ANGULAR DEPENDENCY OF OPTICAL PROPERTIES AND ENERGY PERFORMANCES OF GLAZING AND SOLAR SHADING DEVICES FOR WINDOWS AND FACADES

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Anno Accademico 2003-2004
to my parents and my sister Elena
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Chapter 1

Introduction

Energy Efficiency  Increased efficiency in end uses of energy has long been recognized
an important element for achieving both energy policy and environmental protection ob-
jectives. This position has been recently reconfirmed e.g. by the Green Paper on Security
of Supply, which states, inter alia: "...the European Union will only reduce its external
energy dependence through a determined policy of demand management. This policy of
demand management is all the more necessary in that it is the only way of meeting the
challenge of climate change".
In this perspective the EU and member states are enacting legislation with the aim of
reinforcing the measures for energy efficiency and demand management.
In the building sector for example the EU Council and Parliament approved in December
2002 the Directive on the energy performance of buildings with the objective to reduce
consumption in building while ensuring comfort.

Energy Efficiency in Buildings  About one third of the energy consumption in Europe
is due to buildings, mostly used to provide indoor thermal and visual comfort to the
occupants: habitants, workers or clients.
A smart building design can reduce drastically this energy consumption. Windows and
transparent facades can have significative influence in the building energy balance since
they provide daylight and allow direct penetration of solar radiation. This influence on the
energy balance is steadily increasing due to architectural choices towards a large fraction
of glazed areas compared to total building envelope area.
Window and Energy Efficiency  In other words windows can be considered as "passive" energy systems. We use the expression "energy efficiency in building" rather than "windows efficiency" because efficiency depends on the whole building design and on its use and location. It can be defined as the capability to satisfy indoor comfort request with as low as possible energy demand to run active heating, cooling and lighting systems etc.

Studies on window labelling and rating [16] [29] propose correlations between window performance parameters and energy efficiency in buildings.

In winter or cold climate thermal losses can be reduced by use of insulated windows, using for instance double glass units with low emissive coating and heavy gas fill, which achieve very low values of thermal transmittance. This recommendation has already been applied by buildings codes in most of the north European countries proving important reductions in annual energy consumption.

On the other hand in summer and warm climate the most relevant issue is how to prevent indoor overheating.

This leads our attentions to solar control devices, whose characterization is discussed in this thesis. Glazing spectral selectivity can maximize daylight and minimize thermal loads in the Near Infrared (NIR) spectrum. Shading devices can reflect and redirect solar beam in order to reduce incoming energy and to avoid glare affects. A combination of this devices can prevent overheating and at the same time provide visual comfort. Dynamical options as switching the optical properties of an electrochromic glazing or operating Venetian blinds can also be very important to control solar irradiation according to users request and sun position etc.

Window and angular dependent properties  Information on optical performances of commercial glazing are usually available only at normal incidence but solar irradiation very seldom hits a vertical surface at normal incidence. The direct annual solar irradiation impinging on a south directed vertical surface versus incidence angle has its maximum value around 45° for Madrid and 60° for Stockholm [18]. This results in the need of angular characterization of glazing and shading properties in order to better estimate the actual window energy performances, specially for solar control devices. For standard glasses the prediction of off normal properties is straightforward by use of Fresnel laws, but for advanced coated glasses the problem is much more complicated and not fully solved even if important progresses have been achieved within the recent European project "ADOPT" [14].
The main window optical and energy parameters are introduced in Chapter 2. In Chapter 3 is showed a preliminary discussion on spectral and off normal calculation of double glass units properties taking care of polarization effects. Then the state of the art on existing predictive algorithms for coated glazing angular dependency and a comparison of models with experimental data on a selection of advanced glazing are presented.

An experimental spectral and angular characterization of electrochromic glazing and components for external shading devices are included respectively in Chapter 4 and Chapter 5. The description of the optical experimental apparatus used is given in appendix A.

In Chapter 6 is discussed a model for the determination of the solar factor of a system combining glazing with internal Venetian blinds originally developed by Tilmann Kuhn [30] at Fraunhofer ISE in Freiburg (Germany). The original version presents two parameters whose values are deduced from an experimental off normal characterization of glazing and from a direct calorimeter measurement on the window system through a best fit procedure. In order to obtain a fully predictive model, thus to restrict the needed input to data that can be generally provided by the manufactures or found in software databases (i.e. the optical spectral properties at normal incidence) implementation with angular predictive algorithms for coated glazing is discussed and an extension of the thermal problem formulation is proposed. Moreover, an additional broad band formulation is introduced to solve the optical spectral problem. A case study of window system optimized for daylight application has been selected and a sensitivity analysis and a wide experimental validation based on direct calorimetric measurements are included. The description of the calorimeter experimental apparatus is given in appendix B.
Chapter 2

Glazing and shading: generalities and standards

2.1 Glazing

We include in this section some optics fundamentals (see also [3] and [8]) on the interaction of electromagnetic radiation with plane surfaces, that are typically of interest in glazing physic. We will also introduce our notation according to current European Normative on glazing optical properties EN410 [10].

2.1.1 Optics fundamentals

When an electromagnetic radiation of a certain wavelength impinges upon a plane interface between two optically different materials, respectively with $N_1$ and $N_2$ complex indexes of refraction, Snell’s Law states that:

$$N_1(\lambda) \sin \theta_1 = N_2(\lambda) \sin \theta_2$$

We call:

- $r$, amplitude reflection coefficient, the ratio between the amplitudes of the reflected (back) and the incident electromagnetic waves.

- $t$, amplitude transmission coefficient, the ratio between the amplitudes of the transmitted (forward) and the incident electromagnetic waves.

For oblique incidence $r$ and $t$ depend on the polarization mode of the incidence radiation. The incident electromagnetic wave can be represented as superposition of two polarization modes:
• *s*-polarized, this is the situation in which the Electric field is perpendicular (from the German “*senkrecht*”) to the plane of incidence, also called *TE*-mode.

• *p*-polarized, this is the situation in which the Electric field is parallel to the plane of incidence, also called *TM*-mode.

Using subscript *s* and *p* for the polarization modes *r* and *t* are functions of $\theta_1$, $N_1(\lambda)$ and $N_2(\lambda)$ (deriving $\theta_2$ from Snell’s Law 2.1) and are given by the Fresnel’s Formulas:

\[
\begin{align*}
    r_s &= \frac{N_1 \cos \theta_1 - N_2 \cos \theta_2}{N_1 \cos \theta_1 + N_2 \cos \theta_2} \\
    r_p &= \frac{N_2 \cos \theta_1 - N_1 \cos \theta_2}{N_2 \cos \theta_1 + N_1 \cos \theta_2} \\
    t_s &= \frac{2N_1 \cos \theta_1}{N_1 \cos \theta_1 + N_2 \cos \theta_2} \\
    t_p &= \frac{2N_2 \cos \theta_1}{N_2 \cos \theta_1 + N_1 \cos \theta_2}
\end{align*}
\]

When considering the energy carried by an electromagnetic radiation of a certain wavelength, we use symbols $\rho$ and $\tau$ to denote the fractions of incoming energy that are respectively reflected and transmitted through the interface. It can be shown that:

\[
\begin{align*}
    \rho_{p/s} &= \frac{t_{p/s}^2}{r_{p/s}^2} \quad (2.2) \\
    \tau_{p/s} &= \frac{N_2 \cos \theta_2}{N_1 \cos \theta_1} \cdot t_{p/s}^2 \quad (2.3)
\end{align*}
\]

**Brewster’s angle** At this angle the radiation reflected from a interface between two dielectric media is completely *s*-polarized. From Fresnel’s equations 2.2 we can derive for the case in which the index refraction of the incidence medium is real, $N_1 = n_1$, the following formula:

\[
\Theta_B = \arctan \frac{n_2}{n_1} \quad (2.4)
\]

For instance for an interface between air and standard clear glass ($n_2 = 1.526$) the value of the Brewster angle is $\theta_B = 57^\circ$. 
Figure 2.1: Solar and Light weight functions deduced by standardized Solar global irradiance on Earth, $S(\lambda)$, and Daylight illuminance spectra, $D(\lambda)$, and normalized to their maximal values.

### 2.1.2 Energy and visual properties

**Spectrum of solar irradiation on Earth and human eye-sensitivity**

Solar Irradiation on Earth is composed of a direct and a diffuse contribute due to scattering by atmospheric particles. Direct and diffuse components have different spectral distributions. Typically Rayleigh scattering is responsible for blue sky since scattering is larger for shorter wavelengths. Moreover the spectrum of solar irradiation on Earth shows absorption peaks due to the molecular gas present in the atmosphere. At large solar zenith angle the equivalent "air mass" crossed by Solar radiation increases and as a consequence the diffuse contribute and the absorption phenomena are larger. This is also an effect that should be investigated on angular dependency of glazing properties. In this study we refer for simplicity to the European Standard[10], where a fixed Global Solar Irradiance Spectrum is assumed in all estimation of solar properties, which means that we assume the same spectral composition of solar radiation irrespective of the zenith angle.

Visible radiation is confined between $380\text{nm}$ and $780\text{nm}$. In this range according to standardized solar spectrum we find $57\%$ of solar energy reaching the Earth’s surface, only a few percent is in the Ultraviolet (UV) band while the rest, about $40\%$, is in the Near Infrared (NIR) band.
Optical properties  We consider here a general semitransparent plane object (a simple glass or a glazing system) and for a radiation that impinges on it at a certain angle $\theta$ and wavelength $\lambda$, with a specified polarization state, we define the fractions of incoming energy that are transmitted, reflected and absorbed as:

- $\tau(\lambda, \theta)_{s/p} = \text{spectral directional - hemispherical transmittance}$
- $\rho(\lambda, \theta)_{s/p} = \text{spectral directional - hemispherical transmittance}$
- $\alpha(\lambda, \theta)_{s/p} = \text{spectral directional - hemispherical transmittance}$

which satisfy the relation:

$$\tau(\lambda, \theta)_{s/p} + \rho(\lambda, \theta)_{s/p} + \alpha(\lambda, \theta)_{s/p} = 1 \quad (2.5)$$

These quantities refer to properties specific of the devices and are independent from the source spectrum and from the detector sensitivity ($s/p$ stands for the polarization mode of the incoming radiation, when it is omitted properties refer to unpolarized radiation). They are fundamental to characterize a simple or complex device (i.e. a single glass) or to deduce the properties of an assembled system from its individual components (i.e. a double glass unit).

In order to evaluate the fraction of total energy reflected, absorbed or directly transmitted by a specific device the spectrum of the radiation source and its angular dependency have also to be known.

