Experimental evaluation and ray-tracing modelling of the energy and optical properties of glazing systems with selective coatings

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SUMMARY

Transparent materials play an important role on energy and comfort requirements of buildings; in the present work, a series of optical measurements has been carried out with a spectrophotometer on several kind of glazing, equipped with different coatings. A theoretical model was used to predict the optical properties of multilayered coated glazing systems, starting from characteristics of the single components. This model and a ray tracing approach (implemented with a commercial simulation code) were validated through experimental measurements, showing a satisfactory agreement and revealing that, for high thickness and diffusive glazing systems, the theoretical simulations are to be preferred, since the spectrophotometer analyses could bring to wrong results. The passage to simulation tools permits a wider investigation of all different panes combinations, with a little effort; it is therefore possible to change many variables such as glass thickness, type of coating, type of glass and coating position, at the aim of fulfilling to requirements of every single application.

INTRODUCTION

The installation of more energy efficient glazing for new and existing buildings in Europe could save around 150 Mtons of CO$_2$ every year [1]; this represents almost 25\% of the total EU greenhouse reduction target for 2020. Research in the field of glazing systems technology received a boost passing from single pane to low-emittance window systems, and again to low thermal transmittance, vacuum glazing, electrochromic windows, thermotropic materials, silica aerogels and transparent insulation materials (TIM) [2, 3, 4]. Transparent selective coatings represent an interesting option for the control of solar heat gain, especially in existing constructions.

Transparent selective coatings and films are being manufactured nowadays by all major glass and glazing companies all over the world. They represent quite an advanced technology and are being increasingly used in double and even triple glazing systems to improve window performance. Each glass coating for windows could represent an answer to specific requirements [5]:
- low-emission coatings diminish the thermal transmittance (suitable for colder climates);
- solar control coatings block the overheating in sunny days and, as a consequence, the load and the energy consumption of air conditioning systems. It is important to underline that light transmittance can not reach a value higher than about twice the g-value, therefore, a low solar factor influences also the visible factor;
- hydrophilic coatings solve the problem of condensation in coldest part of the glass panes: with this solution, the condensation occurs in forms of a sheet of water and does not disturb the view through the glass;
UV control films may be used to preserve works of art and more in general materials which are sensitive to light.

The modelling of complex fenestration systems (CFS), including multi-layer glass panes, solar control films, translucent materials and shading devices, has been done by various researchers [6, 7, 8]. Advanced optical models based on the bidirectional optical property distribution functions were also proposed [9, 10], giving a high level of precision, but requiring large amount of experimental data and complex calculations. Besides, many researchers studied multilayer window systems, using ray tracing techniques to model multi-reflection and multi-transmission phenomena [11, 12, 13].

In order to predict the performance of multilayer glazing, obtained by combining different panes and coatings whose properties are known, a theoretical prediction model of the lighting transmittance and reflectance of complex glazing is described and then compared with a commercial code, based on the ray tracing technique. Finally, both models are validated by means of experimental results, carried out on a single and a double sheet glazing with different selective coatings. Spectral transmittance and reflectance measurements were carried out and single number indexes were calculated from experimental data, to characterize the lighting performance of the glazing systems.

METHODS

The measurement campaign for the evaluation of optical and energy properties of simple glazing has been conducted by a Shimadzu SolidSpec-3700; it works in the 240 ÷ 2600 nm wavelength range with an accuracy up to 0.2 nm in the UV and visible range and 0.8 nm in the infrared range.

It is equipped with three detectors: a photomultiplier for the UV-VIS spectral band, a gallium and indium arsenide photodiode for the NIR I range and a low temperature sulphide lead (PbS) for the NIR II. When a measure of reflection or diffuse transmittance is required, it is possible to use the integrating sphere (fig. 1).

As far as the theoretical model, the propagation of solar radiation through different layers of a multilayer system is derived from the model proposed by Pfrommer [14]; each interface is defined by its transmissivity, front and back reflectivity, by means of the transfer matrix that is written as follows [15]:

![Figure 1. The spectrophotometer used for the experimental campaign and the integrating sphere.](image)
\[
\begin{bmatrix}
-\frac{\rho_b}{\tau} & \frac{1}{\tau} \\
\tau - \frac{\rho_f \rho_b}{\tau} & \frac{\rho_c}{\tau}
\end{bmatrix}
\] (1)

The path of light through components whose function is to attenuate the wave intensity (for example, glass substrate or air gaps) is characterized in a similar way:

\[
\begin{bmatrix}
0 & \frac{1}{\tau} \\
\tau & 0
\end{bmatrix}
\] (2)

