THERMAL AND ELECTRICAL PERFORMANCE OF SEMI-TRANSPARENT PV WINDOWS: NUMERICAL SIMULATIONS AND EXPERIMENTAL STUDY

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ABSTRACT: As semi-transparent photovoltaic windows are advancing within the building and window industry, the need for deeper understanding and quantification of their thermal and electrical behaviour is paramount. The objective of this work is to study and predict the thermal response and electric performance of a typical double-glazed insulated unit integrating STPV technologies on its outer glass layer. PV operating cell temperatures of up to 55.3°C were measured through an experimental study of a prototype STPV window. A numerical model was developed and verified based on the experimental data. The simulations showed that the highest operating cell temperatures occurred during the fall season with operating cell temperatures of up to 60°C, for a south-facing office façade incorporating STPV windows, located in Toronto, Canada.

Keywords: Building Integrated PV (BIPV), façade, c-Si, modelling

1 INTRODUCTION

Semi-transparent PV (STPV) windows are PV technologies that fall under the broader category of building integrated photovoltaics (BIPV). STPV can replace conventional windows and skylights in new or retrofit commercial, institutional and high-rise residential buildings. In highly-glazed buildings where reducing cooling energy costs are important, double-glazed units with low-emissivity coatings are generally adopted to reduce heat transfer by long-wave radiation. The outer glass layer often requires low solar transmittance to reduce transmission of solar radiation. STPV windows have the capability to reduce solar heat gains, generate solar electricity [1–3] while still providing satisfactory daylighting levels and views to the outdoors [4–6].

However, STPV windows & skylights tend to operate at higher temperatures than open rack systems [7,8]. High operating temperatures (75°C and above) impact adversely the electric conversion efficiencies and lifespan of the window. Prolonged exposure to high operating cell temperatures can result in a failure of the window components (e.g. sealants, gaskets) and possibly cell degradation or damage (in the case of thin film polymer PV technologies).

The objective of this work is to study and predict the thermal response and electric performance of a typical double-glazed insulated unit integrating STPV technologies on its outer glass layer. An experimental study on a STPV prototype window is performed and the measurements are used to develop a numerical model. The model is then used to perform climate-based simulations and predict the temperature profile and solar energy generation of the STPV window on a yearly basis. The proposed model can be extended to any multi-layered c-Si STPV windows with various electrical, thermal and optical properties.

In section 2 a description of the experimental study performed for a STPV window is presented. The experimental study focuses on the thermal response of the STPV window under realistic weather conditions. The description of the thermal/electrical simulation model of the STPV window can be found in section 3 while sections 4 and 5 present the experimental simulation results and conclusions derived from this study.

2 EXPERIMENTAL STUDY OF A STPV WINDOW

2.1 STPV prototype window

A STPV prototype window (figure 1) was designed and assembled utilizing standard 15.6 mm poly-Si opaque PV cells. The opaque PV cells were spaced to allow the sunlight to pass through the unfilled space between them.

The STPV module (outer layer of the STPV window) assembly consists of (outer-to-inner layer): (i) 3.2 mm tempered, antireflective-coated, white glass, (ii) Ethylene-Vinyl Acetate (EVA) encapsulant layer, (iii) poly-Si PV cells layer with a packing factor of 0.77, (iv) EVA encapsulant layer, and (iv) Polyvinyl Fluoride (PVF) transparent backsheet.

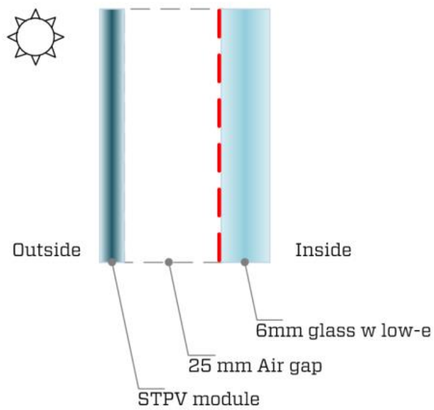

Figure.1 Schematic of the STPV window tested and then simulated through a numerical model.