So to consider "solar" or "light" angular optical properties of a device we will refer to a spectral integration of the device properties and we will make use of the following symbols and formulas:

**Solar direct transmittance**

$$\tau_e(\theta) = \frac{\int S(\lambda) \tau(\lambda, \theta) d\lambda}{\int S(\lambda) d\lambda} \quad (2.6)$$

**Light transmittance**

$$\tau_v(\theta) = \frac{\int D(\lambda) \tau(\lambda, \theta) d\lambda}{\int D(\lambda) d\lambda} \quad (2.7)$$

where $S(\lambda)$ and $D(\lambda)$ correspond to spectra of solar irradiation and human eye sensitivity.
**Total solar energy transmittance**  Commonly described also with the name *Solar factor* or *g – value*. This is the main performance parameter for solar control devices since it gives the fraction of total solar energy transmitted through a semitransparent device that separates internal from external environment. It considers the radiation which is transmitted directly (i.e. with the same wavelength) and the secondary heat flux that is driven by the increase of the device temperature due to the absorbed radiation. The quote of the secondary thermal flux that flows inside, \( q_i \), is added to the *direct solar transmittance* to give the *g – value*.

\[
g = \tau_e + q_i
\]  

(2.8)

For a single pane \( q_i \) the is proportional to the absorption \( \alpha_e \) and inversely proportional to the thermal resistance which faces outside normalized on the total resistance, \( N_t \), and neglecting the conductive resistance in the pane is given by:

\[
q_i = N_t \alpha_e = \frac{R_{out}}{R_{tot}} \alpha_e = \frac{h_i}{h_i + h_e}
\]  

(2.9)

where \( h_e \) and \( h_i \) are respectively the external and the internal convective-radiative heat transfer.

According to EN410 standard boundary conditions are:

\[
h_e = 23 \text{ W/(m}^2\text{K)} \quad h_i = 3.6 + 4.4\frac{\epsilon_i}{0.837} \quad \text{W/(m}^2\text{K)}
\]  

(2.10)

where \( \epsilon_i \) is the corrected emissivity in the inside surface.

For a double glass unit the secondary heat transfer can be calculated by use of the following formula:

\[
q_{i,dgu} = N_1 \alpha_{e,1} + N_2 \alpha_{e,2} = \frac{U}{h_e} \cdot \alpha_{e,1} + (1 - \frac{U}{h_i}) \alpha_{e,2}
\]  

(2.11)

where \( \alpha_{e,1} \) and \( \alpha_{e,2} \) are respectively the absorption in the outer and inner panes.
2.2 Glazing and Shading devices

2.2.1 Angles definitions

The discussion of a complex window system which includes blinds involves the use of a number of angles whose definitions are reported below for clarity (see also [2]).

- \( \theta_z \) **Zenith angle**, the angle between the vertical and the line to the Sun.
- \( \alpha_s \) **Solar altitude**, the complement of the zenith angle.
- \( \gamma_s \) **Solar azimuth**, whose value is zero if the projection of the sun line on the horizontal surface is in the south direction.
- \( \gamma \) **Surface azimuth**, (orientation) null if the projection of the normal to the surface is in the south direction.
- \( \beta \) **Surface inclination**, the angle between the plane of the surface and the horizontal. \((\beta_k \text{ will be used to indicate blinds inclination, or slat-angle}).\)
- \( \tilde{\gamma} \) **Relative azimuth**, here defined as \( \tilde{\gamma} = \gamma_s - \gamma \).
- \( \theta \) **Incidence angle**, the angle between the normal to the surface and the direction of the radiation (see 2.2.1). For vertical surfaces is given by

\[
\theta = \arccos (\cos \alpha_s \cos \tilde{\gamma}) \tag{2.12}
\]

- \( \alpha_p \) **Profile angle**, the projection of the solar altitude on a vertical plane that contain the normal to the surface in question (see 2.2.1). For vertical surfaces is given by

\[
\alpha_p = \arctan \left( \frac{\tan \alpha_s}{\cos \tilde{\gamma}} \right) \tag{2.13}
\]
Figure 2.2: representation of main angles definition ([2])

Figure 2.3: Solar altitude angle $\alpha_s$ ($\widehat{BAC}$) and profile angle $\alpha_p$ ($\widehat{DEF}$) for a surface R ([2])
2.2.2 Standards

For the determination of the solar factor of a window system including shading device a detailed algorithm which makes use of iterative thermal calculations is described in standard ISO15099 [20] and implemented in WIS software (Window Information System).

We present here the simplified method included in the Europea Normative EN13363-1 ([26]) for a window system composed of an exterior glazing and an interior shading device. A proposal for a Reference method, prEN13363-2, is also in developing phase within the CEN.

According to formulas in EN13363-1 the Total solar energy transmittance is given by:

\[ g_{\text{tot}} = g_{\text{glz}} (1 - g_{\text{glz}} \rho_{e,\text{shd}} - \alpha_{e,\text{shd}} \frac{G}{G_2}) \] (2.14)

where \( G \) can be interpreted as the total thermal transmittance of the system and is defined as

\[ G \equiv \frac{1}{U} \frac{1}{G_2} \quad [W/m^2K] \] (2.15)

where \( U \) is the thermal transmittance of the glazing and \( G_2 = 18W/(m^2K) \) is assumed as fixed valued for the thermal transmittance of the blinds; the two thermal resistances are considered in series.

For a venetians blinds shading system in closed position the transmittance, absorption and reflectance of the individual blinds are assumed: \( \tau_{\text{shd}} = \tau_{\text{bld}} \) and \( \rho_{\text{shd}} = \rho_{\text{bld}} \).

If the blinds are tilted at 45° and there is no direct radiation crossing the venetians system, then a simple correlation is proposed to take care of multi-reflections of diffuse and redirected radiation on the blinds:

\[ \tau_{e,\text{shd}}(45^\circ) = 0.65 \tau_{e,\text{bld}} + 0.15 \rho_{e,\text{bld}} \]

\[ \rho_{e,\text{shd}}(45^\circ) = \rho_{e,\text{bld}}[0.75 + 0.70 \tau_{e,\text{bld}}] \] (2.16)
Chapter 3

Advanced real glazing: simplified calculations and angular dependency

In this chapter we consider different simplification on standard calculation and existing models for predicting the dependency of glazing optical properties from angle of incidence. The described algorithms are tested on a case study composed by a set of single and double glass units. For each individual pane an experimental characterization of spectral optical properties at normal incidence and at 60° incidence has been provided by Fraunhofer ISE. The set includes samples with different coatings and produced by different companies. All these samples are commercially available. We gratefully acknowledge the Fraunhofer ISE for giving rights to use and publish this data.
3.1 Description of the case studies

In the table below the individual panes are listed with their coating typologies:

<table>
<thead>
<tr>
<th>sample number</th>
<th>coating typology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>none</td>
</tr>
<tr>
<td>2</td>
<td>single silver</td>
</tr>
<tr>
<td>3</td>
<td>double silver (A)</td>
</tr>
<tr>
<td>4</td>
<td>double silver (B)</td>
</tr>
<tr>
<td>5</td>
<td>hard coating</td>
</tr>
</tbody>
</table>

The first sample is a standard clear glass and is included mainly to create typical double units in combination with coated glass. The two "double silver" coated glasses are renamed A and B since they are provided by different companies.

A Silver layer in the coating structure provides low emissivity and partial selectivity (sample 2). Coatings with double silver layers (in samples 3 and 4) reach the highest performances in spectral selectivity, combining very low NIR-emissivity (0.04) and very high NIR reflectance due to interference mechanism.

The last sample (number 5) is also used in solar control applications. It has the advantage that it is mechanically more stable and heat resistant and it is suitable also for many application and industrial processes. On the contrary it has the disadvantage that absorption is more important and, as a consequence, the index of selectivity $\tau_v/g$ is lower. Moreover it has a quite large Infrared (IR) emissivity and so to improve the thermal resistance in the double glass unit it can be combined with a Low-emissive coated glass (sample 2).

We include at the end of this section graphs of spectral properties at normal incidence for each individual pane. See figures: 3.2, 3.3, 3.4, 3.5, 3.6.

Starting from these five individual panes (samples) we virtually create a set of six double glass units (dgu) that includes an Heat Mirror typology and a certain number of high performance Solar Control glazing.

<table>
<thead>
<tr>
<th>name</th>
<th>external pane</th>
<th>gas fill</th>
<th>internal pane</th>
<th>$U_{c.o.g.}(\frac{W}{m^2K})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Clear</td>
<td>sample 1</td>
<td>16mm Air</td>
<td>sample 1</td>
<td>2.6</td>
</tr>
<tr>
<td>Heat Mirror</td>
<td>sample 1</td>
<td>16mm Argon</td>
<td>sample 2</td>
<td>1.12</td>
</tr>
<tr>
<td>Solar Control A</td>
<td>sample 3</td>
<td>16mm Argon</td>
<td>sample 1</td>
<td>1.12</td>
</tr>
<tr>
<td>Solar Control B</td>
<td>sample 4</td>
<td>16mm Argon</td>
<td>sample 1</td>
<td>1.12</td>
</tr>
<tr>
<td>Solar Control C</td>
<td>sample 5</td>
<td>16mm Air</td>
<td>sample 1</td>
<td>2.6</td>
</tr>
<tr>
<td>Solar Control D</td>
<td>sample 5</td>
<td>16mm Argon</td>
<td>sample 2</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Figure 3.1: Heat Mirror and Solar Control configurations with coating respectively in second and third position.

Figure 3.2: Sample 1 - Clear Glass: Spectrum of optical properties at normal incidence
Figure 3.3: Sample 2 - Single Silver coated glass: Spectrum of optical properties at normal incidence

Figure 3.4: Sample 3 - Double Silver (A) coated glass: Spectrum of optical properties at normal incidence
Figure 3.5: Sample 4 - Double Silver (B) coated glass: Spectrum of optical properties at normal incidence

Figure 3.6: Sample 5 - "hard coated" glass: Spectrum of optical properties at normal incidence
3.2 Recommendations on calculations

In this section two variants on calculations of optical properties for double unit glazing are described and tested with respect to standard EN410.

3.2.1 Influence of broad bands calculations

A number of existing window simulation software use only solar and light broad band values to characterize their glass component. In many cases the use of spectral properties at normal incidence as input for the calculation is possible and in principle it should be recommended, since it allows more accuracy in the results. On the other hand broad band calculation has some advantage because it reduces drastically the number of data that have to be processed. For instance in ray-tracing simulation.

In same cases a multi-band approach could be a good compromise between the need of accuracy and the desired limit of computational efforts. The suitability of a multi-band approach is based on its capability to be standardized and to approximate spectral curves with a step functions. Since spectral selectivity in solar control coated glass mainly discriminate among UV (Ultraviolet), VIS (Visible) and NIR (Near Infrared) radiation (see for example figures 3.4, 3.5, 3.6) we propose hear a three bands approach and test its accuracy.

