EXPERIMENTAL GLASS OPTICAL DATA OF NEW GLAZING SYSTEMS TO IMPROVE ENERGY SAVINGS

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Abstract
Transparent spectrally selective coatings on glass or polymeric substrates have been recently proposed to optimize daylighting and energy performances of glazing systems. Although a wide choice of these materials is available, the experimental and numerical characterization of their properties is still not complete. Optical measurements on several single and double sheet glazings with different solar-control coatings have been carried out with a spectrophotometer. The aim is to define optimal combinations of glazings and coatings to realize energy efficient multi-sheet systems. Transmittance and reflectance measurements have been carried out referring to different angles of incidence of daylight. The paper presents the first experimental results and a discussion on the influence of various parameters (such as glazing thickness, kind of coating, angle of incidence) on the energy performances of glazing systems. A comparison has been carried out using experimental data to build multisheet glazings and data extracted from WINDOW software. Simulations were performed with the hourly simulation program IENUS. The program was developed to assess the building energy demand with different kinds of climatic data and of daylighting.

Keywords Experimental analysis, innovative glazing materials, energy savings.

INTRODUCTION

Industries in these last years have developed and produced different types of transparent materials and lighting control systems to improve the functionality of buildings, taking at the same time full advantage of the potential energy saving coming from daylight. The attempt is to maximise energy savings by reducing solar heat gain in summer and exploiting solar energy in winter, always reducing possible situations of discomfort.

Although glazing systems are extremely important for building energy efficiency, Italian and International Standards [1, 2] consider the problem in a very simplifying way, providing the mean solar transmittance coefficient only for a few kinds of windows, and referring then to the certifications of the specific materials for other values.
Research in the field of glazing systems technology received a boost passing from single pane to low-emittance (low-e) window systems, and still to low thermal transmittance (low-U) and electrochromic windows. At the present state of art, the alternative candidates for low-U windows are silica aerogels, transparent insulation materials (TIM) and vacuum glazings.

The Authors have already done a lot of work from a numerical point of view to understand and foresee the behaviour of a typical environment where innovative window systems can be applied, such as offices. The field of dynamic windows and other innovative glazing systems, following the steps of LBNL and other groups [3, 4, 5, 6], have been explored in terms of energy efficiency and environmental quality [7, 8]. Some experimental tests are hard to be developed, since studies on some materials are still in progress. Anyway, it is an interesting possibility to create ad hoc glazing systems for specific situations improving so far HVAC energy savings; this is the main aim of the present research.

Specifically, the paper presents an experimental approach to the problem and a definition and validation of a method, still to be completely developed. In this paper single and double sheet optical measurements have been carried out with a spectrophotometer for several kind of glazings with different coatings, to define optimal glazing combinations for energy-efficient multi-sheet glazing systems.

Transmittance and reflectance measurements have been carried out referring to different angles of incidence of light. Energy indexes have been calculated from experimental data to characterize the performances of the glazing systems. Optical measurements have been also compared with numerical results obtained by WINDOW simulation program [9]. Energy consumptions with the proposed glazing systems have been evaluated with the hourly simulation program IENUS (Integrated ENergy Use Simulation), originally developed by the Authors [10], [11], to study innovative glazing systems, lighting and thermal system controls, and validated against calorimetric and energy consumption measurements.

INSTRUMENTATION

A spectrophotometer VARIAN Cary 2300, working in the wavelength range 185 nm – 3152 nm with an accuracy up to 0.2 nm in the UV and visible range and 0.8 in the infrared range, has been used for the experimental campaign (Figure 1).

When a measure of reflection is required, it is possible to use the integrating sphere, with range 300 – 2000 nm, whose way of working is presented in Figure 2.
The limit imposed by the sphere (2000 nm) practically has no influence on the correctness of measurements, as generally for almost every kind of material the values of transmittance are quite the same in the range 2000 – 2500 nm. An accurate description of the instrument is presented in [12, 13].