A double-glazed insulated unit (referred to as "STPV window" herein) was assembled comprised of the STPV module as the outer layer of the window and a 6mm glass (incorporating a low emissivity coating) as the inner one. A 25 mm sealed air cavity separates the two glass layers. The STPV prototype window is frameless with dimensions of 1948 mm × 976 mm. The solar spectral transmittance of the outer and inner glass layers of the STPV window were measured using a Cary5000 UV/Vis/NIR spectrophotometer (figure 2). The electrical, optical and thermal properties of the STPV window are summarized in Table 1.

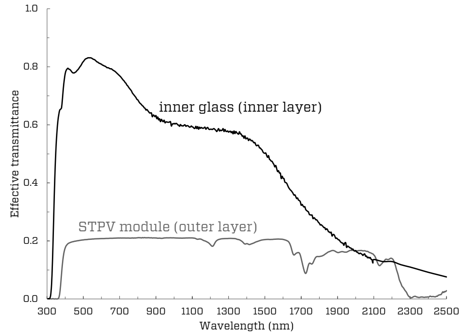

Figure.2 Hemispherical spectral transmittance of the outer and inner glass layer of the double-glazed STPV prototype window tested and simulated.

2.2 Description of the experimental study

The STPV prototype window study was performed under the indoor solar simulator located in the P.Fazio Solar Simulator – Environmental Chamber (SSEC) laboratory, at Concordia University, Montreal, Canada [9].

Table 1. Electrical, optical and thermal properties of the STPV window tested and simulated.

Electrical	Cell technology	Poly-Si
	η_{mp}	0.13
	P_{mp} (W)	240.40
	V_{oc} (V)	37.61
	I_{sc} (A)	8.52
	$\mu_{P,mp}$ (%/°C)	-0.43
Optical	Number of PV cells	60
	Packing factor	0.77
	Solar transmittance	0.136
	Visible transmittance	0.172
Thermal	U-value ($W{\cdot}m^{-2}{\cdot}°K^{-1}$)	2.013
	Solar heat gain coefficient	0.238

Note: The electrical properties were measured under Standard Testing Conditions (STC)

The indoor solar simulator is a continuous lampfield consisting of eight metal halide (MHG) lamps emulating sunlight (figure 3). The spectral quality of the lamps fulfills the ISO 9806:2013 [10] specifications, with approximately 80% of the emitted radiation lying in the range in which the incidence angle modifier varies by no more than 2%. A spectral mismatch correction factor is applied to accommodate for the difference between the solar simulator spectrum and the AM 1.5 Reference spectrum [11,12].

The irradiance intensity can vary from 500 W/m^2 to 1200 W/m^2, with a uniformity of up to 97% (depending on the dimensions of the window) and a temporal stability of ±1% during the testing period.

An artificial sky apparatus, located in front of the lamps, is used to remove the IR radiation generated by the lamps while a linear, variable-speed fan is used to reproduce the wind effects on the outer surface of the STPV window.

The STPV window was mounted on a thermally-calibrated solar calorimeter apparatus used to emulate the indoor thermal environment of a typical office building (ambient room air and surface temperatures set to (21±1°)C [13]. In addition, the STPV window was connected to an electronic load that functioned as a current sink at the maximum power point.

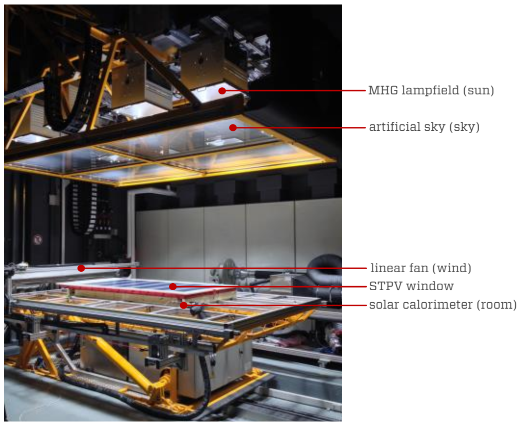

Figure.3 STPV window prototype tested under the solar simulator of the P. Fazio SSEC laboratory at Concordia University, Montreal, Canada.

