Portable Window Energy Meter (PoWEM)

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BACKGROUND

Windows are one of the most important components in the building. They serve to provide multiple roles, such as view, egress, and natural light. At the same time they need to provide comfortable environment for occupants. This multi-role complexity of windows affect the amount of energy that the windows are responsible for in the building. The U.S. Department of Energy (DOE) estimates that the amount of energy lost annually through windows is approximately $35 billon, or close to one quarter of all HVAC energy in a building. This amount can be reduced using energy efficient windows. The performance of the window is measured using thermal and solar-optical performance indices, U-Factor (thermal transmittance), SHGC (Solar Heat Gain Coefficient), VT (Visible Transmittance), and AL (Air Leakage). While U-factor is purely thermal performance index, and VT is purely optical performance index, SHGC is the combination of those two. The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. The visible transmittance (VT) is an optical property that indicates the amount of visible light transmitted.

Most locations have building energy codes that mandate minimum performance levels for U, SHGC and sometimes VT for windows, doors, and skylights. The builder, contractor or homeowner must adhere to the code requirements, which typically cover windows for new construction as well as replacement windows.

Thermal and solar-optical performance indices of new fenestrations products are relatively easy to obtain by measuring them in laboratory setting using either hot box, solar calorimeter or integrating sphere. Also, when detailed window construction information is known, such as glazing system composition, frame drawings and bill of materials, etc. computer modeling can be done with great degree of accuracy. The problem is to assess performance of windows in existing buildings. Detailed information about the fenestration product normally has been lost and reconstructing product details to allow computer modeling would be almost impossible, so the ability to measure thermal and solar-optical properties in-situ are very important. Provided that glazing represents large portion of fenestration product area and that it contains larger fraction of variabilities and unknowns, the ability to measure glazing performance in-situ would accomplish most of the goal.

This document describes design, construction and validation of the device that measures SHGC and VT of glazing systems (single or multiple glazings), installed in windows in existing buildings. This device is named Portable Window Energy Meter (PoWEM). When deployed commercially, this instrument might be used by code officials, energy auditors, rating agencies, forensic experts, etc. to verify energy indices of installed fenestration products. It will also help consumers to make informed decisions about window replacement and retrofits by facilitating energy audits and assessment of energy performance of installed windows during their lifespan

DECSRIPTION

The principle of PoWEM is the measurement of heat flow through the window glazing using a set of strategically placed surface heat flux meters, while maintaining uniform temperature condition of the interior of the measurement apparatus, while also measuring incident solar radiation on the window.

Figure 1 shows a schematic of the setup. High absorptance surface (a) is exposed to the solar radiation (or an equivalent source) and is positioned at a small distance behind a window (b).

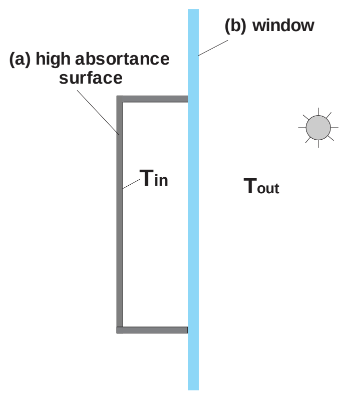

Figure 1 – Schematic of the Measurement Setup

SHGC is the ratio of heat gain through the test specimen to the incident solar radiation and is calculated using the following generalized equation:

$$SHGC = \frac{Q_s - U \cdot (T_o - T_i)}{E_s} \tag{1}$$

Where: Q_S = Heat flux trough test specimen;
U = Thermal transmittance;
T_o = Outside environmental temperature;
T_i = Temperature inside the PoWEM measurement chamber;
E_S = Solar irradiation incident on test specimen;

However, in order to obtain SHGC from this equation, it is necessary to know the thermal transmittance of the specimen, U. It is an obstacle because this measurement requires to be done in another specialized measurement setup called Hot Box, which is large scale laboratory apparatus, unsuitable for in-situ measurements. If the temperature differential between inside and outside is close to zero, T_o - $T_i \approx 0$, than U-factor portion of that equation disappears and the measurement is reduced to measurement of incident radiation and total heat flux through specimen, Q_s and E_s and SHGC becomes simple ratio of the two

$$SHGC = \frac{Q_s}{E_s} \tag{2}$$

The heat flux through the test specimen, Q_S is measured by heat flow meters mounted at the back of the apparatus.

The major part of this concept is to maintain the inside temperature, T_i equal to the outside temperature, T_o, making the determination of U-factor unnecessary. Figure 2 shows a schematic representation of the device. The inside surface temperature in PoWEM is maintained by thermoelectric elements. The heat exchanged by the edges of the apparatus are substantially reduced by well insulating edges and using polished surface for low radiant heat transfer. The outside temperature is measured using thermistor and the solar radiation is measured using radiometer. The signals are transmitted wirelessly to the logic board.

