EXPERIMENTAL AND RAY TRACING EVALUATION OF THE TRANSMITTANCE OF GLAZING SYSTEMS WITH SELECTIVE COATINGS, AT VARIOUS ANGLES OF INCIDENCE

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ABSTRACT

The application of selective coatings in glazings allows a more efficient management of heating and cooling loads of a building. The solar, visible and UV transmittance are three of the most important parameters for the evaluation of glazing lighting and energy performance, which depends significantly on the rays angle of incidence. The goal of the research is to define the transmittance of glazing systems equipped with selective coatings, varying the rays angle of incidence. A ray tracing simulation code is adopted, previously validated through an experimental campaign conducted with a spectrophotometer. The ray tracing simulations were useful to provide good estimations of the optical properties of coated double sheet glasses, in any irradiation condition, once the properties of the single components are measured.

INTRODUCTION

The use of transparent selective coatings and films is becoming more and more diffused among all major glass and glazing manufacturers 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. There are many different available coatings and the applications are correspondingly various: optical filters, heat mirrors, low-emittance films, protective and decorative coatings (Leftheriotis et al., 2000; Seeboth et al., 2000).

Films are generally made of thin layers of polyester, stuck together with an extremely even and thin layer of glue; to protect the metallic surface of the film, a further layer used as an anti-scratch protection is laminated and coupled with the film (Hutchins and Platezer, 1996).

Many researchers have investigated the optical properties of selective coatings and films for window applications. Roos et al. investigated the effect of the angle of incidence of solar radiation on the optical properties of solar control windows (Roos et al., 2000); Nostell presented the results of a wide experimental campaign on various coatings (Nostell, 2000), while Durrani et al. measured the optical properties of three-layer systems on glass substrates (Durrani et al., 2004).

The modelling of complex fenestration systems, including multi-layer glass panes, solar control films, translucent materials and shading devices, has been done by various researchers. Rubin et al. presented various equations to model the optics of composite systems (Rubin et al., 1998).

Alvarez et al. modelled the heat transfer of multiple-layer glazings with selective coatings (Alvarez et al., 2005), while Li et al. evaluated the benefits as regards lighting and cooling energy consumption in an office building using solar film control (Li et al., 2003).

Laouadi and Parekh developed optical models of complex fenestration systems based on the bidirectional optical property distribution functions (Laouadi and Parekh, 2007a, b). The approach is extremely rigorous, since it allows the predicting of the effects of complex glazings on the view-through, window luminance and visualization of indoor objects illuminated by the window. However, for simple thermal or lighting calculations to be used for building design or for window product ratings, the approach suggested by Maestre and Laouadi and Parekh appears to be too sophisticated – since a large amount of experimental data must be collected and complex calculations must be carried out – and actually not necessary for the required level of detail.
Maestre et al. developed a new model for the angle-dependent optical properties of coated glazings (Maestre et al., 2007), while Singh and Garg defined an empirical fit for angle-dependent g-values of glazings, involving optical constants of each glazing: spectral refractive indices and spectral extinction coefficients (Singh and Garg, 2010).

Finally, many researchers studied multilayer window systems, also using ray tracing techniques to model multi-reflection and multi-transmission phenomena (Kuhn et al., 2000; Maamari et al., 2006; Chow et al., 2007, Asdrubali et al., 2009).

The approach followed in this paper starts from data obtained from single components at normal incidence, to be used in any glazings combination and at various angles of incidence inside a ray tracing modeling environment.

**DESCRIPTION OF THE PROCEDURE PROPOSED**

Starting from experimental data, it is possible to evaluate solar, visible and UV transmittance, as defined by EN 410 (EN 410, 2011):

\[
\tau_s = \frac{\sum_{\lambda=300}^{2500} S_s \tau(\lambda)V(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{2500} S_s V(\lambda)\Delta\lambda}
\]

(1)

\[
\tau_v = \frac{\sum_{\lambda=300}^{2500} D_v \tau(\lambda)V(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{2500} D_v V(\lambda)\Delta\lambda}
\]

(2)

\[
\tau_{uv} = \frac{\sum_{\lambda=280}^{380} U_v \tau(\lambda)V(\lambda)\Delta\lambda}{\sum_{\lambda=280}^{380} U_v V(\lambda)\Delta\lambda}
\]

(3)

where:

- \( S_s \) is the relative spectral distribution of the solar radiation;
- \( D_v \) is the relative spectral distribution of illuminant D65;
- \( U_v \) is the relative spectral distribution for the UV, \( \tau(\lambda) \) is the spectral transmittance of glazing; \( V(\lambda) \) is the spectral luminous efficiency for photopic vision defining the standard observer for photometry, \( \Delta\lambda \) is the wavelength interval.

The spectrophotometer used for the experimental measurements is a Shimadzu SolidSpec 3700, that allows to evaluate absolute transmission coefficient and relative reflection coefficient in the wavelength range between 240 and 2600 nm, with an accuracy up to 0.2 nm in the UV and visible range and 0.8 nm in the infrared range. The reliability of the measurement of reflection coefficients decreases with thick sample, therefore, materials with a thickness greater than 6mm had not been tested.