The spectrophotometer has also a goniometer, which is used to perform transmittance measurements varying the angle of incidence of radiation.
METHODOLOGY

According to UNI 7885 [14], the sample is cut in adequate dimensions, so to completely cover the opening through which the luminous flux passes; after a measure of thickness that must be within the range of tolerance, it is polished before entering into the measuring cell. Measurements are developed varying the wavelength in the range 300 – 2500 nm, with a step up to 10 nm between two following measures, according to European Standard EN 410 [15]. Generally each measure is repeated three times and the average over the three series of data is calculated.

Each time the spectrophotometer is started up, a baseline, which is a calibration to adapt the instrument to environment conditions, takes place.

Some preliminary tests, to verify the correctness of the measures and with the aim to validate the measuring procedure for future work, have been developed with glazings of common use, provided with certificates. Also the problem of repeatability of measurements has been considered and verified so to assure the “stability” of the instrument.

SAMPLES

The experimental campaign considered different single and double sheet glasses commonly used for buildings glazings; three different coatings were applied to the glasses, to obtain different combinations. In particular, St. Gobain float glasses of 4 and 6 mm thickness were considered as single sheet glasses, while St. Gobain Climalit of various thicknesses (4-6-4 and 6-12-6 mm) were used as double sheet glasses. Silver, sputtered and UV control films, manufactured by Intelligence Solar, were applied to the various glasses, according to the combinations in table 1.

MEASUREMENT RESULTS

A lot of trials have been conducted to characterise the optical properties of the considered glazing materials, that in future should be used to build up new window systems; optical data have been measured as a function of wavelength and of the angle of incidence of light. For the sake of brevity, only a few examples of measurements results are here reported.
Table 1. Description of the samples.

<table>
<thead>
<tr>
<th>Code</th>
<th>Glass</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSF4</td>
<td>Single sheet, 4 mm</td>
<td>None</td>
</tr>
<tr>
<td>SSF4A</td>
<td>Single sheet, 4 mm</td>
<td>Silver</td>
</tr>
<tr>
<td>SSF4B</td>
<td>Single sheet, 4 mm</td>
<td>Sputtered</td>
</tr>
<tr>
<td>SSF4C</td>
<td>Single sheet, 4 mm</td>
<td>UV control</td>
</tr>
<tr>
<td>SSF6</td>
<td>Single sheet, 6 mm</td>
<td>None</td>
</tr>
<tr>
<td>SSF6A</td>
<td>Single sheet, 6 mm</td>
<td>Silver</td>
</tr>
<tr>
<td>SSF6B</td>
<td>Single sheet, 6 mm</td>
<td>Sputtered</td>
</tr>
<tr>
<td>SSF6C</td>
<td>Single sheet, 6 mm</td>
<td>UV control</td>
</tr>
<tr>
<td>DSC46</td>
<td>Double sheet, 4-6-4 mm</td>
<td>None</td>
</tr>
<tr>
<td>DSC46A</td>
<td>Double sheet, 4-6-4 mm</td>
<td>Silver</td>
</tr>
<tr>
<td>DSC46B</td>
<td>Double sheet, 4-6-4 mm</td>
<td>Sputtered</td>
</tr>
<tr>
<td>DSC46C</td>
<td>Double sheet, 4-6-4 mm</td>
<td>UV control</td>
</tr>
<tr>
<td>DSC612</td>
<td>Double sheet, 6-12-6 mm</td>
<td>None</td>
</tr>
<tr>
<td>DSC612A</td>
<td>Double sheet, 6-12-6 mm</td>
<td>Silver</td>
</tr>
<tr>
<td>DSC612B</td>
<td>Double sheet, 6-12-6 mm</td>
<td>Sputtered</td>
</tr>
<tr>
<td>DSC612C</td>
<td>Double sheet, 6-12-6 mm</td>
<td>UV control</td>
</tr>
</tbody>
</table>

Figure 3 plots the transmittance (%) as a wavelength function for a 4 mm float glass with a UV control film, for different angles of incidence; as can be seen, there are relevant differences only for high values of the angle (>60°).

Figure 3. Transmittance as a function of wavelength and of the angle of incidence for a 4mm single sheet glazing with UV control coating (Sample SSF4C)

Figures 4 and 5 present the influence of the coating on the transmittance and reflectance (%) as a wavelength function for a 4 mm float glass. It can be noticed that all films – except the UV control one – reduce significantly the transmittance in all the wavelength range and correspondently increase the reflectance; some films,
and in particular the silver one, present a particularly high value of reflectance in the visible range ("Mirror effect").