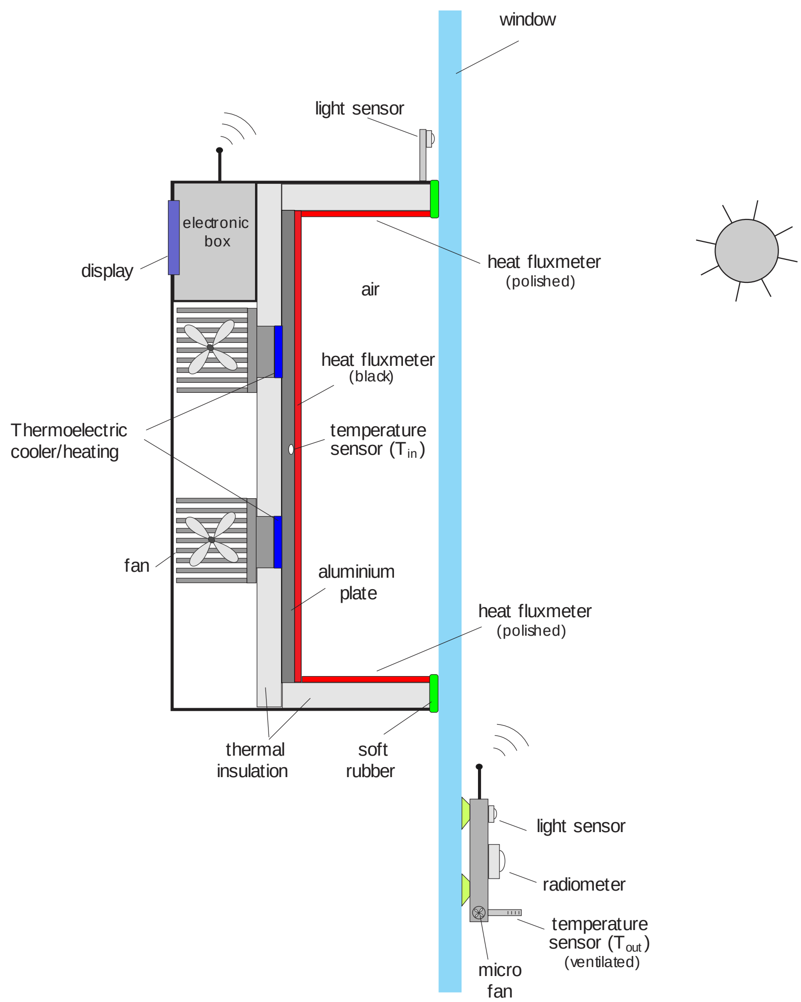

Figure 2 – Schematic Diagram of PoWEM

The back side of the PoWEM consists of highly absorbent metal plate (Aluminum alloy) lined on one side with calibrated surface heat flux sensors and painted black, which measure heat transferred into the apparatus, and with thermoelectric elements on the other side, including fans for heat dissipation, which maintain temperature inside the apparatus, T_i.

The space between the back plate surface and the window is relatively narrow and is designed to achieve the inside heat transfer coefficient (h_i) close to standardized value (NFRC 100). The device is affixed to the window by means of two suction cups, mounted on the side of the apparatus.

The Visible Transmittance (VT), being independent of thermal performance is determined by measuring incident solar radiation and transmitted solar radiation in the visible portion of the solar spectrum only (i.e., 380 nm to 780 nm). VT is then calculated as the ratio between the inside and outside visible light radiometer.

$$VT = \frac{E_{v,i}}{E_{v,o}}$$

Where:

$E_{v,i}$ = Transmitted visible solar radiation

$E_{v,o}$ = Incident visible solar radiation

On the back side of the device, there is a logic board and LCD display. Logic board collects all individual measurements and processes them to calculate SHGC and VT and displays it on an LCD panel.

The estimated measurement error is around 5%, which is perfectly acceptable to in situ measurement.

Figure 3 shows finished PoWEM device, viewed from the back and front sides. Figure 5 shows inside wiring and construction.