A ray-tracing software, Trace-Pro (Lambda Research Corporation, 2008), has been used for the evaluation of thicker and more complex systems. The code contains a ray tracing program for optical analysis of solid models and it traces rays using the so-called “generalized ray-tracing”. 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 requires the geometrical dimension of the material (length, width, thickness and shape), the refractive index and the absorption coefficient \( \alpha_{\text{mat}}(\lambda) \) according to Beer-Lambert law:

\[
\Phi_f = \Phi_0 * \exp(-\alpha_{\text{mat}}(\lambda) * d)
\]

(4)

Where \( \Phi_f \) and \( \Phi_0 \) represent the transmitted and the incident flux and \( d \) stands for the thickness of the material where the ray travels. The absolute transmission factor has been measured through the spectrophotometer, thus the absorption coefficient could be evaluated trough the following equation:

\[
\alpha_{\text{mat}}(\lambda) = -\ln \frac{\tau_s(\lambda)}{d}
\]

(5)

The evaluation of the refractive index \( n(\lambda) \) has been made by means of a theoretical model that uses the spectrophotometer’s measurements of the total reflection coefficient for normal incidence. In this case, the reflection coefficient is given by the Fresnel’s law:

\[
R(\lambda) = \left( \frac{n_1(\lambda) - n_2(\lambda)}{n_1(\lambda) + n_2(\lambda)} \right)^2
\]

(6)

Where \( n_1 \) and \( n_2 \) are the refractive index of the two media and \( R(\lambda) \) is the reflection coefficient of the interface. If the first media is air \( n_1=1 \) and the equation (6) becomes:

\[
R(\lambda) = \left( \frac{1 - n_2(\lambda)}{1 + n_2(\lambda)} \right)^2
\]

(7)

\( R \) represents the first order reflection, and it isn’t affected from what happens after the interface. On the other hand, the total reflection coefficient \( R_t \) considers also the others reflections engendered by the second interface (fig. 1 and eq. 8).

\[
R_t(\lambda) = R_1(\lambda) + \sum_{n=1}^{\infty} R_n(\lambda)
\]

(8)

Nevertheless, if the media is surrounded by air and its absorption coefficient is known, the total reflection coefficient \( R_t \) of the media could be defined as a function of \( R_t(n(\lambda)) \) and \( a(\lambda) \):
where \( a(\lambda) \) represents the absorption coefficient of the material, estimated from the spectrophotometric measurements and the following equation:

\[
a(\lambda) = 1 - R_T(\lambda) - \tau_s(\lambda)
\]  

(10)

Solving the geometric series, eq. (9) becomes:

\[
R_t(\lambda) = R_t(\lambda) + \frac{(1 - R_t(\lambda))^{1 - \alpha(\lambda)} \times R_t(\lambda)}{1 - (1 - \alpha(\lambda))^{1 - \alpha(\lambda)} \times R_t(\lambda)}
\]  

(11)

If the media total reflection coefficient \( R_t \) can be measured using a spectrophotometer, the only unknown quantity is the parameter \( R_t \). Then, by means of eq. (7), it is possible to estimate also the refraction index \( n(\lambda) \). Four different values of \( n(\lambda) \), for every wavelength, solve eq. (11), but only one is physically acceptable. It is at the end possible to model the optical behaviour of glass and films using the ray-tracing code.

In fig. 2 a capture of the code results for a double glass is reported: it is possible to see the incident light from the left-hand side, the rays reflected, the ones transmitted and their deviation due to interfaces refraction.

The model proposed gives an acceptable estimation of the material optical behaviour only if the diffuse reflection coefficient is null.

MEASUREMENT SETUP FOR VALIDATION PROCESS

The spectrophotometer used for the measurement campaign 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.

At the aim of executing measurements at oblique angles of incidence, an accessory was built: a double goniometer with two slots where two identical samples have to be fixed (fig. 3). The geometrical analysis (Asdrubali et al., 1999) shows that if the two samples have the same inclination, the double deviations due to the materials’ refraction are equal and opposite, therefore, the ray exits from the accessory without resulting shifts from the incident direction.

The ray tracing model and the experimental measurements results are compared in figg. 4 and 5 for a double glass equipped respectively with a solar protective - high visibility film and a solar protective-low reflection film, for two angles of incidence: 0 and 60°.
While the first graph underlines a substantial match between the two methods, the behaviour of the solar protective-low reflection film deserves a deeper analysis. In fact, if at normal incidence the lines practically overlap, at 60° (and also with other incidence angles) some differences arise: in particular, a shift of the peaks towards lower frequencies is noticed. This phenomenon is probably due to the interference of multiple reflections of light among the reflecting surfaces. The interference could be destructive or constructive depending on the wavelength, the angle of incidence, the thickness of the layers and their refractive index, according to the following equation that describes the phase difference $\delta$ between two succeeding reflections (Hernandez, 1986):

$$\delta = \frac{2\pi}{\lambda} 2nd \cos \theta$$ (4)

When the incidence angle changes, with certain films, this circumstance could lead to the effect previously described. The ray tracing model, cannot catch this peculiarity, therefore, it emphasizes the attenuation, but there is no jumping of peaks and antinodes within the spectrum.