**Figure 4.** Transmittance as a function of wavelength for a 4mm single sheet glazing with different coatings (Samples SSF4, SSF4A, SSF4B, SSF4C)

![Transmittance graph for different coatings](image)

**Figure 5.** Reflectance as a function of wavelength for a 4mm single sheet glazing with different coatings (Samples SSF4, SSF4A, SSF4B, SSF4C)

![Reflectance graph for different coatings](image)

Figures 6, 7 and 8 present the same results for a 4-6-4 mm double sheet glazing, showing the influence on the transmittance and reflectance of the angle of incidence and of the kind of coating.
Figure 6. Transmittance as a function of wavelength and of the angle of incidence for a 4-6-4 mm double sheet glazing with UV control coating (Sample DSC46C)

Figure 7. Trasmittance as a wavelength function for a 4-6-4 mm double-sheet with different coatings (Samples DSC46, DSC46A, DSC46B, DSC46C)
Figure 8. Reflectance as a wavelength function for a 4-6-4 mm double-sheet with different coatings (Samples DSC46, DSC46A, DSC46B, DSC46C).

Finally, Figure 9 presents the influence of the glass thickness, plotting the transmittance for two different double sheet glazings, with the same sputtered coating.

Figure 9. Transmittance as a wavelength function for different double-sheet glazings with the same sputtered coating (Samples DSC46B and DSC612B).
ENERGY EVALUATIONS

According to the procedures indicated in EN 410 [15] and in UNI EN ISO 10077-1 [16] the main energy parameters were calculated from the measured values, and in particular:
- the direct solar transmittance factor $\tau_e$;
- the direct solar reflectance factor $\rho_e$;
- the thermal transmittance $U$;
- the rejected energy (%).

The results are reported in Table 2.

Table 2. Energy performances of the samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\tau_e$</th>
<th>$\rho_e$</th>
<th>$U$ (W/m²K)</th>
<th>Rejected energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSF4</td>
<td>0,83</td>
<td>0,07</td>
<td>5,75</td>
<td>14</td>
</tr>
<tr>
<td>SSF4A</td>
<td>0,14</td>
<td>0,51</td>
<td>5,74</td>
<td>77</td>
</tr>
<tr>
<td>SSF4B</td>
<td>0,29</td>
<td>0,15</td>
<td>5,74</td>
<td>57</td>
</tr>
<tr>
<td>SSF4C</td>
<td>0,75</td>
<td>0,08</td>
<td>5,74</td>
<td>20</td>
</tr>
<tr>
<td>SSF6</td>
<td>0,79</td>
<td>0,07</td>
<td>5,68</td>
<td>17</td>
</tr>
<tr>
<td>SSF6A</td>
<td>0,14</td>
<td>0,48</td>
<td>5,67</td>
<td>77</td>
</tr>
<tr>
<td>SSF6B</td>
<td>0,27</td>
<td>0,13</td>
<td>5,67</td>
<td>57</td>
</tr>
<tr>
<td>SSF6C</td>
<td>0,71</td>
<td>0,08</td>
<td>5,67</td>
<td>23</td>
</tr>
<tr>
<td>DSC46</td>
<td>0,69</td>
<td>0,13</td>
<td>3,36</td>
<td>26</td>
</tr>
<tr>
<td>DSC46A</td>
<td>0,12</td>
<td>0,43</td>
<td>3,36</td>
<td>76</td>
</tr>
<tr>
<td>DSC46B</td>
<td>0,32</td>
<td>0,20</td>
<td>3,36</td>
<td>55</td>
</tr>
<tr>
<td>DSC46C</td>
<td>0,64</td>
<td>0,14</td>
<td>3,36</td>
<td>30</td>
</tr>
<tr>
<td>DSC612</td>
<td>0,57</td>
<td>0,11</td>
<td>2,92</td>
<td>35</td>
</tr>
<tr>
<td>DSC612A</td>
<td>0,10</td>
<td>0,26</td>
<td>2,92</td>
<td>73</td>
</tr>
<tr>
<td>DSC612B</td>
<td>0,25</td>
<td>0,14</td>
<td>2,92</td>
<td>59</td>
</tr>
<tr>
<td>DSC612C</td>
<td>0,52</td>
<td>0,11</td>
<td>2,92</td>
<td>38</td>
</tr>
</tbody>
</table>