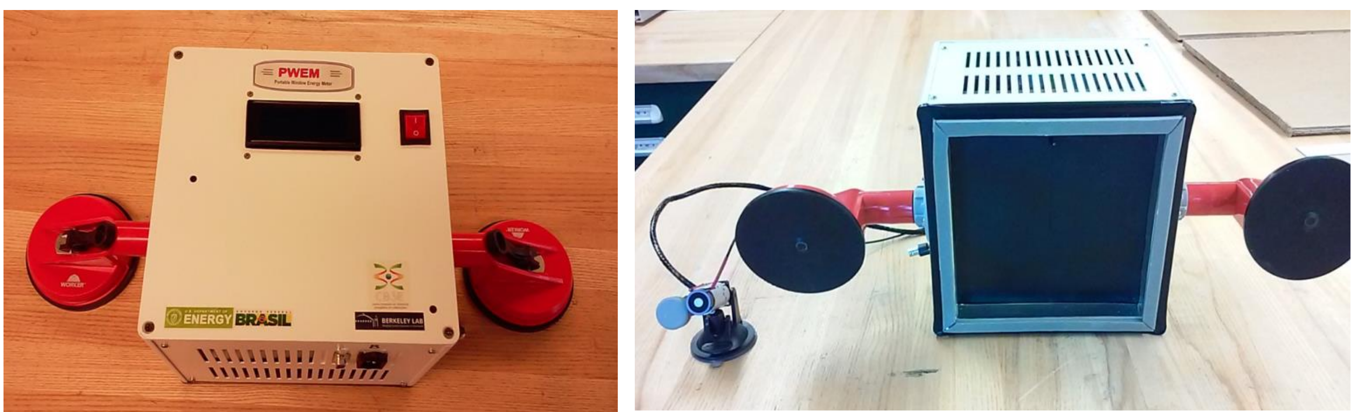

Figure 3 – Finished PoWEM Apparatus

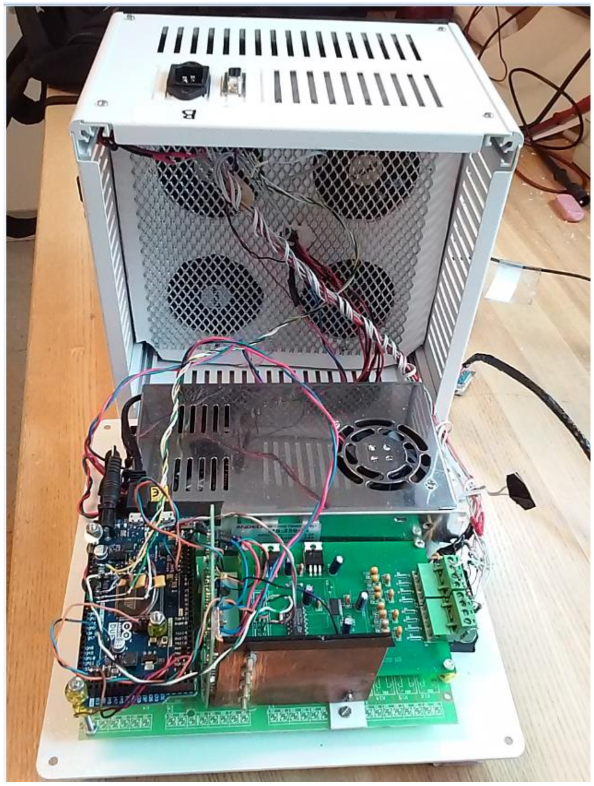

Figure 4 - Open view of PoWEM

Figure 5 shows SHGC measurement a commercial glazing by the PoWEM.

Figure 5 – PoWEM in action, measuring SHGC of a Commercial Window Glazing

VALIDATION

Validation was done on a variety of known glass samples and glazing systems. First set of measurements were done on single glazing samples 6" x 6" in size. The following set of glazing samples were used:

Table 1 - Glass Sample Properties

Name	Tickness (mm)	τ_s	$R_{s,f}$	A_s	ε_f	ε_b
Clear Glass	3.0	0.885	0.081	0.034	0.85	0.85
CCN50_a	4.0	0.376	0.323	0.301	0.065	0.85
CCN50_b	4.0	0.376	0.341	0.283	0.84	0.065
N14_a	4.0	0.138	0.406	0.457	0.378	0.85
N14_b	4.0	0.138	0.306	0.556	0.85	0.378

Figure 6 shows the set up to test glass samples (single glazing) using an Eppley Pyranometer as reference, and Figure 7 shows results of measurements as a time series and showing lag in data after change-over.