From spectrophotometric measurements of total transmission \( T \) and total front reflection \( R_f \) made on single glass panes (hypothesizing the symmetry of reflection: \( \rho_f = \rho_b \)), it is possible to obtain the attenuation factor \( \tau_s \) (function of the glass thickness) and the air-glass interface reflectivity \( r_s \) (therefore, the glass interface transmissivity \( t_s = 1 - r_s \)):

\[
\left( \frac{1}{R_f} \right) = \begin{bmatrix}
\frac{1}{1-r_s} & -\frac{r_s}{1-r_s} \\
\frac{r_s}{1-r_s} & 1-r_s - \frac{r_s^2}{1-r_s}
\end{bmatrix} \begin{bmatrix}
0 & \frac{1}{\tau_s} \\
\tau_s & 0
\end{bmatrix} \begin{bmatrix}
1 - r_s - \frac{r_s^2}{1-r_s} & \frac{r_s}{1-r_s} \\
-\frac{r_s}{1-r_s} & 1
\end{bmatrix} \left( \frac{0}{T} \right)
\] (3)

Once the glass is characterized, the influence of coating could be taken into account, starting from measurements with the same glass substrate, covered by the coating and measuring both front and back reflection:

\[
\left( \frac{1}{R_f} \right) = \begin{bmatrix}
\frac{1}{t_c} & -\frac{r_c'}{t_c} \\
\frac{r_c'}{t_c} & \frac{r_c r_c'}{t_c^2}
\end{bmatrix} \begin{bmatrix}
0 & \frac{1}{\tau_s} \\
\tau_s & 0
\end{bmatrix} \begin{bmatrix}
1 - r_s - \frac{r_s^2}{1-r_s} & \frac{r_s}{1-r_s} \\
-\frac{r_s}{1-r_s} & 1
\end{bmatrix} \left( \frac{0}{T} \right)
\] (4)

\[
\left( \frac{1}{T} \right) = \begin{bmatrix}
\frac{1}{t_c} & -\frac{r_c'}{t_c} \\
\frac{r_c'}{t_c} & \frac{r_c r_c'}{t_c^2}
\end{bmatrix} \begin{bmatrix}
0 & \frac{1}{\tau_s} \\
\tau_s & 0
\end{bmatrix} \begin{bmatrix}
1 - r_s - \frac{r_s^2}{1-r_s} & \frac{r_s}{1-r_s} \\
-\frac{r_s}{1-r_s} & 1
\end{bmatrix} \left( \frac{0}{R_b} \right)
\] (5)

The three independent equations derived from the above relations permit the definition of each coating properties \( r_c, r_c' \) and \( t_c \). The composition of any combination of glass and coating is now possible, considering that air or any other gas space with no optical function can be modelled by a transfer matrix with unitary attenuation factor (the results of these equations are used in the Annexes of the European Standard [16]).

The optical characteristics of multilayer transparent materials could be derived from single layers properties also by using ray tracing techniques; a ray tracing model, available from one of the existing commercial tools [17], is used to predict the properties of coated multiple layer glazing. The code contains a ray tracing program for optical analysis of solid models and it traces rays using the so-called “Generalized Raytracing”. This technique allows the launching of rays into a model without making any assumptions as far as the order in which objects and
surface will be intersected. At each intersection, individual rays may be absorbed, reflected, refracted, diffracted and scattered.

The software needs the single glass (thickness \( d \)) spectral absorbance \( \alpha(\lambda) \), that can be derived from the knowledge of the attenuation factor \( \tau \), obtained from spectrophotometer measurements:

\[
\alpha(\lambda) = -\frac{\ln \tau(\lambda)}{d}
\]  

Furthermore, each surface of the glass is defined by interface characteristics such as glass-air interface reflectivity \( r_s \) and transmissivity \( t_s \), again from measurements on single glasses.

When a coating is applied, the ray tracing software models the glass-coating interface assigning a bidirectional behavior to the glass surface (\( r_c \) and \( t_c \) on the front side and \( r'_c \) and \( t_c \) for the back side), so avoiding the creation of the coating volume.