It may be noticed that:
- UV-control coatings do not improve significantly the optical and energy properties of the glasses;
- Silver coatings improve significantly the optical and energy properties of the glasses; in particular $\tau_e$ is decreased down to 0.14 for single sheet glasses and to 0.10 for double sheet glasses; $\rho_e$ is increased up to 0.51 for single sheet glasses and to 0.43 for double sheet glasses; rejected energy is increased up to 77% for single sheet glasses and 73% for double sheet glasses;
- Sputtered coatings show a behaviour which is intermediate between the other two kinds of coatings;
- All coatings – because of their extremely low thickness – do not introduce variations as far as the thermal transmittances of the samples.

ENERGY SIMULATIONS

The validation of the measurements is based on a series of simulations developed with the hourly simulation program IENUS (Integrated ENergy Use Simulation). IENUS was initially developed to assess the building energy demand with different kinds of climatic data, daylighting and artificial lighting control strategies due to active control systems, glazing materials, specifically innovative window systems.

IENUS is an advanced dynamic simulation program integrating the visual and thermal aspects linked to energy efficiency and global comfort in buildings. It uses inherently not CPU time consuming algorithms. Its main feature, respect to other available packages such as DOE 2.1 [17] or ADELINE [18], is the flexibility towards the use of different input data; this feature becomes particularly important for innovative materials, as experimental data are often incomplete. In IENUS, thermal algorithm is based on the transfer function method with different sets of coefficients; illuminance calculations instead are based on pre-calculations of the indoor natural illuminance by a variation of the Solar System Luminous Efficacy method introduced by [19]; different calculation modules allow simulating the management of the visual and thermal environment. The original simulation package was validated against calorimetric and energy consumption measurements performed in office spaces in Mediterranean climate. Glazing data that are generally required to develop the simulations are specifically: a) solar transmittance, b) visible transmittance, c) solar absorbance, d) thermal transmittance, e) solar heat gain coefficients.

A comparison, using experimental data and the data extracted from WINDOW software concerning the glazing materials of Tab. 1 has been carried out; only double sheet windows have been considered, and specifically the ones marked with DSC46, DSC46B, DSC612, DSC612B.

The simulation has been developed from an energetic point of view. The room considered for the test is a 5m x 7m x 3m typical office room, with only one external wall, where it is placed a 3m x 2m central window opening, with the center at 1.8 m from the floor. Room furnishing is ordinary without carpet. The thermal transmittance of the external wall is 0.80 W/(m²K). The envelope construction weight is about 200 Kg/m² of floor. All
internal wall surfaces are lambertians, and present visible reflectances of 0.8 and 0.2 respectively for the ceiling and the floor, and of 0.5 for lateral walls.

An internal shading device, with an on/off strategy that closes the curtain when the direct solar radiation impinging on it after flowing through the glazing system is greater than 30 W/m² is considered, to protect occupants from glare. The internal curtain presents a shading coefficient $SC$ of about 0.4. The direct light transmitted through the curtain is up to 50%, while the direct light transmitted diffusely is about 10%. The angular dependence of the curtain light transmission is not taken into account during illuminance and thermal calculations.

Integration of natural and artificial light management is obtained with a photosensor connected to a controller. It detects the illuminance and turns on the lamps, 600 W, when it is necessary, to guarantee a minimum illuminance on the working plane, placed at 0.8m above the floor, at about 500 lux, according to the EN 12464 [20]. An on/off strategy for artificial light is considered to operate.

The numerical analysis was developed with the aim of understanding the approximations introduced in a building energy analysis evaluation, with the test materials previously characterised, and consequently to validate the procedure of measurement followed. Simulations have been developed for three main orientations, South, West, and North.