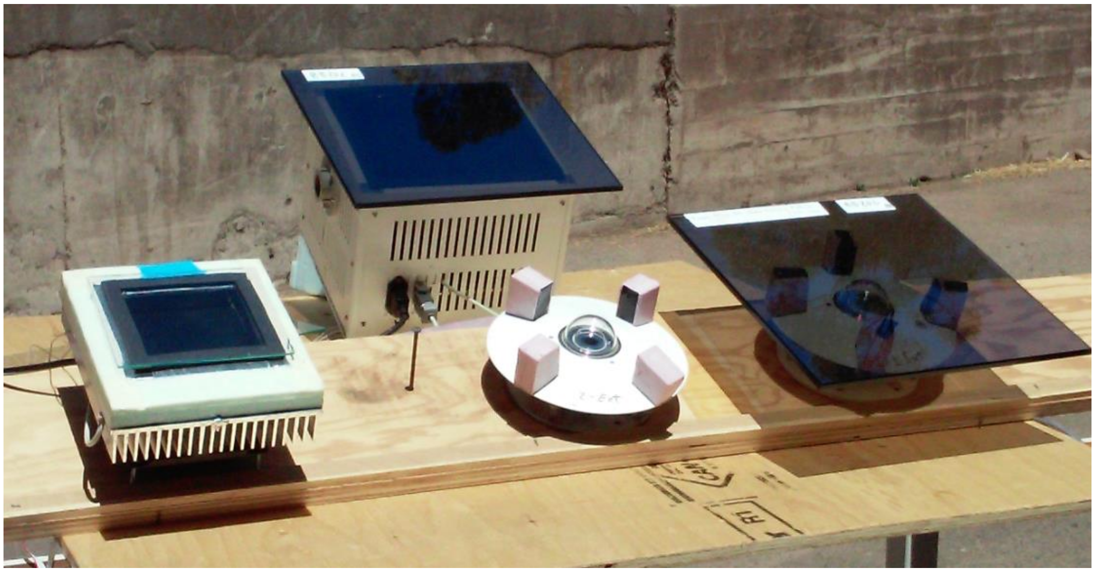

Figure 6 - Set up testing glass samples

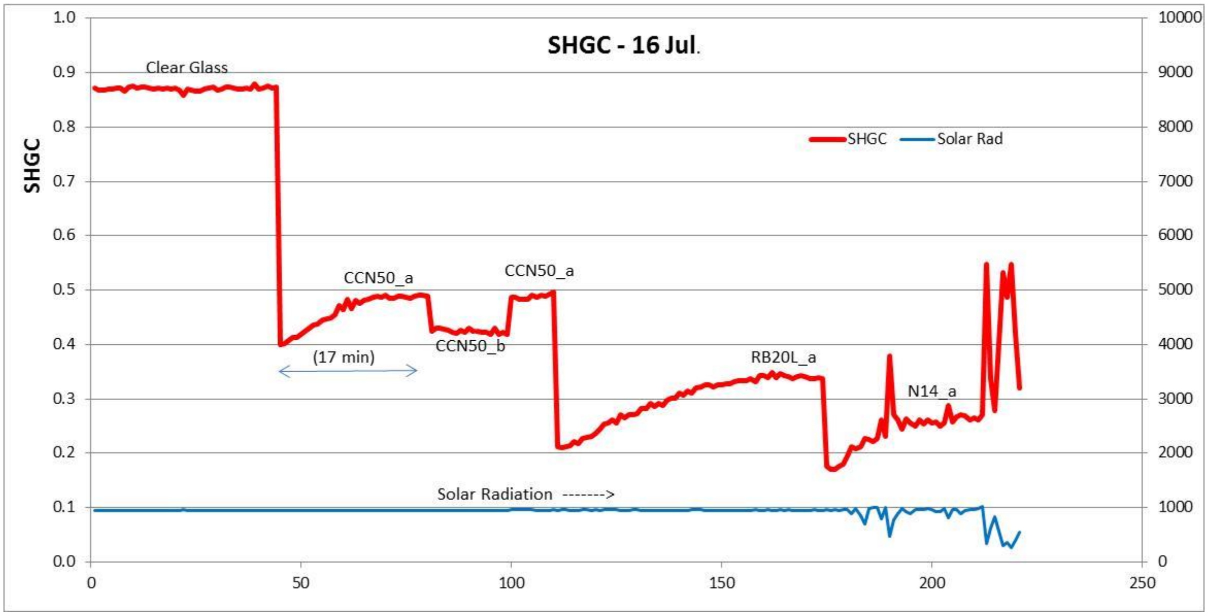

Figure 7 - Typical data measured

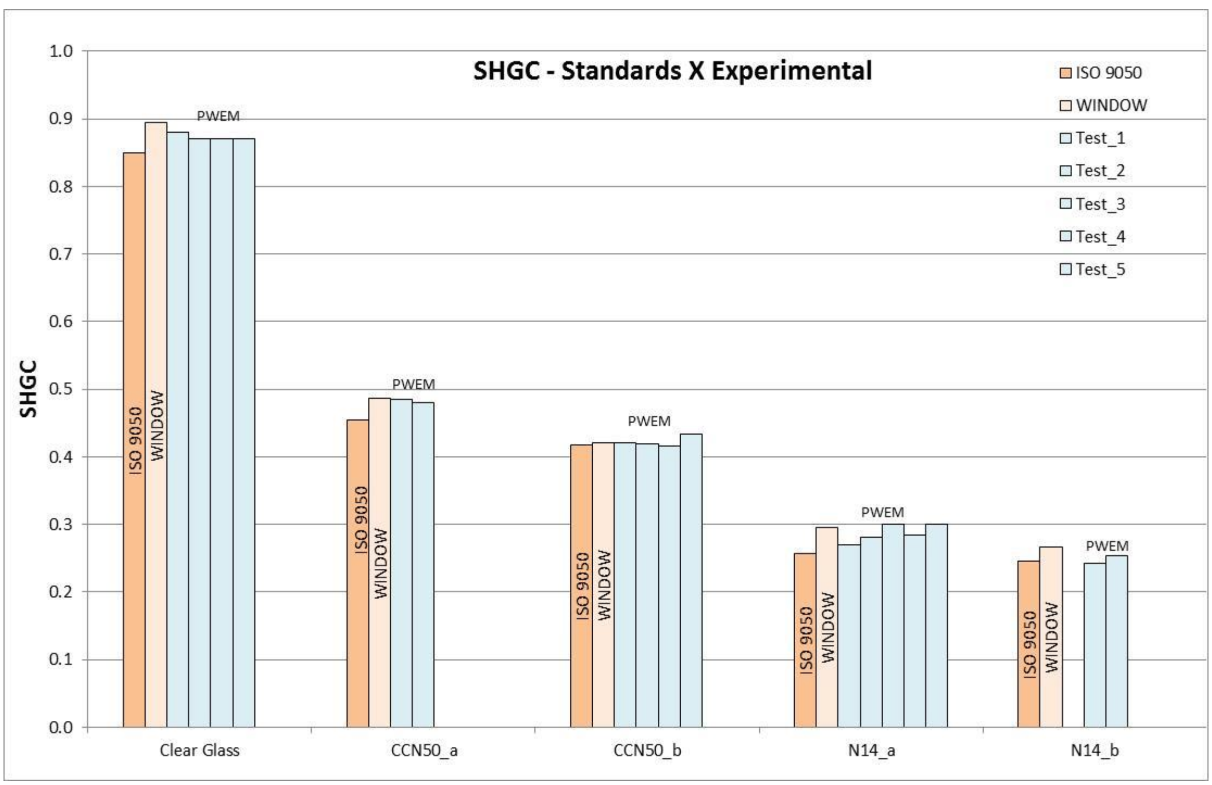

Figure 8 - Comparison Between Experimental and Simulation SHGC

Figure 8 shows SHGC measurement of several glass samples by the PoWEM and calculated by WINDOW program (ISO 15099) and ISO 9050/ISO 10292 set of standards that are widely used in Europe. It can be seen that the SHGC measured by the PoWEM agrees very well with calculated values. Some variation was detected, such as in the glass sample N14_a and N14_b. The next section shows the analysis and tests performed to understand the phenomena involved.

1.1 Analytical Model

The objective of the analytical model was to figure out the reason(s) of the variations in the experimental results. The heat exchange by longwave radiation and natural convection