**RESULTS**

The first step of the study consists of measuring through the spectrophotometer five different coatings alone, in terms of transmittance, front (f) reflection and back (b) reflection. In table 1 the description of the five samples as given by manufacturers is reported, together with the single-number indexes \( \tau_v \), \( \rho_v \), \( \tau_e \) and \( \rho_e \) as defined by EN 410 [16]. It is also indicated the positioning on multiple glazing: external, if it lays in the external part of the outer pane, internal, if it is attached in the internal side of the outer pane or in the external side of the inner pane. In the sample description, the number stands for the type of coating and G stands for the glass; the first character is referred to the external part.

<table>
<thead>
<tr>
<th>N.</th>
<th>Description</th>
<th>( \tau_v ) (%)</th>
<th>( \rho_v^f ) (%)</th>
<th>( \tau_e ) (%)</th>
<th>( \rho_e^f ) (%)</th>
<th>( \rho_v^b ) (%)</th>
<th>( \rho_e^b ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High solar protection (external)</td>
<td>53.0</td>
<td>40.0</td>
<td>34.6</td>
<td>53.1</td>
<td>32.0</td>
<td>41.6</td>
</tr>
<tr>
<td>2</td>
<td>High solar protection – low reflection (external)</td>
<td>54.3</td>
<td>15.9</td>
<td>44.7</td>
<td>19.4</td>
<td>14.7</td>
<td>16.9</td>
</tr>
<tr>
<td>3</td>
<td>Solar protective - low reflection (internal)</td>
<td>71.8</td>
<td>8.7</td>
<td>43.5</td>
<td>13.4</td>
<td>7.6</td>
<td>19.2</td>
</tr>
<tr>
<td>4</td>
<td>Solar protective - high visibility (internal)</td>
<td>64.8</td>
<td>26.0</td>
<td>48.5</td>
<td>38.7</td>
<td>23.1</td>
<td>32.2</td>
</tr>
<tr>
<td>5</td>
<td>Low emission (internal)</td>
<td>30.5</td>
<td>60.3</td>
<td>20.1</td>
<td>69.2</td>
<td>44.5</td>
<td>48.0</td>
</tr>
</tbody>
</table>

Afterwards, the measurements are repeated on single glasses (6 mm thickness) with coating (tab. 2). Comparing the performance of coating on air and with a glass substrate, it is immediately clear the evident reduction of the transmittance, while it is less obvious the reduction on reflection, testifying the strongly different behavior of the interfaces coating-air and coating-glass. The results of tests on coated single glasses are also used to prepare a base and a mean of validation for the theoretical model and the ray tracing simulation. The validation is executed with a double glass with one pane covered internally with a scarcely diffusive coating (sample 3), to be sure that the measurement is not influenced by components of diffuse light that does not reach the detectors.
Table 2. Single-number measured optical-energy characteristics for coated single glazing.

<table>
<thead>
<tr>
<th>N.</th>
<th>Description</th>
<th>( \tau_v ) (%)</th>
<th>( \rho_v^f ) (%)</th>
<th>( \tau_e ) (%)</th>
<th>( \rho_e^f ) (%)</th>
<th>( \rho_v^b ) (%)</th>
<th>( \rho_e^b ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</td>
<td>High solar protection + glass</td>
<td>36.2</td>
<td>24.1</td>
<td>22.6</td>
<td>38.1</td>
<td>15.2</td>
<td>16.6</td>
</tr>
<tr>
<td>2G</td>
<td>High solar protection – low reflection + glass</td>
<td>51.9</td>
<td>13.1</td>
<td>40.5</td>
<td>16.3</td>
<td>10.7</td>
<td>10.5</td>
</tr>
<tr>
<td>3G</td>
<td>Solar protective - low reflection + glass</td>
<td>68.5</td>
<td>6.8</td>
<td>40.6</td>
<td>8.8</td>
<td>6.8</td>
<td>11.1</td>
</tr>
<tr>
<td>4G</td>
<td>Solar protective - high visibility + glass</td>
<td>62.8</td>
<td>22.0</td>
<td>43.9</td>
<td>34.5</td>
<td>17.3</td>
<td>19.8</td>
</tr>
<tr>
<td>5G</td>
<td>Low emission + glass</td>
<td>27.0</td>
<td>51.3</td>
<td>15.5</td>
<td>59.1</td>
<td>31.5</td>
<td>28.6</td>
</tr>
</tbody>
</table>

In fig. 2 the comparison among the experimental results and the theoretical and software models are reported. The curves are practically overlapping, showing the possibility to trust on both theoretical model and ray tracing simulation.