The results of the simulations are presented in Tables 3, 4, 5. The overall energy consumption and the partial energy requirements are here reported for the four considered windows, in terms of percentage errors. Percentage errors are evaluated comparing the results of the simulations for the measured windows in respect to the results obtained simulating the windows with the most similar characteristics to the ones tested, that it was possible to generate with the software WINDOW.

Results show very little differences between the reference and the “measurement” cases, considering both the overall energy consumption and the partial energy requirements, i.e. cooling, heating and artificial lighting. All the cases are under the 10% of approximation, which can be considered a very good result, considering the sensible approximations introduced in a building energy analysis. Only the heating consumption presents values higher than the fixed 10%. This fact can be justified considering that heating gives a low contribute to the overall consumption; this means that the comparison is between very low values of consumption, leaving the possibility and risk of high (but less significant) error percentages.

All these considerations mean that the reported measures are strictly in accord with what is numerically represented in specific software and, more significantly, that is possible to physically combine different glazing materials to realise new (generally double glazed) windows searching for optimal combinations from visual and energetic viewpoints.
Table 3. Percentage errors in respect to reference case, South.

<table>
<thead>
<tr>
<th></th>
<th>DSC46 [%]</th>
<th>DSC46B [%]</th>
<th>DSC612 [%]</th>
<th>DSC612B [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>2.0</td>
<td>12.9</td>
<td>-1.7</td>
<td>5.2</td>
</tr>
<tr>
<td>Heating</td>
<td>-51.9</td>
<td>-18.0</td>
<td>-32.5</td>
<td>-3.5</td>
</tr>
<tr>
<td>Cooling</td>
<td>0.7</td>
<td>1.2</td>
<td>2.9</td>
<td>-2.0</td>
</tr>
<tr>
<td>Lighting</td>
<td>4.5</td>
<td>21.3</td>
<td>-6.9</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Table 4. Percentage errors in respect to reference case, West.

<table>
<thead>
<tr>
<th></th>
<th>DSC46 [%]</th>
<th>DSC46B [%]</th>
<th>DSC612 [%]</th>
<th>DSC612B [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>1.0</td>
<td>-2.5</td>
<td>-1.1</td>
<td>-2.1</td>
</tr>
<tr>
<td>Heating</td>
<td>-53.8</td>
<td>-9.3</td>
<td>-31.3</td>
<td>-1.1</td>
</tr>
<tr>
<td>Cooling</td>
<td>0.8</td>
<td>-6.3</td>
<td>2.1</td>
<td>-5.1</td>
</tr>
<tr>
<td>Lighting</td>
<td>1.7</td>
<td>0.0</td>
<td>-3.6</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 5. Percentage errors in respect to reference case, North.

<table>
<thead>
<tr>
<th></th>
<th>DSC46 [%]</th>
<th>DSC46B [%]</th>
<th>DSC612 [%]</th>
<th>DSC612B [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>2.5</td>
<td>-2.3</td>
<td>-2.7</td>
<td>-1.3</td>
</tr>
<tr>
<td>Heating</td>
<td>-54.9</td>
<td>1.4</td>
<td>-40.1</td>
<td>-2.6</td>
</tr>
<tr>
<td>Cooling</td>
<td>1.5</td>
<td>-6.0</td>
<td>2.1</td>
<td>-3.3</td>
</tr>
<tr>
<td>Lighting</td>
<td>3.9</td>
<td>0.0</td>
<td>-6.4</td>
<td>0.0</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The paper presents an experimental approach to the problem of creating ad hoc glazing systems for specific situations improving so far HVAC energy savings. A definition of the method and a validation by numerical simulations was the main aim of this research. The method here validated will consist in the future in an attempt to identify the possible glazing solutions, by experimental tests based on the combination of commercial and non commercial panes, to assure the maximum of energy saving, always respecting environmental quality needs. An original model will also be developed and validated to predict the optical properties of multi-sheet glazings, starting from the measured properties of different single sheet glasses. A lot of experimental data are now under development: first trials concerned commercial materials, but it would be interesting to consider also innovative materials, such as electrochromics, aerogel and honeycomb solutions.
REFERENCES