has been implemented in a tilted cavity, in order to emulate test conditions. The model was one-dimensional, steady state and taking into account the multi-reflections in the glass. The outside glass surface exchange heat by forced convection to the outside laminar air flow and also by infrared radiation to the sky. In this analysis the sky temperature was considered 10 ^{o}C below the outside air temperature. The solar radiation was considered normal to the glass surface. Figure 9 shows a schematic of the model.

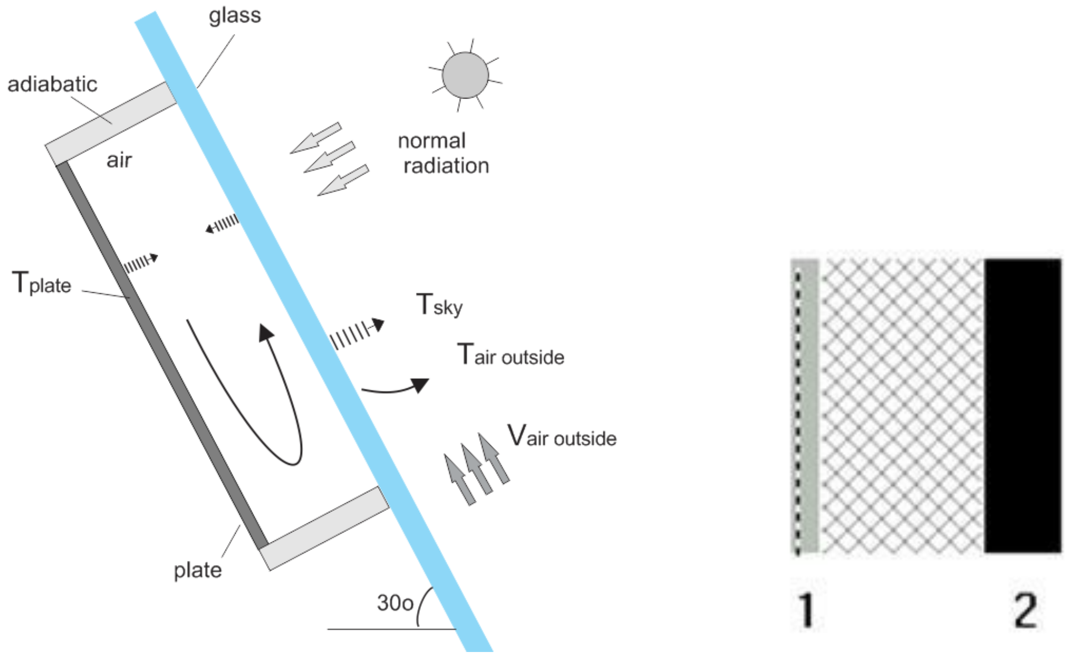

Figure 9 - Schematic of the Analytical Model and Model’s Representation in WINDOW Program

Figure 10 shows a comparison between different models and experimental results. Models emulate the apparatus, considering a tilt equal to 30º, solar radiation normal to the glass, outside air velocity equal to 2 m/s and solar radiation equal to 1000 W/m^2.

