained by spectrophotometric characterization in the SSV laboratory in Venice and the values are reported in table 3.

Table 2. spectrophotometric characterization of the BIPV samples

Node	τ_{sol} [-]	ρ_{sol} [-]	ε [-]	thickness [mm]
Extraclear glass	0.9	0.08	0.84	4
Photovoltaic cell	0.4	0.13	0.72	0.2
Clear glass	0.84	0.08	0.84	4
Air	-	-	-	12
Low-e clear glass	0.48	0.3	0.03	4
Clear Glass	0.84	0.08	0.84	4

The heat balance equations from (1) to (5) are referred to the stratigraphy of Figure 3b, and they are related to each node of the double glazing system. The parameters are: $\rho_n c_n s_n$, respectively density [kg m^{-3}], the specific heat [J kg^{-1} K^{-1}] and a thickness [m] of the n-th node; $\Delta\tau$ time timestep [s]; $h_{c,int}$, $h_{c,int}$, respectively internal and external convection coefficient [W m^{-2} K^{-1}]; $q_{th,abs,n}$ LW radiation absorbed by the n-th node [W m^{-2}]; I_{ext} external radiation [W m^{-2}]; λ_1 thermal conductivity of the n-th node [W m^{-1} K^{-1}]; T_n temperature of the n-th node [° C]; T_n^0 temperature of the n-th node at the previous timestep [° C]; η_{cell} conversion efficiency of the photovoltaic cell.

Node 1: $\frac{\rho_1 c_1 s_1/2(T_1 - T_1^0)}{\Delta\tau} = h_{c,ext}(T_{ext} - T_1) + \frac{\rho_1 c_1 s_1/2}{\Delta\tau} I_{ext} + \frac{\lambda_1}{s_1}(T_2 - T_1)$ (1)

Node 2: $\frac{\left(\frac{\rho_1 c_1 s_1}{2} + \frac{\rho_2 c_2 s_2}{2}\right)(T_2 - T_2^0)}{\Delta\tau} = \frac{\lambda_1}{s_1}(T_1 - T_2) + q_{th,abs,2} + \frac{\frac{\rho_1 c_1 s_1}{2} + \frac{\rho_2 c_2 s_2}{2}}{\Delta\tau}(1 - \eta_{cell})I_{ext} + \frac{\lambda_3}{s_3}(T_3 - T_2)$ (2)

Node 3: $\frac{(\rho_3 c_3 s_3/2)(T_3 - T_3^0)}{\Delta\tau} = h_{c,int}(T_{int} - T_3) + \frac{\rho_3 c_3 s_3/2}{\Delta\tau} I_{ext} + \frac{\lambda_3}{s_3}(T_2 - T_3)$ (3)

Node 4: $T_4 = \frac{T_3 + T_4}{2}$ (4)

Node 5: $\frac{(\rho_5 c_5 s_5)(T_5 - T_5^0)}{\Delta\tau} = h_{c,int}(T_{int} - T_5) + q_{th,abs,5} + \frac{\rho_5 c_5 s_5}{\Delta\tau} I_{ext} + h_g(T_3 - T_5)$ (5)

In table 4 are reported the values obtained from the experimental values of *g* and the ones obtained by numerical simulation.

Table 4. Comparison between experimental and analytical g values

sample ID	PV load condition	Experimental *g*	Numerical *g*
Laminated	Open circuit	0.45 ± 0.04	0.45
Laminated	MPP tracking	0.43 ± 0.04	0.43
Double glazing	Open circuit	0.28 ± 0.03	0.26
Double glazing	MPP tracking	0.27 ± 0.03	0.26

In the case of the single laminated glazing system the model developed obtain values for *g* perfectly corresponding to the experimental values measured by the calorimeter both with the PV circuit open and closed. For the double stratified glazing system the values obtained by numerical model are a bit lower than experimental ones. In conclusion the numerical model demonstrated a good capability to represent the behaviour of *g* of BIPV systems both with the PV circuit open and with MPP tracker on.

5. Concluding remarks

The research focuses on the detailed characterization of BIPV modules and their interaction with the energy balance. In order to accurately describe the thermal and energy characteristics of BIPV systems, an experimental characterization of a glazing system photovoltaic sample was carried out. This test specimen represents one of the most common BIPV system on the market.

From experimental measurements performed by means of the hot plate with guard ring, the thermal conductance referred to average temperature $T_m = 10$ °C. This parameter was equal to 2.26 (W m^{-2} K^{-1}) in very good agreement with the values obtained for calculation applying EN 673. The calculated conductance was 2.19 W m^{-2} K^{-1} and was approximately 3% lower than the values obtained by measurements with a hot plate.

The solar gain factor was also measured using the Solar Calorimeter equipped with solar simulator on a single laminated and a double glazing BIPV system. A numerical model has been developed and it is validated by means of experimental measurements. The results obtained applying the proposed model are in very good agreement with the measured values.

References

[1] Misara, S., Henze, N. And Sidelev, A., "Thermal Characteristics of BIPV (U-Value and g-value)", (2011).
[2] Henze, N., Glotzbach, T., Misara, S., Roos, M. And Schultz, B., "Characterisation of photovoltaic modules for building integration", (2011).
[3] Jelle, B.P. and Breivik, C., "State-of-the-art Building Integrated Photovoltaics". Energy Procedia, 20, (2012), pp. 68-77.
[4] EN 674, 2011, "Glass in building – Determination of thermal transmittance (U value) – Guarded hot plate method".
[5] ISO 8302, 1991," Thermal insulation -- Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus".
[6] Chen, F., Wittkopf, S.K., Khai Ng, P. and Du, H., "Solar heat gain coefficient measurement of semi-transparent photovoltaic modules with indoor calorimetric hot box and solar simulator", Energy and Buildings, 53(0), (2012), pp. 74-84.
[7] EN 410, 2011, "Glass in building – Determination of luminous and solar characteristics of glazing".
[8] EN 673, 2011, "Glass in building – Determination of thermal transmittance (U value) – Calculation method".
[9] Scarpa M., Mazzali U., Peron F. "Modeling the energy performance of living walls: Validation against field measurements in temperate climate" - Energy and Buildings 79 (2014) pp. 155–163.