**Three bands calculation** for a generic X property we define:

\[
X_{UV-e} = \frac{\int_{380nm}^{300nm} S(\lambda) X(\lambda) d\lambda}{\int_{380nm}^{300nm} S(\lambda) d\lambda} \\
X_{VIS-e} = \frac{\int_{780nm}^{780nm} S(\lambda) X(\lambda) d\lambda}{\int_{780nm}^{780nm} S(\lambda) d\lambda} \\
X_{NIR-e} = \frac{\int_{2500nm}^{2500nm} S(\lambda) X(\lambda) d\lambda}{\int_{2500nm}^{2500nm} S(\lambda) d\lambda}
\]

\[
w_{UV-e} = \frac{\int_{380nm}^{290nm} S(\lambda) d\lambda}{\int_{2500nm}^{300nm} S(\lambda) d\lambda} = 3.4\% \\
w_{VIS-e} = \frac{\int_{780nm}^{780nm} S(\lambda) d\lambda}{\int_{2500nm}^{300nm} S(\lambda) d\lambda} = 57.0\% \\
w_{NIR-e} = \frac{\int_{2500nm}^{2500nm} S(\lambda) d\lambda}{\int_{2500nm}^{300nm} S(\lambda) d\lambda} = 39.6\%
\]

\[
X_{dgu}^{3bands} = w_{UV-e} X_{UV-e} + w_{VIS-e} X_{VIS-e} + w_{NIR-e} X_{NIR-e}
\]
**Input:** Three bands characterization of individual panes.

(Values obtained from detailed spectral data through the use of Formulas 3.1 and 3.2)

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>$\tau_e(0^\circ)$</th>
<th>$\rho_e(0^\circ)$</th>
<th>$\tau_v(0^\circ)$</th>
<th>$\rho_v(0^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 410</td>
<td>0.823</td>
<td>0.083</td>
<td>0.893</td>
<td>0.088</td>
</tr>
<tr>
<td>UV-e</td>
<td>0.528</td>
<td>0.071</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIS-e</td>
<td>0.874</td>
<td>0.086</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIR-e</td>
<td>0.776</td>
<td>0.078</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Clear glass.*

<table>
<thead>
<tr>
<th>Sample 2</th>
<th>$\tau_e(0^\circ)$</th>
<th>$\rho_e(0^\circ)$</th>
<th>$\rho'_e(0^\circ)$</th>
<th>$\tau_v(0^\circ)$</th>
<th>$\rho_v(0^\circ)$</th>
<th>$\rho'_v(0^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 410</td>
<td>0.515</td>
<td>0.325</td>
<td>0.236</td>
<td>0.789</td>
<td>0.095</td>
<td>0.125</td>
</tr>
<tr>
<td>UV%</td>
<td>0.243</td>
<td>0.269</td>
<td>0.106</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIS%</td>
<td>0.713</td>
<td>0.131</td>
<td>0.144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIR%</td>
<td>0.252</td>
<td>0.609</td>
<td>0.381</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Glass with low emissive coating.*

<table>
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<th>$\rho_e(0^\circ)$</th>
<th>$\rho'_e(0^\circ)$</th>
<th>$\tau_v(0^\circ)$</th>
<th>$\rho_v(0^\circ)$</th>
<th>$\rho'_v(0^\circ)$</th>
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<tr>
<td>EN 410</td>
<td>0.309</td>
<td>0.249</td>
<td>0.428</td>
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<td>UV-e</td>
<td>0.109</td>
<td>0.118</td>
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</tr>
<tr>
<td>VIS-e</td>
<td>0.500</td>
<td>0.136</td>
<td>0.160</td>
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<tr>
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</table>

*Selective glass with "double silver" coating A.*

<table>
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<tr>
<th>Sample 4</th>
<th>$\tau_e(0^\circ)$</th>
<th>$\rho_e(0^\circ)$</th>
<th>$\rho'_e(0^\circ)$</th>
<th>$\tau_v(0^\circ)$</th>
<th>$\rho_v(0^\circ)$</th>
<th>$\rho'_v(0^\circ)$</th>
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<tr>
<td>UV-e</td>
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<td>0.214</td>
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<tr>
<td>VIS-e</td>
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<td>0.099</td>
<td>0.146</td>
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<td>NIR-e</td>
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<td>0.362</td>
<td>0.765</td>
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</table>

*Selective glass with "double silver" coating B.*

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<tr>
<th>Sample 5</th>
<th>$\tau_e(0^\circ)$</th>
<th>$\rho_e(0^\circ)$</th>
<th>$\rho'_e(0^\circ)$</th>
<th>$\tau_v(0^\circ)$</th>
<th>$\rho_v(0^\circ)$</th>
<th>$\rho'_v(0^\circ)$</th>
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<tr>
<td>EN 410</td>
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<td>0.116</td>
<td>0.145</td>
<td>0.533</td>
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<td>0.115</td>
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<td>UV-e</td>
<td>0.330</td>
<td>0.157</td>
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<tr>
<td>VIS-e</td>
<td>0.515</td>
<td>0.139</td>
<td>0.115</td>
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<td>NIR-e</td>
<td>0.363</td>
<td>0.079</td>
<td>0.184</td>
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</tr>
</tbody>
</table>

*Solar control glass with "hard coating".*
**Output:** comparison of results for double glass units from different calculation procedure: EN410 (spectral), three bands and solar/light band

<table>
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<tr>
<th></th>
<th>$\tau_e(0^\circ)$</th>
<th>$\rho_e(0^\circ)$</th>
<th>$\rho_e'(0^\circ)$</th>
<th>$\tau_v(0^\circ)$</th>
<th>$\rho_v(0^\circ)$</th>
<th>$\rho_v'(0^\circ)$</th>
<th>$g(0^\circ)$</th>
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<tr>
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<td><strong>Solar control A</strong></td>
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<td>0.262</td>
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<td>0.541</td>
<td>0.137</td>
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<td>0.137</td>
<td>0.171</td>
<td>0.307</td>
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<tr>
<td>EN 410</td>
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<td>0.215</td>
<td>0.344</td>
<td>0.496</td>
<td>0.085</td>
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</tr>
<tr>
<td>Solar control D</td>
<td>$\tau_e(0^\circ)$</td>
<td>$\rho_e(0^\circ)$</td>
<td>$\rho'_e(0^\circ)$</td>
<td>$\tau_v(0^\circ)$</td>
<td>$\rho_v(0^\circ)$</td>
<td>$\rho'_v(0^\circ)$</td>
<td>$g(0^\circ)$</td>
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<td>------------------</td>
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</tr>
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<td>0.277</td>
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</tr>
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</table>

**Conclusions** Comparisons show that "one (solar or light) band" calculations in some cases can lead to significant relative errors (about 5%). It is particularly so for Solar Control D, where we combine two panes which have spectral selectivity. The influence of broad band approximation is clearly very small when one of the two panes has "grey" - i.e. not spectral - properties, for example in combination with clear glass. Anyway in all the cases three bands calculation show high accuracy with respect to standard EN 410, with relative errors often smaller than ±1%.
3.2.2 Influence of distinct calculation for $p$ & $s$ polarization modes

This section deals with a problem that was first introduced by Arne Roos in [4] where he concludes with recommendations to use the polarized properties when calculating glazing properties at off normal incidence. We present here a detailed analysis of the errors by comparing the results of the "exact" calculation (which takes into account the polarization effects) and of "simplified" calculations (which ignores polarization effects) for our selection of double glass units.

**Theoretical prescriptions**  At normal incidence the following formula to calculate the spectral transmittance of a double glass unit is well established in literature.

$$\tau_{dgu}(\lambda, 0) = \frac{\tau_1(\lambda, 0)\tau_2(\lambda, 0)}{1 - \rho'_1(\lambda, 0)\rho_2(\lambda, 0)} \quad (3.3)$$

It is also well established that when considering off normal incidence this formula doesn’t extend directly to spectral angular properties of single panes for unpolarized light. In fact it applies to each set of spectral properties separately for each polarization mode.

$$\tau_{dgu,s/p}(\lambda, \theta) = \frac{\tau_{1,s/p}(\lambda, \theta)\tau_{2,s/p}(\lambda, \theta)}{1 - \rho'_{1,s/p}(\lambda, \theta)\rho_{2,s/p}(\lambda, \theta)}$$

$$\tau_{dgu}(\lambda, \theta) = \frac{1}{2} [t_{dgu,p}(\lambda, \theta) + t_{dgu,s}(\lambda, \theta)] \quad (3.4)$$

The reason is that even if the radiation incident on the first surface is unpolarized, when the incidence angle is different from zero the radiation transmitted by the first pane is partially polarized.

This means that in principle to calculate angular properties of a double or triple glass unit for each non zero incidence angle and for each pane a set of six spectral data is necessary $(\tau_p(\lambda, \theta), \rho_p(\lambda, \theta), \rho'_p(\lambda, \theta)\tau_s(\lambda, \theta), \rho_s(\lambda, \theta), \rho'_s(\lambda, \theta))$. Such an experimental characterization can be very costly. Moreover in the next chapter we will discuss about modelling angular properties and here we just anticipate that most common softwares and algorithms predict and process only properties related to unpolarized radiation. This fact justifies our present question about how large is the error generated by a simplified calculation in which polarization effects are not considered. We consider here this simplification for the transmittance, deriving it as a naif extension of 3.3, omitting for brevity spectral and angular specifications:

$$\overline{\tau}_{dgu} = \frac{\tau_1\tau_2}{1 - \rho'_1\rho_2} \quad (3.5)$$
**Error analysis** We expect that errors will be related to the degree of polarization induced by single panes so we define:

\[
0 < \epsilon_i \equiv \frac{\tau_{i,p} - \tau_{i,s}}{\tau_{i,p} + \tau_{i,s}} = \frac{\tau_{i,p} - \tau_{i,s}}{2\tau_i} < 1 \quad i = 1, 2 \tag{3.6}
\]

and

\[
0 < \delta_i \equiv \frac{\rho_{i,s} - \rho_{i,p}}{\rho_{i,p} + \rho_{i,s}} = \frac{\rho_{i,s} - \rho_{i,p}}{2\rho_i} < 1 \quad i = 1, 2 \tag{3.7}
\]

where physical knowledge has suggested to invert the order in the differences to get positive quantities. So we can rewrite:

\[
\tau_{i,p} = \tau_i(1 + \epsilon_i) \quad i = 1, 2 \tag{3.8}
\]

\[
\tau_{i,s} = \tau_i(1 - \epsilon_i) \quad i = 1, 2 \tag{3.9}
\]

\[
\rho_{i,p} = \rho_i(1 - \delta_i) \quad i = 1, 2 \tag{3.10}
\]

\[
\rho_{i,s} = \rho_i(1 + \delta_i) \quad i = 1, 2 \tag{3.11}
\]

and by substitution in 3.4:

\[
\tau_{dgu,p} = \frac{\tau_1\tau_2[1 + (\epsilon_1 + \epsilon_2) + \epsilon_1\epsilon_2]}{1 - \rho_1'\rho_2[(1 - (\delta_1' + \delta_2) + \delta_1'\delta_2)]}
\]

\[
\tau_{dgu,s} = \frac{\tau_1\tau_2[1 - (\epsilon_1 + \epsilon_2) + \epsilon_1\epsilon_2]}{1 - \rho_1'\rho_2[1 + (\delta_1' + \delta_2) + \delta_1'\delta_2]}
\]

\[
\tau_{dgu} = \frac{1}{2} \tau_1\tau_2 \left[ (1 - \eta - \eta\delta_1'\delta_2) + \eta(\delta_1' + \delta_2) \right] + \frac{(1 + \epsilon_1\epsilon_2) - (\epsilon_1 + \epsilon_2)}{(1 - \eta - \eta\delta_1'\delta_2) - \eta(\delta_1' + \delta_2)}
\]

\[
= \frac{\tau_1\tau_2}{1 - \eta} \cdot \frac{(1 + \epsilon_1\epsilon_2)(1 - \eta - \eta\delta_1'\delta_2) - \eta(\epsilon_1 + \epsilon_2)(\delta_1' + \delta_2)}{1 - 2\eta\delta_1'\delta_2 + \eta^2[(\delta_1'\delta_2)^2 - (\delta_1' + \delta_2)^2]}
\]

\[
= \frac{\tau_{dgu}}{1 - 2(\delta_1'\delta_2)\zeta + (\delta_1'\delta_2)^2 - (\delta_1' + \delta_2)^2\zeta^2} \tag{3.12}
\]

where

\[
\eta \equiv \rho_1'\rho_2 \tag{3.13}
\]

\[
\zeta \equiv \frac{\eta}{1 - \eta} = \frac{\rho_1'\rho_2}{1 - \rho_1'\rho_2} \tag{3.14}
\]
Typically \( \eta \) is not larger than 0.5 and as a consequence \( 0 < \zeta < 1 \). Based on this we expand Formula 3.12 in sum of powers of \( \zeta \) up to the second order. We will check afterwards that \( \eta \) and \( \zeta \) are small enough to ensure that this is a consistent and suitable approximation.