3 DEVELOPMENT OF A STPV WINDOW SIMULATION MODEL

A numerical model was developed to predict the electrical performance and thermal response of the STPV prototype window integrated on commercial building façades. The STPV window model was developed on MATLAB [14] and coupled with EnergyPlus [15] to simulate the annual energy performance of a perimeter office under continental climatic conditions (Northeastern United States and Southeastern Canada) [16]. The STPV window model was verified experimentally.

3.1 Description of the STPV window model

The numerical model presented below was developed for the STPV window tested. However, the model can be extended to any multi-layered c-Si STPV windows with various electrical, thermal and optical properties.

The energy balance equations correspond to each surface of the STPV window (where surface-1 being the outer surface of the STPV module and surface-4 being the inner surface of the inner glass). The model assumes that: i) The STPV module and inner glass have negligible thermal capacitance, ii) STPV module layers (glass-frontsheet, EVA, PV cells and transparent PVF-backsheet) are treated as a single equivalent layer, iii) heat transfer is one-dimensional and perpendicular to the window layers, iv) each surface is isothermal with uniform thermal and optical properties, iv) radiation absorbed in each layer is equally distributed between inner and outer surfaces of the layer, and v) STPV module and inner glass are opaque to IR radiation.

- For surface-1 (outer surface of the STPV module)

$$\left(E_o\varepsilon_1-\varepsilon_1\sigma T_1^4\right)+h_o(T_o-T_1)+\left(\frac{\alpha_1 S}{2}-\frac{P_{STPV}}{2A_{STPV}}\right)= \\ =U_{STPV}(T_1-T_2) \quad (1)$$

- For surface-2 (inner surface of the STPV module)

$$U_{STPV}(T_1-T_2)+\left(\frac{\alpha_1 S}{2}-\frac{P_{STPV}}{2A_{STPV}}\right)= \\ =\left(\sigma\frac{\varepsilon_2\varepsilon_3(T_2^4-T_3^4)}{1-(1-\varepsilon_2)(1-\varepsilon_3)}\right)+h_{gap}(T_2-T_3) \quad (2)$$

- For surface-3 (outer surface of the inner glass)

$$\left(\sigma\frac{\varepsilon_2\varepsilon_3(T_2^4-T_3^4)}{1-(1-\varepsilon_2)(1-\varepsilon_3)}\right)+h_{gap}(T_2-T_3)+\frac{\alpha_2 S}{2}= \\ =U_{glass}(T_3-T_4) \quad (3)$$

- For surface-4 (inner surface of inner glass)

$$U_{glass}(T_3-T_4)+\frac{\alpha_2 S}{2}= \\ =(\varepsilon_4\sigma T_4^4-E_{in}\varepsilon_4)+h_{in}(T_4-T_{in}) \quad (4)$$

where the solar power generated (P_{STPV}) is calculated as the product of the operating current (*I)* and voltage (*V*) at the maximum power point:

$$P_{STPV}=VI \quad (5)$$

The equivalent one-diode model is utilized [17,18] to predict the operating current and voltage at the maximum power point, on a given time-step:

$$I=I_L-I_D-I_{sh}= \\ =I_L-I_o(e^{\frac{V+IR_s}{\alpha}}-1)-\frac{(V+IR_s)}{R_{sh}} \quad (6)$$