Nevertheless, if we take a look to the global parameters (tab. 1), such as the solar, visible and UV transmittance, only at high angles, differences become significant, underlining that even in the worst conditions, the simulation results remain close to the experimental ones. Besides the variations of these parameters with the angles of incidence, reflects the data gathered from Literature.

### Table 1 Solar, visible and UV transmittance (%) for a double glass equipped with a solar protective - high visibility film, varying the angle of incidence

<table>
<thead>
<tr>
<th>Angle of incidence</th>
<th>Solar transmittance</th>
<th>Visible transmittance</th>
<th>UV transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>44</td>
<td>44</td>
<td>60</td>
</tr>
<tr>
<td>10°</td>
<td>44</td>
<td>43</td>
<td>60</td>
</tr>
<tr>
<td>20°</td>
<td>44</td>
<td>43</td>
<td>59</td>
</tr>
<tr>
<td>30°</td>
<td>43</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td>40°</td>
<td>42</td>
<td>38</td>
<td>59</td>
</tr>
<tr>
<td>50°</td>
<td>38</td>
<td>33</td>
<td>55</td>
</tr>
<tr>
<td>60°</td>
<td>29</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td>70°</td>
<td>11</td>
<td>8</td>
<td>17</td>
</tr>
</tbody>
</table>

### SIMULATIONS CAMPAIGN

The behaviour of transparent materials depends from many factors and the requirements for perfect glazings are often antithetical. Generally speaking, coatings with good performance in the visible range are preferred for lighting reasons; a high value of solar transmittance 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 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.

The simulations campaign considered different double sheet glasses commonly used in buildings; three different films were applied to the glasses, to obtain different combinations. In particular a 6 mm thick float glass was used as the single component of a double sheet glass and four different films were applied to one side of the glazings (tab. 2).

### Table 2 Description of the samples analysed.

<table>
<thead>
<tr>
<th>Code</th>
<th>Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar protection - high visibility</td>
</tr>
<tr>
<td>2</td>
<td>Low emission</td>
</tr>
<tr>
<td>3</td>
<td>Solar protection - low reflection</td>
</tr>
<tr>
<td>4</td>
<td>High solar protection – low reflection</td>
</tr>
</tbody>
</table>

Figures 6-9 synthesize the ray tracing results, in terms of solar, visible and UV transmittance at different incidence angles.

As expected, the solar protective coating blocks most of sun energy (samples 1, 3 and 4); the same happens
for the low emission coating (sample 2) 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 correspondence to lower wavelengths.

Besides, all the coatings tested show an interesting capacity of reflecting the UV part of the solar spectrum, often undesired in the indoor environment. As far as the performance in the visible bands, samples 2 and 4 pay their reflective aptitude with very low levels of visible transmittance, circumstance that results usually unwanted for the occupants of inner rooms; samples 1 and 3 keep the visibility at acceptable levels.

At the light of the above mentioned results, the instrument of ray tracing reveals itself as a useful tool to fulfil the needs of defining the complete characteristics of complex glazing systems, with limited resources, once the single components properties are known.

In fact, it is illustrated how the accuracy of the model showed satisfactory, therefore, with practically instantaneous simulations, the behaviour at each angle of incidence could be obtained. The results are particularly helpful in dynamic building simulations, when hourly parameters are needed. For instance, when a building simulation software takes into account of the height of the sun above the horizon, the transparent surfaces behaviour could be described by the curves obtained through the ray tracing evaluations.

CONCLUSION
A wide campaign was carried out for glazings with different coatings, to define the transparent surfaces properties varying the angles of incidence. Ray tracing simulations provide good estimations of coated glazing optical properties, as demonstrated by means of a calibration and a validation process with experimental data.

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 ray tracing method allows the accomplishment of this need in a quick and precise manner, reducing dramatically the time and the resources spent for the experimental measurements.

NOMENCLATURE
- a absorption coefficient [-]
- D distribution of illuminant D65 [-]
- d thickness of the pane [-]
- n refractive index [-]
R reflection coefficient of the Interface
S relative spectral distribution of the solar radiation [-]
U relative distribution of the UV part of global solar radiation [-]
V spectral luminous efficiency for photopic vision [-]
v visible
UV ultraviolet

Greek symbols
α spectral absorbance [-]
Δ interval [-]
λ wavelength [m]
Φ light incident flux [W]
τ spectral transmittance [-]

Subscripts
BL Beer-Lambert
e solar
i interface
t total

REFERENCES