\[
\tau_{dgu} = \tau_{dgu} \cdot \left\{ 1 + \epsilon_1 \epsilon_2 + \zeta[(1 + \epsilon_1 \epsilon_2)\delta_1' \delta_2 - (\delta_1' + \delta_2)(\epsilon_1 + \epsilon_2)] + \zeta^2[(\delta_1' \delta_2)^2(1 + \epsilon_1 \epsilon_2) + (\delta_1' + \delta_2)^2(1 + \epsilon_1 \epsilon_2) - 2\delta_1' \delta_2(\delta_1' + \delta_2)(\epsilon_1 + \epsilon_2)] + o(\zeta^2) \right\}
\]

We see that the relative error (sum of terms in column in 3.15) on the determination of the double glass unit transmittance mainly depend on the product \( \epsilon_1 \cdot \epsilon_2 \) of single relative polarization degree for the individual transmittance. This also show that the simplified calculation can lead to systematic underestimations. Terms of first and second order in \( \zeta \) have no defined sign and it can be show, that even if \( \delta_i \) is quite large same errors compensation exist. The values of \( \epsilon_i \) depends on the angle of incidence and show a peak only around the (pseudo) Brewster’s angle 2.4.

In the following tables we present first the degree of polarization of each pane at 60° evaluating \( \epsilon_i \) and \( \delta_i \) for broad band properties, visual and solar. Then comparing simplified and exact calculation we will also compare the factive relative error with our evaluation up to second order, named \( \varepsilon \) and derived using formula 3.15 with \( \epsilon_{i,e/v} \) and \( \delta_{i,e/v} \) as input.

**Input**  Characterization of single panes:

<table>
<thead>
<tr>
<th>Input</th>
<th>Characterization of single panes:</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample 1</td>
<td>( \tau_e(60°) )</td>
</tr>
<tr>
<td>p</td>
<td>0.886</td>
</tr>
<tr>
<td>s</td>
<td>0.544</td>
</tr>
<tr>
<td>average</td>
<td>0.740</td>
</tr>
<tr>
<td>( \epsilon_s )</td>
<td>( \delta_s )</td>
</tr>
<tr>
<td>0.20</td>
<td>0.99</td>
</tr>
</tbody>
</table>

<p>| sample 2 | ( \tau_e(60°) )  | ( \rho_e(60°) )  | ( \rho'_e(60°) )  | ( \tau_v(60°) )  | ( \rho_v(60°) )  | ( \rho'_v(60°) )  |
| p     | 0.471  | 0.320  | 0.205  | 0.736  | 0.145  | 0.144  |
| s     | 0.368  | 0.431  | 0.342  | 0.650  | 0.190  | 0.247  |
| average | 0.420  | 0.376  | 0.274  | 0.693  | 0.168  | 0.195  |
| ( \epsilon_s )  | ( \delta_s )  | ( \delta'_s )  | ( \epsilon_v )  | ( \delta_v )  | ( \delta'_v )  |
| 0.12    | 0.15   | 0.25   | 0.06   | 0.13   | 0.26   |</p>
<table>
<thead>
<tr>
<th>Sample</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.263</td>
<td>0.225</td>
<td>0.453</td>
<td>0.536</td>
<td>0.097</td>
<td>0.163</td>
</tr>
<tr>
<td>s</td>
<td>0.198</td>
<td>0.324</td>
<td>0.526</td>
<td>0.426</td>
<td>0.214</td>
<td>0.214</td>
</tr>
<tr>
<td>average</td>
<td>0.231</td>
<td>0.274</td>
<td>0.490</td>
<td>0.481</td>
<td>0.156</td>
<td>0.188</td>
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<td>0.18</td>
<td>0.07</td>
<td>0.11</td>
<td>0.37</td>
<td>0.14</td>
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<tr>
<td>$\delta_s$</td>
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<td>0.18</td>
<td>0.07</td>
<td>0.11</td>
<td>0.37</td>
<td>0.14</td>
</tr>
<tr>
<td>$\delta'_s$</td>
<td>0.14</td>
<td>0.18</td>
<td>0.07</td>
<td>0.11</td>
<td>0.37</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.275</td>
<td>0.157</td>
<td>0.336</td>
<td>0.580</td>
<td>0.028</td>
<td>0.039</td>
</tr>
<tr>
<td>s</td>
<td>0.161</td>
<td>0.293</td>
<td>0.576</td>
<td>0.339</td>
<td>0.108</td>
<td>0.315</td>
</tr>
<tr>
<td>average</td>
<td>0.218</td>
<td>0.225</td>
<td>0.456</td>
<td>0.459</td>
<td>0.118</td>
<td>0.177</td>
</tr>
<tr>
<td>$\epsilon_s$</td>
<td>0.26</td>
<td>0.30</td>
<td>0.26</td>
<td>0.26</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>$\delta_s$</td>
<td>0.26</td>
<td>0.30</td>
<td>0.26</td>
<td>0.26</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>$\delta'_s$</td>
<td>0.26</td>
<td>0.30</td>
<td>0.26</td>
<td>0.26</td>
<td>0.76</td>
<td>0.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.504</td>
<td>0.040</td>
<td>0.021</td>
<td>0.629</td>
<td>0.044</td>
<td>0.011</td>
</tr>
<tr>
<td>s</td>
<td>0.249</td>
<td>0.240</td>
<td>0.351</td>
<td>0.327</td>
<td>0.262</td>
<td>0.322</td>
</tr>
<tr>
<td>average</td>
<td>0.376</td>
<td>0.140</td>
<td>0.186</td>
<td>0.478</td>
<td>0.153</td>
<td>0.167</td>
</tr>
<tr>
<td>$\epsilon_s$</td>
<td>0.34</td>
<td>0.71</td>
<td>0.89</td>
<td>0.32</td>
<td>0.71</td>
<td>0.94</td>
</tr>
<tr>
<td>$\delta_s$</td>
<td>0.34</td>
<td>0.71</td>
<td>0.89</td>
<td>0.32</td>
<td>0.71</td>
<td>0.94</td>
</tr>
<tr>
<td>$\delta'_s$</td>
<td>0.34</td>
<td>0.71</td>
<td>0.89</td>
<td>0.32</td>
<td>0.71</td>
<td>0.94</td>
</tr>
</tbody>
</table>

**Output**  Results of comparisons for double glass units:

<table>
<thead>
<tr>
<th>Double clear glasses</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$\eta(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>exact</td>
<td>0.596</td>
<td>0.211</td>
<td>0.717</td>
<td>0.239</td>
<td>0.660</td>
<td></td>
<td></td>
</tr>
<tr>
<td>simplified</td>
<td>0.569</td>
<td>0.238</td>
<td>0.685</td>
<td>0.271</td>
<td>0.632</td>
<td></td>
<td></td>
</tr>
<tr>
<td>relative error</td>
<td>-4.5%</td>
<td>-12.4%</td>
<td>-4.5%</td>
<td>13.4%</td>
<td>-4.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>-4.6%</td>
<td>-4.7%</td>
<td>-4.7%</td>
<td>13.4%</td>
<td>-4.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\zeta$</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat mirror</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$\eta(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>exact</td>
<td>0.343</td>
<td>0.356</td>
<td>0.306</td>
<td>0.587</td>
<td>0.274</td>
<td>0.268</td>
<td>0.438</td>
</tr>
<tr>
<td>simplified</td>
<td>0.338</td>
<td>0.361</td>
<td>0.310</td>
<td>0.582</td>
<td>0.276</td>
<td>0.275</td>
<td>0.478</td>
</tr>
<tr>
<td>relative error</td>
<td>-1.4%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>-0.9%</td>
<td>0.7%</td>
<td>2.6%</td>
<td>-1.0%</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>-1.6%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>-0.9%</td>
<td>0.7%</td>
<td>2.6%</td>
<td>-1.0%</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>
### Discussion and conclusions

From the previous table one can see that the errors $\varepsilon$ evaluated according to Formula 3.15, are in very good agreement with actual relative errors, that is the difference between "exact" and "simplified" calculation. This is also confirmed by the values of $\zeta$ that we have chosen as the parameter for the expansion of Formula 3.12. Some slight difference is due to broad band input for $\epsilon_i$ and $\delta_i$. This validates our formalism for the error analysis. The same approach can be extended to the reflectance and the solar factor error analysis with some lengthy calculation. Care should be taken in extending this method to triple glass units, only because the broad bands evaluation of $\epsilon_i$ and $\delta_i$ could have more influence on the results.

The comparisons show that the estimation of the magnitude of the relatives error for the solar transmittance is also valid for the solar factor, being on the safe side. In fact due
to compensation of errors between transmittance and absorptions the influence of simplified calculation on the solar factor is lower than its influence on the solar transmittance in all the presented cases.

According to our expectation the relative error on the solar factor is more important for combination of glasses whose properties present similarities in their angular dependency and in this case with ”effective” Brewster angle around 60° (Clear glass, Solar Control B and C).