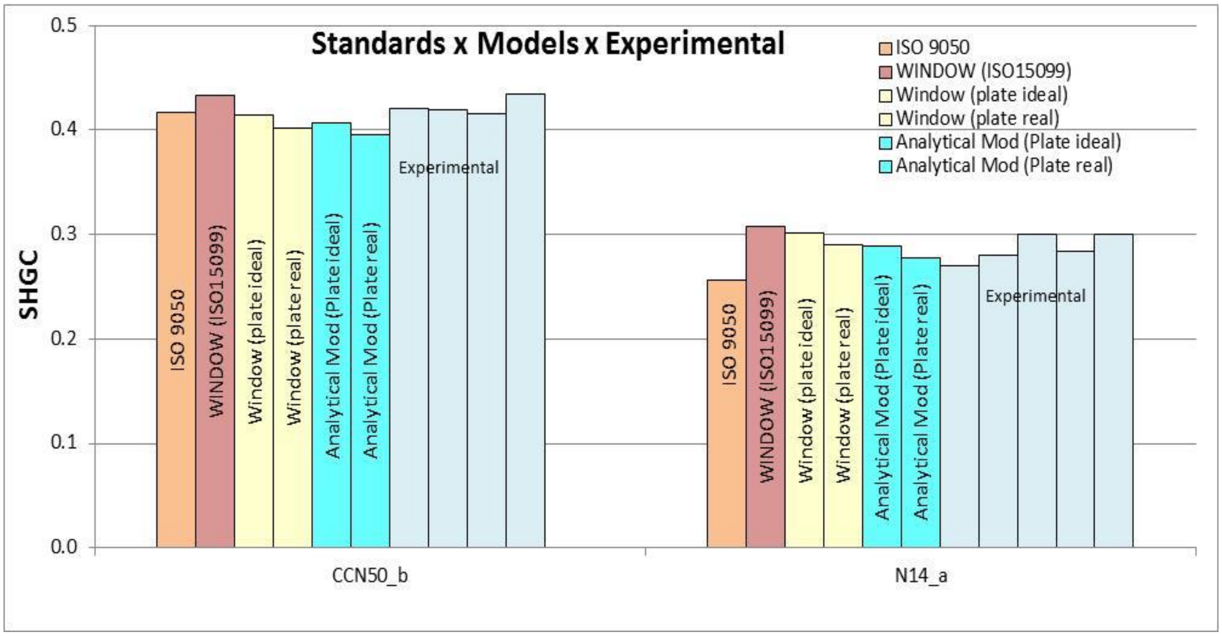

Figure 10 - Comparison between the models, experimental results and standard values for two different glasses

It can be seen that the models indicate the same trend. The figure shows, also, the variation due the absorptivity of the back plate. Actual plate has an absorptivity equal to 0.95 and emissivity equal 0.88 resulting in a reduction of the SHGC, compared whit an ideal plate (blackbody). The core functionality of this equipment is the maintenance of the plate temperature equal to outside air temperature. Figure 11 shows the influence of the plate temperature obtained by the analytical model compared with experimental results. The data agree very well, and also it can be seen the importance of the temperature control.

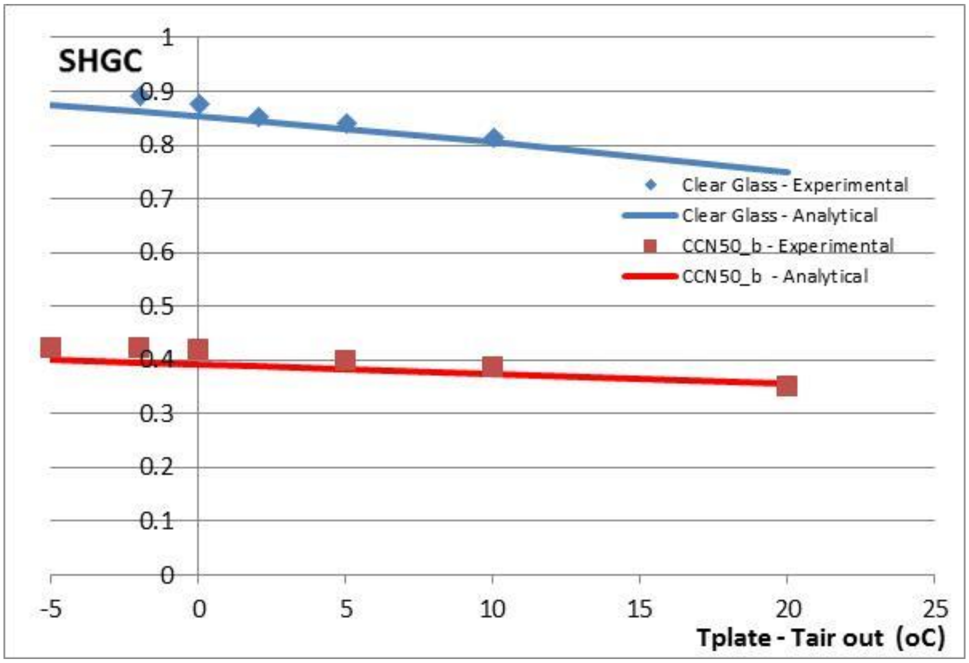

Figure 11 - Influence of the plate temperature

The tests are performed in clear days, so the sky temperature can be lower than air temperature, increasing the longwave heat exchange of the glass. Figure 12 shows a sensible influence of the Sky Temperature on the SHGC (Analytical Model). Combined with outside air velocity, the SHGC changes significantly.