![Image](image1.png)

Figure 2. Comparison among experimental data, theoretical model and ray tracing of sample 3, in terms of transmittance and front reflectance.
For highly diffusive materials and large thickness samples, the measurement setup has to face some uncertainties due to the fact that the window that links the survey with the integrating sphere (fig. 1) has limited dimensions (11 x 21 mm). Therefore, it is possible that some rays do not reach the hole and they are not accounted in the total transmission and reflection, with the consequence of an underestimation of these properties. At the light of the previous consideration, the combination of different coatings in multiple glazing are evaluated through the theoretical model and the ray tracing, which show similar results in every configuration. Table 3 synthesizes the ray tracing results for double glazing with single coatings, in terms of total light transmittance, external light reflectance, direct solar energy transmittance and direct solar energy reflectance: the three internal coatings are positioned on the external side of the inner glass (in the sample description A stands for air gap). As expected, the solar protective coating blocks most of sun energy; the same happens for the low emission coating (sample 5) which, even if it is designed to work in the far infrared region for transmittance improvement, it shows a low level of emission also in the solar spectrum bands. Besides, the visible reflectance resulted the highest of the tested samples: this property is unwanted especially on continuous transparent façades, because of the glare phenomenon.

The low emission coating is also subjected to a series of tests, varying its position on glass panes surfaces and adding another glass to form a triple glazing (fig. 3).

Table 3. Single-number measured optical-energy characteristics for coated double glazing.

<table>
<thead>
<tr>
<th>N.</th>
<th>Description</th>
<th>(\tau_v) (%)</th>
<th>(\rho_v) (%)</th>
<th>(\tau_e) (%)</th>
<th>(\rho_e) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1GAG</td>
<td>High solar protection + glass + air gap + glass</td>
<td>32.4</td>
<td>24.9</td>
<td>18.8</td>
<td>38.4</td>
</tr>
<tr>
<td>2GAG</td>
<td>High solar protection – low reflection + glass + air gap + glass</td>
<td>46.2</td>
<td>14.7</td>
<td>33.0</td>
<td>17.3</td>
</tr>
<tr>
<td>GA3G</td>
<td>Glass + air gap + solar protective - low reflection + glass</td>
<td>60.9</td>
<td>11.2</td>
<td>34.2</td>
<td>10.6</td>
</tr>
<tr>
<td>GA4G</td>
<td>Glass + air gap + solar protective - high visibility + glass</td>
<td>56.3</td>
<td>23.2</td>
<td>36.5</td>
<td>26.5</td>
</tr>
<tr>
<td>GA5G</td>
<td>Glass + air gap + Low emission + glass</td>
<td>24.7</td>
<td>44.3</td>
<td>13.4</td>
<td>40.3</td>
</tr>
</tbody>
</table>

Figure 3. Comparison of visible and solar transmittance for different positions of glazing and coating 5.
The graph underlines that, if the solar energy is almost stopped, the visible performance results poor: the last configuration (three glasses and two coatings) corresponds to a practically opaque glazing.

The coupling of external coatings with internal ones is also implemented (fig. 4), at the aim of finding optimal combinations according to different requirements; the nomenclature of glazing is the same used in tables 2 and 3.

![Figure 4. Comparison of visible and solar transmittance for coupling of coating 5 with other external coatings.](image)

The most effective limitation of solar energy transmission is guaranteed (as expected) from the coating pair solar protective - low emission; however, a more balanced compromise is obtained when the low reflection coating is used externally and both low reflection and high visibility coatings are applied internally.

**DISCUSSION**

The behavior of transparent materials depends from many factors and the requirements for perfect glazing are often antithetical. Generally speaking, coatings with good performance in the visible range are preferred for lighting reasons; a high value of solar factor seems better in cold climates, because of the enhancement of heat gain, but it is not in itself a positive characteristic, since in summer season and at particular angles of incidence it brings to higher energy cooling consumptions.

On the other hand, the efforts to limit solar energy transmission has the consequence of reducing the visible properties of transparent surfaces, especially when the solar protection is highly stressed.

A wide experimental campaign was carried out for several kind of glazing with different coatings, to define optimal glazing combinations for light-energy efficient multi-sheet glazing systems. After a calibration and a validation process with experimental data, ray tracing simulations provide good estimations of coated glazing optical properties. Results showed that, more than the glass thickness, the coating types and position constitute the most influent parameter to assess glazing properties. The best combination of glass panes and coatings depends strictly by requirements of every single application, therefore, a large comparative optical analyses of what is available in terms of coating and glasses is desirable in each design.
process of buildings transparent surfaces. The instrument of ray tracing permits to fulfill these needs with limited resources, once the single components properties are known.

REFERENCES