One can see that $\delta_i$ values are very high for the clear glass, and for hard and double silver ”B” coated glasses. Actually this behavior was not expected for double silver coating typology. Silver based coating bring usually to low effective index of refraction and as a consequence lower values of the pseudo Brewster angle [21]. We have repeated this analysis for other types of double silver glasses obtaining as a result a behavior similar to the double silver A coating in our case study. This means that sample 3 is probably more ”representative” in its ”category” but also that some distinction should be done for coating provided by different manufactures and industrial process. We remind that in this case study samples 3 and 4 are produced by different companies.
3.3 Modelling angular dependency

In order to calculate the correct amount of solar energy which is transmitted through a glazing system, the solar factor and its angular dependency need to be known. In fact the most typical angle of incidence of solar radiation is in the range $45^\circ - 75^\circ$. This is also the range in which differences in the angular variation function among different coatings are largest. In principle the angular optical properties of a glass could be computed in a straightforward way by use of Fresnel Equations (2.2) and transfer matrix ([3]) if the complex index of refraction and thickness of each film and substrate were known. Unfortunately this knowledge on coating structure are typically not available. For a uniform clear or absorbing glass the index of refraction can be derived by solving the inverse problem at normal incidence [8]. This method is also named standard glass model and reported in [12]. For coated glass the inverse problem is much more complicated and has no analytical solution. In this context the issue of angular dependency of optical properties of coated glass has been object of a recent European project named ADOPT [14]. In this section we briefly describe and discuss performance of a "standard" algorithm and the main predictive algorithms validated within ADOPT project (see also [21]).

3.3.1 Review of existing models

<table>
<thead>
<tr>
<th>model</th>
<th>input</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHRAE reference (*)</td>
<td>$\tau(\lambda, 0), \rho(\lambda, 0)$</td>
<td>$\tau(\lambda, \theta), \rho(\lambda, \theta)$</td>
</tr>
<tr>
<td>Empirical model</td>
<td>$g, q-value$</td>
<td>$g(\theta)$</td>
</tr>
<tr>
<td>Hybrid Equivalent Uncoated Model (HEUM)</td>
<td>$\tau(\lambda, 0), \rho(\lambda, 0), \rho'(\lambda, 0)$</td>
<td>$\tau_{s/p}(\lambda, \theta), \rho_{s/p}(\lambda, \theta)$</td>
</tr>
<tr>
<td>Coating plus Substrate Characterization (**)</td>
<td>$\tau(\lambda, 0), \rho(\lambda, 0)$</td>
<td>$\tau_{s/p}(\lambda, \theta), \rho_{s/p}(\lambda, \theta)$</td>
</tr>
<tr>
<td>Characterization (**)</td>
<td>$\tau_{sub}(\lambda, 0), \rho_{sub}(\lambda, 0)$</td>
<td>$\tau_{s/p}(\lambda, \theta), \rho_{s/p}(\lambda, \theta)$</td>
</tr>
</tbody>
</table>

(*) adopted by WINDOW and OPTIC software, (**) implementing WIS software

ASHRAE reference model  This, described in [12], has been adopted by Window5 and Optic5 softwares for modelling angular dependency of optical properties of glazing systems. For clear glass it applies the general method introduced in [8], whose accuracy is very high, while for uncoated glass it applies a simple correlation. We present here the latter and consider it as a "default algorithm for coated glass". According to [12] the values predicted by this algorithm should be affected by relative errors in the range of $\pm 20\%$ at $60^\circ$ angle of incidence.

It consists of two couples of polynomial functions of the cosine of the angle of incidence and whose coefficients have been fitted from two reference cases: a clear and a bronze
glass. The first couple applies when the normal incidence transmittance is higher than 64.5%. The second couple applies in the other case.

\[
\begin{align*}
\tau(\lambda, \theta) &= \tau(\lambda, 0) \cdot t_{\text{ref}}(\theta) \\
\rho(\lambda, \theta) &= \rho(\lambda, 0) \cdot [1 - r_{\text{ref}}(\theta)] + r_{\text{ref}}(\theta)
\end{align*}
\]

where

\[
t_{\text{ref}}(\theta) = \sum_{m=0}^{4} t_m \cos^m \theta
\]

and

\[
r_{\text{ref}}(\theta) = \sum_{m=0}^{4} r_m \cos^m \theta - t_{\text{ref}}(\theta)
\]

with:

<table>
<thead>
<tr>
<th>Condition</th>
<th>m = 0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau(\lambda, 0) &gt; 0.645)</td>
<td>-0.0015</td>
<td>3.335</td>
<td>-3.840</td>
<td>1.460</td>
<td>0.0288</td>
</tr>
<tr>
<td></td>
<td>0.999</td>
<td>-0.563</td>
<td>2.043</td>
<td>-2.532</td>
<td>1.054</td>
</tr>
<tr>
<td>(\tau(\lambda, 0) \leq 0.645)</td>
<td>-0.002</td>
<td>2.813</td>
<td>-2.341</td>
<td>-0.05725</td>
<td>0.599</td>
</tr>
<tr>
<td></td>
<td>0.997</td>
<td>-1.868</td>
<td>6.513</td>
<td>-7.862</td>
<td>3.225</td>
</tr>
</tbody>
</table>

The algorithm applies to \(\tau & \rho\) and to \(\tau & \rho'\) and, of course, the same angular dependency are predicted for front and back reflectance, since the references cases (bronze or clear) are symmetric glasses.

**Hybrid equivalent uncoated model (HEUM)**

This algorithm has been introduced and described in detail by Marco Montecchi, Enrico Nichelatti e Pietro Polato in [22]. It is mainly based on the idea that a thick layer - or a combination of layers - with a suitable complex index of refraction can have the same angular dependency of a coated glass. The authors in [22] have developed this idea testing different equivalent combinations of dense and transparent slabs and they validated two schemes. The choice of the scheme depends on the value of the reflectivity at normal incidence on the coated surface, whether it is higher or lower then the reflectivity on a standard glass surface. We present here the MIX7 scheme, which corresponds to the case of higher reflectivity, since in the context of this work we are mainly interested in solar control and heat mirror glazing and not in anti-reflecting glazing.

The complex refractive index of the thick dense slabs, \(n(\lambda) - ik(\lambda)\), is deduced by minimization for each wavelength of the merit function \(MF(n, k)\), which is given by
Figure 3.7: MIX7 scheme: it is conceived as an average between a symmetric and an antisymmetric scheme.

\[ MF(\lambda, n, k) = \frac{1}{2} \left( \left[ \frac{\tau_{\text{exp}}(\lambda, 0) - \tau_{\text{mix7}}(\lambda, n, k, 0)}{\Delta \tau} \right]^2 + \left[ \frac{\rho_{\text{exp}}(\lambda, 0) - \rho_{\text{mix7}}(\lambda, n, k, 0)}{\Delta \rho} \right]^2 \right) \]  

(3.18)

where \( \tau_{\text{mix7}} \) and \( \rho_{\text{mix7}} \) are computed according to Fresnel equations (2.2) and MIX7 scheme in Figure 3.7, while \( \Delta \tau \) and \( \Delta \rho \) are experimental error bars.

Input values for the model are spectral optical properties of the coated glass at normal incidence. They are processed for both side according to 3.18, i.e for \( \tau & \rho \) and for \( \tau & \rho' \), deriving two suitable refractive indexes \( N = n - ik \) and \( N' = n' - ik' \) for the dense slab. Then Fresnel equations are used to derive:

\[
\begin{align*}
\tau(\lambda, \theta) &= \frac{1}{2} [\tau_{\text{mix7\_front}}(\lambda, n(\lambda), k(\lambda), \theta) + \tau_{\text{mix7\_back}}(\lambda, n'(\lambda), k'(\lambda), \theta)] \\
\rho(\lambda, \theta) &= \rho_{\text{mix7\_front}}(\lambda, n(\lambda), k(\lambda), \theta) \\
\rho'(\lambda, \theta) &= \rho_{\text{mix7\_back}}(\lambda, n'(\lambda), k'(\lambda), \theta)
\end{align*}
\]  

(3.19)

We underline that the two solutions for the complex refractive index from front and back side are mathematically independent. This is physically meaningless, since the transmittance should be the same from both sides. So the model assumes as the resulting value of the transmittance the arithmetic average of the two values (front and back) obtained.
from the calculation. One might say that this is a "pseudo" physical model and the refractive index derived has no physical correspondence with real coating or thin film materials. In fact in the equivalent scheme coherence effects are not considered, due to hypothesis of thick slabs.

**Empirical model** This model has been introduced by Arne Roos and Joakim Karlsson in [18]. It is based on an empirical parametric function for the angular dependency of the solar factor for different types of coated glazing. According to that the angular dependency of \( g \), \( g_{emp}(\theta) \), is modelled as:

\[
g_{emp}(\theta) = g(0) \cdot f_{emp}(\theta, p, q)
\]  

(3.20)

where

\[
f_{emp} = (1 - a \cdot z^\alpha - b \cdot z^\beta - c \cdot z^\gamma)
\]  

(3.21)

with:

- \( a = 8 \)
- \( b = 0.25/q \)
- \( c = (1 - a - b) \)
- \( \alpha = 5.2 + 0.7q \)
- \( \beta = 2 \)
- \( \gamma = (5.26 + 0.06p) + (0.73 + 0.04p) \cdot q \)

and

- \( z = \theta/90^\circ \)
- \( p = \) number of panes
- \( 1 \leq q \leq 10 \) depends on coating typology according to the following classification.
The advantage of this model is that it is of very practical use, even if some knowledge on the coating typology is needed and the list of categories and $q$-values needs to be updated when a new kind of glazing enters in the market. On the other hand its main disadvantage is the limitation to predicting only the solar factor angular dependency.

Glazing angular optical properties are necessary for instance to deduce surface temperatures, and generally they are also necessary to characterize the combination of different devices as glazing and shading in facade systems. It would be very useful to extend this approach deriving similar parametric functions for the angular dependency of the optical properties.

**Coating plus substrate model characterization** This model have been introduced by Ismael Rodrigues and Jose Molina ([27]). The algorithm proposed for coated glass is being implemented in W.I.S. Window Information System software and is briefly described in [7], even if in the current version (2.0.1) bugs have been reported.
3.3.2 Models comparison

We compare here the predictions of the models presented with the experimental data at 60° incidence angle for single glasses and double glass units. All broad band properties and solar factor have been calculated from spectral data according to EN410 ([10]).

Angular broad band properties of single glasses We first consider the single clear glass, sample 1, and compare the results of HEUM and the prediction of ASHRAE model, that includes "standard glass method" for clear glass and reference model for coated glasses, with the experimental value.

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.740</td>
<td>0.151</td>
<td>0.817</td>
<td>0.161</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>0.740</td>
<td>0.151</td>
<td>0.817</td>
<td>0.161</td>
</tr>
<tr>
<td>relative error</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>HEUM</td>
<td>0.741</td>
<td>0.151</td>
<td>0.817</td>
<td>0.161</td>
</tr>
<tr>
<td>relative error</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

The good agreement confirms our expectation on the accuracy of the standard method for clear glass and the consistency of our reproduction of HEUM algorithm.

The following tables contain the comparison between the predictions of ASHRAE model and HEUM for the single coated glasses.