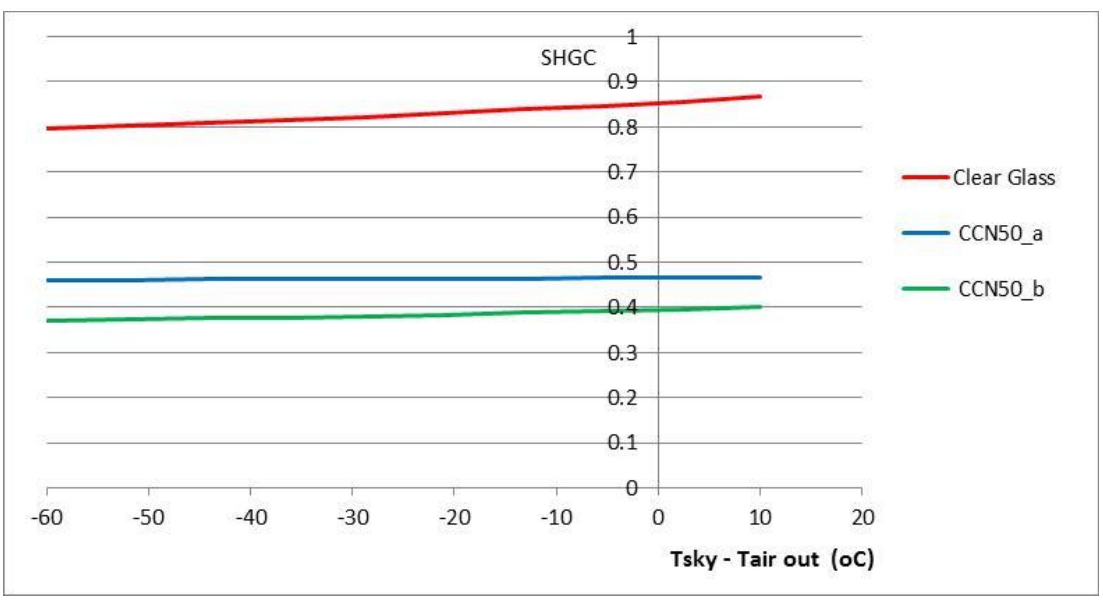

Figure 12 - Influence of the Sky Temperature in the SHGC (Analytical Model)

Another important analysis was done to understand the influence of the outside air velocity. Figure 13 to Figure 15 show the big influence of air velocity on the SHGC and glass temperature.

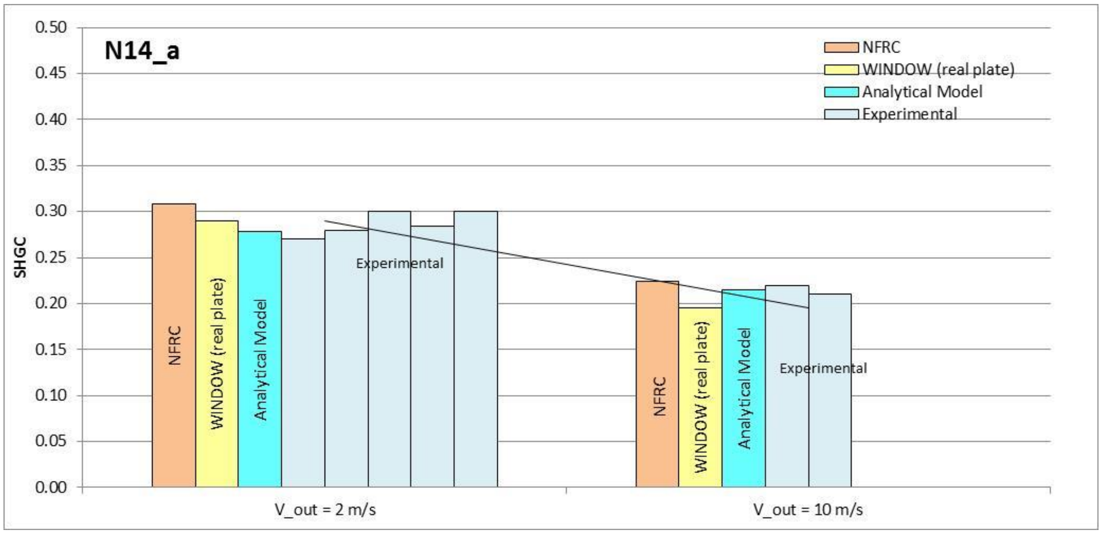

Figure 13 - SHGC for different outside air velocity (Glass N14_a)