where *S* is the solar radiation incident on the STPV window (W/m^2); E_o, E_{in} are the exterior and interior IR radiation incident on the window, respectively (W/m^2); A_{STPV} is the STPV surface area (m^2); T_i is the average temperature of surface *i=1,2,3,4* (K) while T_1 *is* the STPV operating cell temperature; ε_i is the emissivity of surface i; T_o, T_{in} are the outdoor air and indoor air temperatures, respectively (K); h_o, h_{in} are the outdoor and indoor air film convective heat transfer coefficients, respectively (W/m^{2}K); h_{gap} is the convective heat transfer coefficient in the STPV window sealed cavity (W/m^{2}K); U_{STPV}, U_{glass} are the thermal conductances of the STPV module and inner glass, respectively (W/m^{2}K); α_1 α_2 are the ratio of the solar radiation absorbed by the STPV module and the inner glass, respectively; σ is the Stefan-Boltzmann constant (W/m^{2}K^4); I_L, I_D, I_{sh} and I_o are the light current, the diode current, the shunt current and the diode saturation current, respectively (A); R_s, R_{sh}, are the series resistance and the shunt resistance (Ω), respectively; and α is the ideality factor (V).

Equations *(1)* to *(6)* are solved simultaneously for each simulation time-step in order to estimate the operating cell temperature (T_1) and the electrical output of the STPV window.

For comparison purposes, a building-added STPV module naturally ventilated on both its front and rear side (open rack system) was also simulated. The aforementioned equivalent one-diode model was used to predict the electrical output of the system while the operating cell temperature was approximated by [19]:

$$T_1=T_o+Se^{a+b*v}+\frac{S}{S_0}\Delta T \quad (7)$$

where v is the wind speed measured at standard height of 10m (m/s); *a*=-3.56 and *b*=-0.075 are empirically determined coefficients for an open rack system; S_0=1000 W/m^2 is the reference incident solar radiation; and $\Delta T=3$°C represents the temperature difference between the module's back surface and the PV cells on an open rack system.

3.2 Experimental verification of the STPV window model

The STPV window was tested under various solar intensities (from 750 W/m^2 to 1000 W/m^2) and wind conditions (exterior convention heat transfer from 20 W/m^{2}K to 40 W/m^{2}K), utilizing the indoor solar simulator and calorimeter apparatus. The experimental data was then used to verify the proposed numerical model. It was found that the model has the ability to predict STPV window's operating cell temperatures with a mean accuracy of 5% on the measured cell temperature, and the power output with a mean accuracy of 3% on the measured power output (figure 4), within the tested range. It should be noted that all tests were performed under steady-state conditions and for a normal angle of incidence. The proposed model does not have the ability to predict any effects variations in solar spectrum might have on the thermal and electrical response of the STPV window.

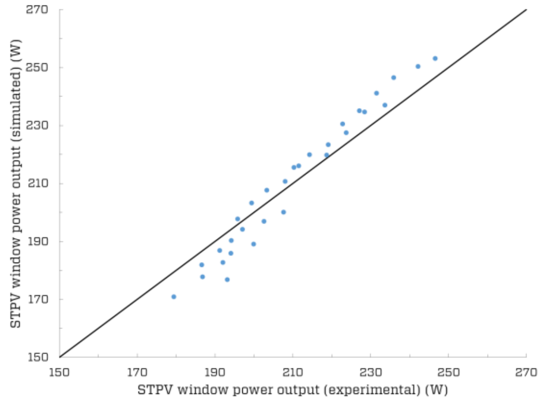

Figure 4. Simulated over experimental data for the power output of the prototype STPV window.

4 RESULTS AND CONCLUSIONS

This section presents the experimental results of the STPV prototype window tested under the Concordia indoor solar simulator. A calorimeter apparatus was used to emulate the indoor building environment. PV operating cell temperatures of up to 55.3°C were observed under 1000 W/m^2 irradiation with an exterior convective film coefficient of 20 W·m^{-2}·K^{-1} and ambient air temperature of 21°C. In addition, IR thermography revealed a temperature difference of up to 11°C between PV cells and the surrounding unfilled space (figure 5). Such temperature differentials are specific to STPV windows utilizing opaque PV cells due to variation of optical properties between cells and encapsulant.