<table>
<thead>
<tr>
<th>Sample 2</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\tau'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.420</td>
<td>0.376</td>
<td>0.274</td>
<td>0.693</td>
<td>0.168</td>
<td>0.195</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>0.451</td>
<td>0.376</td>
<td>0.293</td>
<td>0.703</td>
<td>0.174</td>
<td>0.202</td>
</tr>
<tr>
<td>relative error</td>
<td>+7%</td>
<td>0%</td>
<td>+7%</td>
<td>+1%</td>
<td>+3%</td>
<td>+4%</td>
</tr>
<tr>
<td>HEUM</td>
<td>0.479</td>
<td>0.351</td>
<td>0.268</td>
<td>0.713</td>
<td>0.159</td>
<td>0.185</td>
</tr>
<tr>
<td>relative error</td>
<td>+14%</td>
<td>-7%</td>
<td>-2%</td>
<td>+3%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample 3</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\tau'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.231</td>
<td>0.274</td>
<td>0.490</td>
<td>0.481</td>
<td>0.156</td>
<td>0.188</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>0.263</td>
<td>0.294</td>
<td>0.463</td>
<td>0.510</td>
<td>0.159</td>
<td>0.157</td>
</tr>
<tr>
<td>relative error</td>
<td>+14%</td>
<td>+7%</td>
<td>-5%</td>
<td>+6%</td>
<td>+2%</td>
<td>-16%</td>
</tr>
<tr>
<td>HEUM</td>
<td>0.276</td>
<td>0.273</td>
<td>0.447</td>
<td>0.522</td>
<td>0.160</td>
<td>0.154</td>
</tr>
<tr>
<td>relative error</td>
<td>+20%</td>
<td>0%</td>
<td>-9%</td>
<td>+8%</td>
<td>+3%</td>
<td>-18%</td>
</tr>
</tbody>
</table>
The results show that HEUM leads to a large overestimation of the solar transmittance for all the silver coated glasses. As a consequence we also expect an overestimation of the solar factor. This behavior was already observed in [22] and [18] and it is probably related to very high values of reflectance.

In fact we see in Figures 3.3, 3.4 and 3.5 that for samples 2, 3 and 4 the values of reflectance in the NIR spectrum are around 90% from coated side and around 60% on the uncoated side (front and back reflectance have been defined according to the position of the coated glass in the double unit configuration, see 3.1).

Such values can not be explained without considering coherence effects (i.e. interference) in the structure of the coating. In this cases the assumption of equivalence with a dielectric uncoherent scheme, as MIX7 (in Fig. 3.7), leads the minimization process of the Merit Function 3.18 to very high and unphysical ”equivalent” indexes of refraction. These solutions do not reproduce correctly the angular properties since large $n$ would redirect incident beams to cross the equivalent scheme following a nearly normal direction and boost the Brewster angle (2.4). As a consequence also the predicted decrease in the angular variation of the transmittance are shifted to larger incidences.

ASHRAE model produces also general overestimation of solar transmittance except for sample 5. We will keep in mind this observation for use in the following comparison of the results for double glass units.
Figure 3.8: Models comparison - Sample 2 - Solar range: ASHRAE model and HEUM angular predictions versus experimental values

Figure 3.9: Models comparison - Sample 2 - Visual range: ASHRAE model and HEUM angular predictions versus experimental values
Figure 3.10: Models comparison - Sample 3 - Solar range: ASHRAE model and HEUM angular predictions versus experimental values

Figure 3.11: Models comparison - Sample 3 - Visual range: ASHRAE model and HEUM angular predictions versus experimental values
Figure 3.12: Models comparison - Sample 4 - Solar range: ASHRAE model and HEUM angular predictions versus experimental values

Figure 3.13: Models comparison - Sample 4 - Visual range: ASHRAE model and HEUM angular predictions versus experimental values
Figure 3.14: Models comparison - Sample 5 - Solar range: ASHRAE model and HEUM angular predictions versus experimental values

Figure 3.15: Models comparison - Sample 5 - Visual range: ASHRAE model and HEUM angular predictions versus experimental values
**double glass units** We present here a comparison of the ASHRAE and the Empirical model for our double glass units:

<table>
<thead>
<tr>
<th></th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$g(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Mirror</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.343</td>
<td>0.356</td>
<td>0.306</td>
<td>0.587</td>
<td>0.274</td>
<td>0.268</td>
<td>0.483</td>
</tr>
<tr>
<td>ASHRAE relative error</td>
<td>+5%</td>
<td>+3%</td>
<td>+10%</td>
<td>+0%</td>
<td>+3%</td>
<td>+7%</td>
<td>-1%</td>
</tr>
<tr>
<td>Empirical relative error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.468</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$g(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Control A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.193</td>
<td>0.287</td>
<td>0.428</td>
<td>0.412</td>
<td>0.187</td>
<td>0.288</td>
<td>0.228</td>
</tr>
<tr>
<td>ASHRAE relative error</td>
<td>+11%</td>
<td>+9%</td>
<td>-4%</td>
<td>+3%</td>
<td>+9%</td>
<td>-6%</td>
<td>9%</td>
</tr>
<tr>
<td>Empirical(q=1) relative error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.229</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$g(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Control B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.189</td>
<td>0.233</td>
<td>0.392</td>
<td>0.407</td>
<td>0.139</td>
<td>0.255</td>
<td>0.226</td>
</tr>
<tr>
<td>ASHRAE relative error</td>
<td>+1%</td>
<td>+15%</td>
<td>+1%</td>
<td>-4%</td>
<td>+10%</td>
<td>+12%</td>
<td>0%</td>
</tr>
<tr>
<td>Empirical(q=1) relative error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.229</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$g(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Control C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.313</td>
<td>0.152</td>
<td>0.228</td>
<td>0.427</td>
<td>0.173</td>
<td>0.244</td>
<td>0.393</td>
</tr>
<tr>
<td>ASHRAE relative error</td>
<td>-6%</td>
<td>+28%</td>
<td>+16%</td>
<td>-11%</td>
<td>+29%</td>
<td>+14%</td>
<td>-5%</td>
</tr>
<tr>
<td>Empirical(q=3.5) relative error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.392</td>
</tr>
</tbody>
</table>

Note that we have used here the same $q - value$ associated by the empirical model to "K glass", even if "hard coating" in sample 5 is provided by a different manufacture, with a potentially different process.

<table>
<thead>
<tr>
<th></th>
<th>$\tau_e(60^\circ)$</th>
<th>$\rho_e(60^\circ)$</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
<th>$\rho_v(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
<th>$g(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Control D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.189</td>
<td>0.193</td>
<td>0.310</td>
<td>0.345</td>
<td>0.193</td>
<td>0.271</td>
<td>0.278</td>
</tr>
<tr>
<td>ASHRAE relative error</td>
<td>+4%</td>
<td>+15%</td>
<td>+10%</td>
<td>-5%</td>
<td>+17%</td>
<td>+6%</td>
<td>+1%</td>
</tr>
<tr>
<td>Empirical(q=2) relative error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.279</td>
</tr>
</tbody>
</table>

42
Note that for solar control D we have use for the empirical model a \( q - value = 2 \), which is not listed, but can be guessed from the consideration that since the combination of a single silver coating with a clear glass would have had \( q = 2.5 \) in present combination with an hard coated glass a slightly lower value should be suitable.

Results confirm the good agreement of the empirical model except for glazing with double silver coating (B). It turns out in fact that the two double silver coating, (A) and (B), shows different angular behavior. We have already noted this anomaly in previous section. The reason is probably due to different industrial process.

ASHRAE model gives unexpected good results for Solar Control B and D. We see in Figure 3.19 that ASHRAE reference for a double glass unit composed by a clear and a coated glass has the same angular behavior of the empirical function with \( q = 2 \). From Previous comparison for single glass we could expect a better agreement for Solar Control C, which combines sample 5 and 1. This does not occur because ASHRAE algorithm does not take care of polarization effects and so, according to our analysis in previous section, it gives a systematic underestimation of the transmittance. Therefore it is a compensation of errors, between the prediction on angular dependency and the polarization effects, that causes the good ASHRAE prediction for Solar Control D and B.
Figure 3.16: ASHRAE and experimental Solar factor, Light and Solar Direct transmittances normalized at their normal incidence values compared to empirical function.

Figure 3.17: ASHRAE and experimental Solar factor, Light and Solar Direct transmittances normalized at their normal incidence values compared to empirical function.
Figure 3.18: ASHRAE and experimental Solar factor, Light and Solar Direct transmittances normalized at their normal incidence values compared to empirical function.

Figure 3.19: ASHRAE and experimental Solar factor, Light and Solar Direct transmittances normalized at their normal incidence values compared to empirical function.
Figure 3.20: ASHRAE and experimental Solar factor, Light and Solar Direct transmittances normalized at their normal incidence values compared to empirical function.
Chapter 4

Electrochromic glazing: experimental characterization

Electrochromics windows change their optical properties when a small voltage is applied to the conduction layers of the glazing. A short description of the mechanism is given in the next paragraph. This dynamic offers good opportunities for efficient energy use, taking into account the thermal and visual comfort of occupants. In this chapter we present a characterization of spectral and optical properties of a commercial electrochromic glazing. The experimental work was carried on at ENEA Research Center in Casaccia (Rome). The results have been presented also in [24].

Chromogenic research activities in IEA - TASK 27 and SWIFT EU Project

The Solar Heating and Cooling Programme of the International Energy Agency set up the Task 27- Performance of Solar Facades Components to improve the performance, the durability and the sustainability of solar components to be integrated in the building facade ([31]). In this task two working groups were established to investigate on the energy performance and durability of chromogenic glazing. The activities involve several researchers, coming from European and USA institutions, and representatives of industries. Research activities include the measurements and modelling of luminous, solar and thermal properties of smart glazing, the evaluation of energy performance of buildings equipped with such devices and the users preferences concerning their visual and thermal comfort in working place equipped with chromogenic windows.

The SWIFT (Switchable Facade Technology) project, funded by the European Communities within the V Framework, started in 2000 and finished in 2003 ([32]). The working group, in which are involved universities, research institutes and industries of several European countries, investigated the potentiality of chromogenic glazing in building application.
4.1 Switchable properties

The research on the electrochromic systems is going on since many years, but the idea of the electrochromic glazing for building application is relatively recent. For a general review on chromogenic materials for smart windows we refer to [9].

Electrochromic materials change their optical properties with a reversible electrochemical reaction that is activated by the action of an electric field. The electric power is required only during switching and only a small voltage in direct current is necessary. There are two major categories of electrochromic materials: transition metal oxides and organic compounds. The electrochromic effect occurs in inorganic compounds by dual injection (cathodic) or ejection (anodic) of ions \( A^+ \) and electrons \( e^- \). A typical reaction for a cathodic coloring material using lithium as a coloration ion is:

\[
WO_3(\text{colorless}) + nLi^+ + ne^- \leftrightarrow Li_nWO_3(\text{blue}) \quad (4.1)
\]

A typical complementary anodic reaction is

\[
Li_nV_2O_5(\text{lightyellow}) - nLi^+ - ne^- \leftrightarrow V_2O_5(\text{blue}) \quad (4.2)
\]
Figure 4.2: Schematic of an electrochromic glazing (film thickness is not to scale): the arrows and the voltage signs indicate the action of electric filed during the coloring reactions.