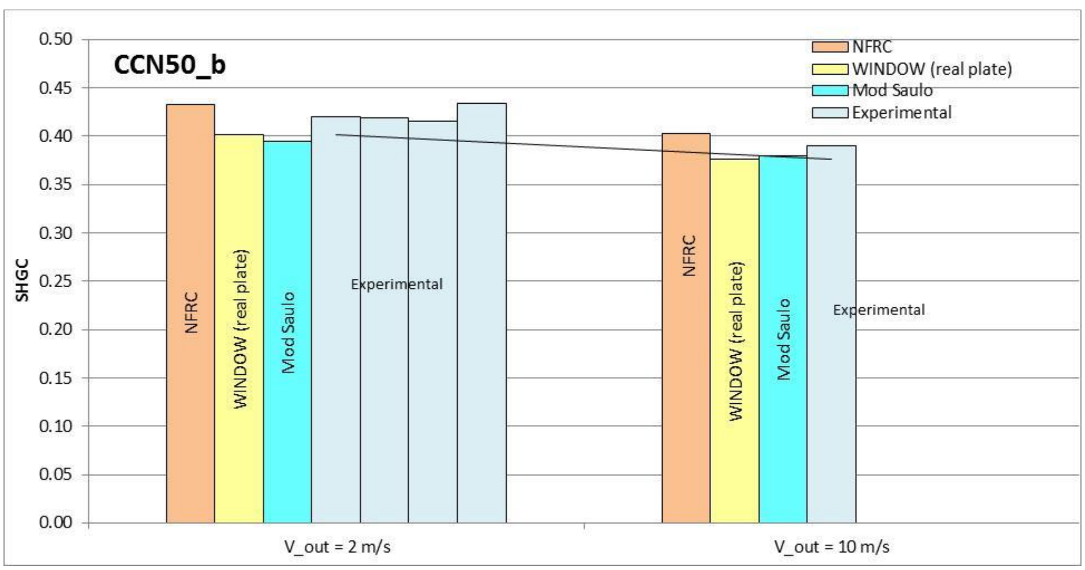

Figure 14 - SHGC for different outside air velocity (Glass CCN50_b)

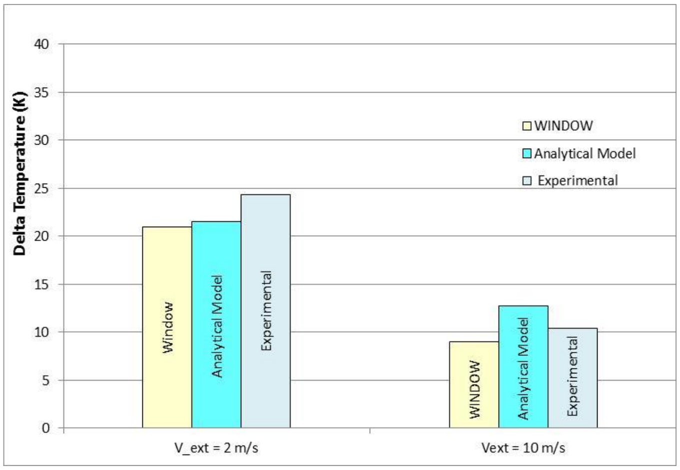

Figure 15 - Glass temperature for different outside air velocity

Figure 16 shows the strong variation of the SHGC with the heat transfer coefficient. Experimental results (PoWEM) and analytical models results are compared. The results show good correlation.

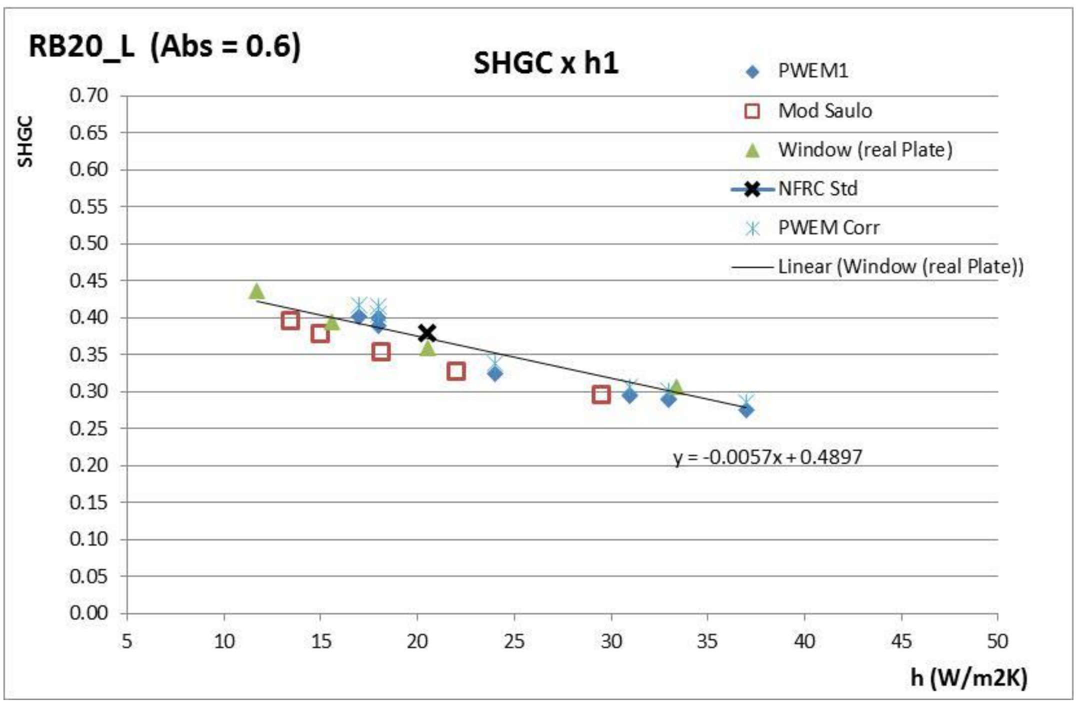

Figure 16 - SHGC function the heat transfer coefficient.

The NFRC standard recommends combined heat transfer coefficient of around 21 W/m^2K (forced convection with wind velocity of 2.75 m/s and black body radiation heat transfer), so to standardize measurement results, they need to be corrected to this value if it is different during the experimental measurement. One way to do this is using the regression curve showed in the Figure 16. The error of the results is estimated to be 5%. More tests need to be conducted to confirm this.