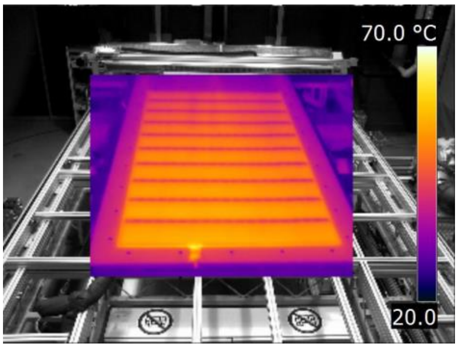

Figure.5 Thermal imaging of the STPV window under 1000 W/m^2 and exterior convective film coefficient of 20 W/m^{2}K.

A simulation study was then performed for the STPV window, utilizing the aforementioned calibrated numerical model, to predict the annual electrical yield of the window and its thermal response. The STPV window was integrated on a south-oriented perimeter office façade located in Toronto, ON, Canada (latitude 43.7°N). The simulations showed that the highest operating cell temperatures occurred during the fall season when the solar altitude is relatively low while solar intensities and ambient temperatures remain relatively high (figure 6). Operating cell temperatures of up to 60°C were predicted for the STPV window.

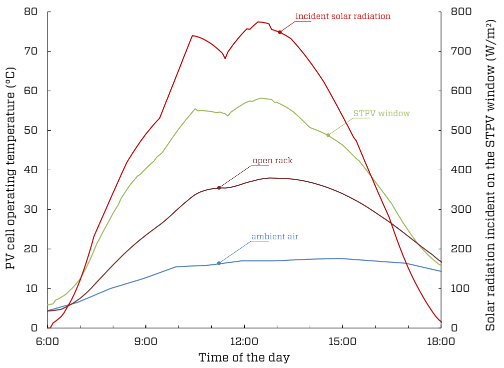

Figure 6. Simulated operating cell temperature for the STPV window and a building-added STPV module (open rack system), on a typical warm day.

When compared to an open rack system, the STPV window operates at most 20°C higher resulting in a maximum 7.5% reduction on the daily electricity yield (figure 7) and up to 5.2% on an annual basis (932 kWh/kW/yr for the STPV window and 981 kWh/kW/yr for the open rack system). It is important to mention that high operating cell temperatures (75°C and above) were not observed either during the experimental testing or through the numerical simulations.

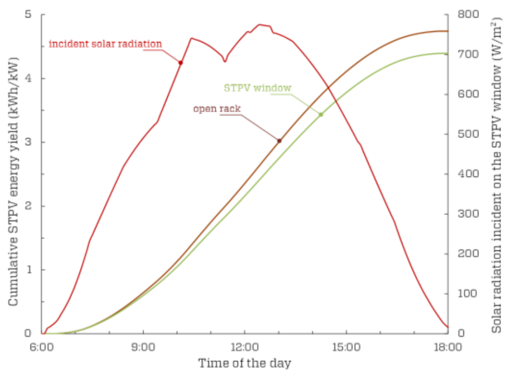

Figure.7 Simulated energy yield for the STPV window and a building-added PV module (open rack system), on a typical warm day.

5 SUMMARY

An experimental study of a prototype STPV window was presented. The experimental study focused on the thermal response of the STPV window under realistic weather conditions, utilizing an indoor solar simulator and a calorimeter apparatus. PV operating cell temperatures of up to 55.3°C were measured under 1000 W/m^2 with an exterior convective film coefficient of 20 W/m^{2}K.

A numerical model was also developed, verified with experimental data. An annual climate-based simulation analysis was performed for a south-facing office façade incorporating STPV windows, predicting operating cell temperatures of up to 60°C during fall.

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