These reactions show that - by using two different materials one layer that colors upon intercalation and one that colors on de-intercalation - both sides of the devices can color at the same time giving greater optical density.

An electrochromic device must have a ion-containing material (electrolyte) in close proximity to the electrochromic layer as well as two transparent conductor for setting up a distributed electric field. An electrochromic glass is typically composed as a sandwich of these layers between two glass substrate. A schematic picture of is given in Figure 4.2.
4.2 Transmittance measurements

For this transmittance measurements we have used the CATRAM apparatus described in appendix A. The laboratory measurements were performed on a 50x50 cm commercial sample produced by Flabeg, the same type of electrochromic glazing was used for the window of the ENEA experimental ”smart” building ”Casa Intelligente”. The sample is a double glazing unit with an electrochromic outer pane (9 mm), an air gap filled with argon and an inner pane (4 mm) with Low-emissive coating. In Figure 4.1 is shown a view through the window of the experimental building with one part clear and the other fully colored.

The ENEA integrating sphere was used for performing spectral and angular measurements on the electrochromic device. The spectral analysis is performed in the range between 350 and 1150 nanometers, the wavelength step was 5 nanometers between 350 and 800 nanometers, and 10 between 800 and 1150 nanometers. 80% of the solar energy falls in the scanned spectrum range.

The spectral transmittance at normal incidence of the sample is plotted in Figure 4.3, the five curves refers to the five states that can be set with the switching control system.

The angular broad band transmittance curves, obtained by experimental spectral data at 0, 30, 45 and 60 degrees, are plotted in Figure 4.4. The measurements were performed with the electrochromic glazing in the bleached and fully colored positions and the integrated results for luminous properties are obtained using the Illuminant A as weight. In the following table the numeric results are reported.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$\tau_{e,bleached}$</th>
<th>$\tau_{v,bleached}$</th>
<th>$\tau_{e, coloured}$</th>
<th>$\tau_{v, coloured}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^\circ$</td>
<td>0.479</td>
<td>0.365</td>
<td>0.144</td>
<td>0.098</td>
</tr>
<tr>
<td>30$^\circ$</td>
<td>0.483</td>
<td>0.349</td>
<td>0.133</td>
<td>0.091</td>
</tr>
<tr>
<td>45$^\circ$</td>
<td>0.457</td>
<td>0.325</td>
<td>0.117</td>
<td>0.080</td>
</tr>
<tr>
<td>60$^\circ$</td>
<td>0.383</td>
<td>0.270</td>
<td>0.091</td>
<td>0.062</td>
</tr>
</tbody>
</table>
Figure 4.3: Spectral transmittance at normal incidence in the 5 states of the EC glazing

Figure 4.4: Light and solar angular transmittance of EC glazing in bleached and colored states
Chapter 5

Characterization of components
for shading devices

We have already mentioned in the previous chapter the Task 27 of the Solar Heating and Cooling Programme of the International Energy Agency ([31]). Within this task has been set up a case study (A1) on Solar Control Devices and their integration. In this case study four components for shading system have been tested. We include the results of an optical characterization on this components that was carried on at ENEA Research Center in Casaccia (Rome). These results are also collected in an internal report for IEA-Task27 ([25]).

5.1 Description of the samples

The measurements were performed on four samples supplied by EMPA (Switzerland). The main characteristics are described in the following table, more detailed descriptions can be found in [23].

<table>
<thead>
<tr>
<th>Code</th>
<th>Sample</th>
<th>Commercial Name</th>
<th>Dimensions</th>
<th>Material</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Lamella</td>
<td>Schenker VR 90</td>
<td>15cm x 15cm</td>
<td>Plastic</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No. 901</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Lamella</td>
<td>Schenker VR 90</td>
<td>15cm x 15cm</td>
<td>Plastic</td>
<td>Brown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No. 071</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Pinhole lamella</td>
<td>Schenker VR 90</td>
<td>15cm x 15cm</td>
<td>Plastic</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No. 901</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>Fabric</td>
<td>Verosol 812</td>
<td>20cm x 20cm</td>
<td>Aluminized</td>
<td>Grey</td>
</tr>
</tbody>
</table>

S1, S2 and S3 are used for exterior shading devices, S4 is a Fabric, with an aluminized exterior surface, to be used as interior glare protection system.
The pinhole lamella sample tested at ENEA was prepared by EMPA, in order to make the sample suitable to be tested with ENEA instruments (the holes are present in all the surface of the sample and not in some stripes only).

5.2 Measurements

5.2.1 Spectral measurements results

Spectral absorption and transmittance measurements were performed on the four samples. The measurement step resolution is 10 nanometers in the range between 350 and 1150 nanometers, covering 80% of the entire solar spectrum. In the figures 5.6, 5.1, 5.2, 5.3, 5.4 and 5.5 the measurement data plots are presented. The graphs include the measurements performed at 0°, 30°, 45° and 60° angle of incidence. We underline here that, even if indicated as normal incidence measurements, the absorption was measured at near-normal incidence (8). For S4 the complete set of measurements was performed with the metallic surface as surface 1. The near normal absorption was also measured with the metallic surface in face 2.
Figure 5.2: Pinhole lamella - Spectral angular absorption

Figure 5.3: Pinhole lamella - Spectral angular transmittance
Figure 5.4: Grey screen - Spectral angular absorption

Figure 5.5: Grey screen - Spectral angular transmittance
5.2.2 Broad-band measurement results

The measurements were performed at different angle of incidence of the light beam. Here, the integrated values of the spectral data are calculated. An homemade program was developed at ENEA for the determination of the broad-band parameters. The algorithms are in accordance with ISO 9050 [3]. Tables 3 and 4 summarize the results obtained for, respectively, the solar and luminous optical properties. The solar parameters are calculated using the solar distribution of ISO 9050 as weight, the luminous parameters are calculated with the illuminant A as weighting curve. It is reminded that, in the following tables, transmittance and absorption are measured values, while reflectance values are obtained as the complement to one of the measured values.

<table>
<thead>
<tr>
<th>S1</th>
<th>$\tau_e$</th>
<th>$\alpha_e$</th>
<th>$\rho_e$</th>
<th>$\tau_v$</th>
<th>$\alpha_v$</th>
<th>$\rho_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>0.303</td>
<td>0.697</td>
<td>0.241</td>
<td>0.759</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>0.283</td>
<td>0.717</td>
<td>0.221</td>
<td>0.779</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$45^\circ$</td>
<td>0.283</td>
<td>0.717</td>
<td>0.222</td>
<td>0.778</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>0.270</td>
<td>0.730</td>
<td>0.211</td>
<td>0.789</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The near normal absorption of S4 was also measured in the back direction (metallic surface in face 2), the absorption and reflectance are respectively: 32.7% and 56.8% in the visible range and 31.4% and 58.1% in the solar range.

### 5.3 Inter-laboratory comparison

The values measured at ENEA are in satisfactory agreement with those obtained by Stazione sperimentale del Vetro and expected by EMPA. The white lamella seems to have a reflectance a little lower than expected (76% in the visible range for ENEA, 78 – 79% for EMPA and SV), the rest of the results are in a good agreement. The pinhole lamella cannot be properly compared because of the different samples, prepared by EMPA in order to fit with the various experimental set up. It must be noted the anomalous behavior of the grey screen, the reflectance constantly decrease from the near-normal to the 60° values. This might be caused by the special texture of the screen, which allows reflectance to increase only at very high angles of incidence.
Chapter 6

Modelling the total solar energy transmittance of a complex system: window with internal Venetian blinds

6.1 Introduction

6.1.1 Brief review

The challenge of modelling the properties of windows including solar shading devices has been attacked by a number of authors.

A simple model for a double glass units with integral Venetian blinds has been introduced in [17]. It is based on the geometrical simplifications of flat slats and takes into account a partially specular behavior of the reflections on the slats.

WIS (Window Information System) has been developed within the European Project WINDAT [33] and it is able to simulate thermal and optical properties of windows with internal, external or integrated venetians blinds. The thermal and optical algorithms are based on standards [20], where slats are assumed to be flat and diffusive[7]. Present WIS version (2.01) should also include an option for ray-tracing calculation but some bugs have been reported for this option, so in fact ray tracing is not yet available within WIS. The WINDAT Thematic Network has also distributed another software named REVIS based on the same ray-tracing method ([19]). For completeness about software designed to simulate windows with sunshades we quote here also ParaSol which performs a dynamic calculations to derive of an effective $g - value$ ([28]).
6.2 Description of the model: original and further formulations

The original formulation of the model we will discuss here has been introduced by Tilmann Kuhn, it has been already used in [15] and it is completely described in [30]. Here we present and discuss its main concept and further versions that we have developed in order to improve the accuracy of the model and its predictive features. All the versions are based on a formulation of the solar factor that combines the angular optical properties of the glazing and of the shading device derived by distinct characterization.

6.2.1 Glazing and blinds combination

When combining glazing and shading optical properties and their angular dependency we face different symmetries. Usually for a glazing system, if no special and oriented structures are integrated, we have incidence angle symmetry, while for a system of horizontal venetians blinds we typically have profile angle symmetry (see Chapter 2 for definitions). For a vertical facade if incoming radiation is in the vertical plane which contains the normal to the surface then it is easy to see the correspondence between the incidence angle and the profile angle, i.e. $\theta = |\alpha_p|$. Presently this is the only case considered by WIS [7] simulating software. When we want to extend our modelling to off normal directions in three dimensions more complicated angle transformations hold (2.12 and 2.13). If we represent both incidence angle and profile angle as functions of the solar altitude and the relative azimuth, than we have that the complete angular dependency of the Solar factor can be represented as follow:

$$g_{tot}(\alpha_s, \tilde{\gamma}, \beta_k) = g_{tot}(X_{i,glz}(\theta(\alpha_s, \tilde{\gamma})), Y_{j,shd}(\alpha_p(\alpha_s, \tilde{\gamma}), \beta_k))$$

(6.1)

Where $\{X_{i,glz}\}$ and $\{Y_{j,shd}\}$ indicate respectively properties of the glazing and of the shading, and $\beta_k$ is the slat angle.

Below we present and compare two broad band formulations of the problem described in 6.1. The former formulation, ”solar-light” has been introduced by Tilmann Kuhn in [30] and is intended to take into account implicitly the spectral properties of glazing and lamellas typically used in solar control applications. The alternative ”three bands” version is proposed here to improve the accuracy of the model by taking into account explicitly the spectral interactions between glazing and shading.
Original "Solar/light" formulation

\[ g_{tot}(\theta, \alpha_p, \beta_k) = g_{glz}(\theta) + \]
\[ - \tau_{e,glz} \cdot \tau_{x,dif,glz} \cdot \rho_{x,shd}(\alpha_p, \beta_k) \]
\[ - \frac{\tau_{e,glz} \cdot (1 - \tau_{x,dif,glz} - \rho'_{x,dif,glz}) \cdot \rho_{x,shd}(\alpha_p, \beta_k)}{1 - \rho'_{x,dif,glz} \cdot \rho_{x,dif,shd}} \]
\[ - \frac{G}{G_2} \cdot g_{glz}(\theta) \cdot (1 - \tau_{x,shd}(\alpha_p, \beta_k) - \rho_{x,glz}(\alpha_p, \beta_k)) \] (6.2)

where in case of Heat Mirror glazing "x" stands for "e" and refers to solar broad band properties, while in case of Solar Control glazing "x" stands for "v" and refers to visual (light) broad band properties as in standards.

Three bands reformulation

\[ g_{tot} = \sum_y w_y \cdot g_{tot,y} \quad y = "UV - e", "VIS - e", "NIR - e" \] (6.3)

where \( w_y \) are the weight factors introduced in 3.1 and \( g_y \) are given by:

\[ g_{tot,y}(\theta, \alpha_p, \beta_k) = g_{glz,y}(\theta) + \]
\[ - \tau_{y,glz} \cdot \tau_{y,dif,glz} \cdot \rho_{y,shd}(\alpha_p, \beta_k) \]
\[ - \frac{\tau_{y,glz} \cdot (1 - \tau_{y,dif,glz} - \rho'_{y,dif,glz}) \cdot \rho_{y,shd}(\alpha_p, \beta_k)}{1 - \rho'_{y,dif,glz} \cdot \rho_{y,dif,shd}} \]
\[ - \frac{G}{G_2} \cdot g_{glz}(\theta) \cdot (1 - \tau_{y,shd}(\alpha_p, \beta_k) - \rho_{y,glz}(\alpha_p, \beta_k)) \] (6.4)

We underline here that in three bands formulation the "VIS-e" integration differs from standard visual (light) integration since in the latter case spectral properties are weighted with eye-sensitivity (2.7). In principle only the former has physical meaning in evaluating the solar factor. The numerical difference depends on the spectral shape of the optical properties in the visual range. If optical properties are gray (i.e spectral curves nearly flat in the visual range) than it can be easily shown that the results of the two integrations are in practice equivalent. We will see that this happens particularly for the lamella considered in our case study. On the other hand results reported in Chapter 3 show that this simplification can be critical for coated glasses.
$\kappa$-parameter  In the original formulation ([30]) the $\kappa$ parameter, that appears in the third term of 6.2 and 6.3, is deduced by fitting model results with a direct calorimeter measurement.

In order to avoid direct measurements of the solar factor, which are very complex and expensive we propose here a fully predictive approach and present a derivation of $\kappa$-parameter. In fact $\kappa$ can be estimated from glazing thermal transmittance and back absorption on individual panes in analogy with the multiplicative factor in the forth term of 6.2 and 6.3, which accounts for blinds absorption.

$$\kappa = G \cdot ((1 - \hat{\gamma}) \cdot R_s + \frac{1}{h_i} + \frac{1}{G_2})$$  \hspace{1cm} (6.5)

$$R_s = \frac{1}{U_{glz}} - \frac{1}{h_i} - \frac{1}{h_e}$$  \hspace{1cm} (6.6)

where:

• $R_s$ is the thermal resistance between the glazing surfaces that face to indoor (blinds) and outdoor environment

• $0 < \hat{\gamma} < 1$ is a parameter that scale an effective outdoor thermal resistance of the glazing to the heat flux generated by the absorbed radiation. If $\hat{\gamma}$ is null all the secondary absorption (from radiation reflected by the blinds) is absorbed on the external surface while for $\hat{\gamma} = 1$ all this energy is absorbed on the indoor surface.

For a general complex glazing $\hat{\gamma}$ can be derived as (Rosenfeld and alias in [6])

$$\hat{\gamma} = \int_0^1 \hat{\alpha}'(\hat{s}) \cdot \hat{\tau}_s(\hat{s}) d\hat{s}$$  \hspace{1cm} (6.7)

where:

• $0 \leq \hat{s} \leq 1$ is the normalized glazing thickness

• $0 \leq \hat{\alpha}'(s) \leq 1$ is the normalized back absorption

• $0 \leq \hat{\tau}_s(\hat{s}) \leq 1$ is the normalized thermal resistance from point 0 (outdoor surface) to point 1 (indoor surface).

Since the thermal resistance of individual panes is generally relatively small we can approximate for a double glass unit $\hat{\gamma}$ as

$$\hat{\gamma} \simeq \frac{\alpha'_2}{\alpha'_{dgu}} \simeq \frac{\alpha'_{dgu,e}(0)}{\alpha'_{dgu,e}(0)}$$  \hspace{1cm} (6.8)

where for simplicity we propose to approximate the result evaluating the solar back absorption at normal incidence.
6.2.2 Glazing characterization

Input data usually available for many commercial glazing are spectral optical properties at normal incidence of each individual pane, thickness, configuration, IR emissivity and gas filling. These data are not sufficient to characterize properties at off normal incidence. To use formulas 6.2 and 6.3 an angular characterization of the solar factor and of the broad band optical properties is necessary. In the original formulation ([30]) the author already suggests to use of the empirical model by fitting the q-parameter with an additional experimental characterization at 60°. This requires the measurement of six spectral properties for each coated glass: transmittance and front and back reflectance for both polarization modes at 60°.

In order to reduce the cost of such a procedure we have already investigated in Chapter 3 the size of errors due to unpolarized angular characterization. Moreover to completely avoid this additional experimental characterization we need to check the accuracy of the predictive algorithms presented in Chapter 3. From that analysis we know that if some information on the coating are available the empirical model can be more precise in the evaluation of the solar factor but it has a lack of information on optical properties and the extension we presented in Chapter 3 is not fully validated. For this reasons we will test and compare both ASHRAE and empirical algorithms in the context of the model presented in this chapter. The use of the ASHRAE model is straightforward while for the latter we define here a procedure to extend it to the glazing optical properties.

**Extension of the empirical model for glazing angular dependency**  In order to deduce optical broad band properties in the case of empirical model we need additional assumption at least about transmittance and absorption angular dependency.

In the context of this model we will assume the following simplifications:

- all broad band transmittances have the same functional dependency from the incidence angle
- the above functional dependency is the same angular dependency of the solar factor according to empirical model,
- (back) absorption is constant till until $\theta = 75^\circ$ and then drops linearly to zero at $\theta = 90^\circ$.

All this assumption are in fact a departure from the desired physical behavior. For instance we have seen in chapter 3 that normalized $\tau_v$ and $\tau_e$ show slight differences in angular dependency, specially in presence of selective coating where the "effective" index of refraction can strongly depend on the wavelength.
We also remark that for a single glass these three hypothesis would be in contradiction, since \( q_i \) in formula 2.8 is proportional to \( \alpha_e \). But in double glass units absorption is distributed on two layers with a percentages of repartition that is also angular dependent, and each layer counts with a different weights to \( q_i \). In particular for our case studies in Chapter 3 these three assumptions give results not far from the reality compared to experimental values at 60°.

So we assume the following angular formulas:

\[
\begin{align*}
g_y(\theta) &= g_y(0^\circ) \cdot f_{p,q}(\theta) \\
\tau_y(\theta) &= \tau_y(0^\circ) \cdot f_{p,q}(\theta) \\
p'_y(\theta) &= \begin{cases} 
p'_y(0^\circ) + \tau_y(0^\circ) \cdot (1 - f_{p,q}(\theta)) & \text{for } \theta \leq 75^\circ \\
1 - \tau_y(0^\circ) \cdot f_{p,q}(\theta) & \text{for } \theta > 75^\circ
\end{cases}
\end{align*}
\] (6.9)

where \( p = 2 \) for double glass unit and \( q \) depend on the coating typologies.

**Diffuse properties**  Deduction of geometrical coefficients for incidence angle symmetry:

We consider a vertical facade and a system of polar coordinates such that in the hemisphere of incident radiation:

\[
0 \leq \theta \leq \frac{\pi}{2} \quad 0 \leq \varphi \leq 2\pi
\]

the **diffuse to hemispherical** value of a certain optical property \( X \) (\( X \) can be spectral or broad band transmittance, reflectance or absorption of the glazing) is given by

\[
X_{dif} = \frac{\int_{\text{hemisph.}} X(\theta) \vec{I}(\theta, \varphi) \cdot \vec{n} d\Omega}{\int_{\text{hemisph.}} \vec{I} \cdot \vec{n} d\Omega} d\Omega = \sin \theta d\theta d\varphi
\] (6.11)

where \( \vec{I} \) describe an isotropic incidence radiation (\( W/m^2 \cdot \text{sterad} \)), \( \vec{n} \) the normal to the surface, and \( X(\theta) \) gives as usual direct to hemispherical angular dependency of \( X \). Since the scalar product \( \vec{I} \cdot \vec{n} = |\vec{I}| \cos \theta \) we obtain:

\[
X_{dif} = \frac{\int_0^{2\pi} d\varphi \int_0^{\frac{\pi}{2}} X(\theta) |\vec{I}| \cos \theta \sin \theta d\theta}{\int_0^{2\pi} d\varphi \int_0^{\frac{\pi}{2}} |\vec{I}| \cos \theta \sin \theta d\theta}
\] (6.12)

\[
= \frac{2\pi |\vec{I}| \int_0^{\frac{\pi}{2}} X(\theta) \cos \theta \sin \theta d\theta}{\pi |\vec{I}|}
\] (6.13)

\[
= 2 \int_0^{\frac{\pi}{2}} X(\theta) \sin \theta \cos \theta d\theta
\] (6.14)
Assuming the availability of a discrete angular characterization at \( N + 1 \) equally spaced incidence angles (extremes included) we can approximate Eq. 6.14 with:

\[
X_{d_i} = \sum_{i=0}^{N} a_i \cdot X(i \frac{\pi}{2N})
\]

(6.15)

\[
\begin{align*}
    a_0 &= a_N = \sin^2 \left( \frac{\pi}{4N} \right) \\
    a_i &= \sin^2 \left( \frac{(2i+1)\pi}{4N} \right) - \sin^2 \left( \frac{(2i-1)\pi}{4N} \right)
\end{align*}
\]

In the following table we report numerical results for \( a_i \) coefficients in case of \( N = 6 \).

<table>
<thead>
<tr>
<th>incidence angles</th>
<th>0°</th>
<th>15°</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
<th>75°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight coefficients</td>
<td>0.0171</td>
<td>0.1294</td>
<td>0.2241</td>
<td>0.2588</td>
<td>0.2241</td>
<td>0.1294</td>
<td>0.0171</td>
</tr>
</tbody>
</table>

### 6.2.3 Shading characterization

**Lamella to shading characterization** In order to derive the optical properties of the shading device to be used in Formulas 6.2 and 6.4, in principle different characterization processes - experimental measurements, simulations and modelling - can be used. We have used TAURO, a ray-tracing tool developed by Fraunhofer ISE, which consist of a Windows Excel interface for OPTICAD. The accuracy of this ray-tracing simulation tool has already been validated in [15].

The input values are:

- lamella optical properties: broad band (solar/light or UV-e, VIS-e and NIR-e) directional to hemispherical, total and diffuse, (at normal incidence) transmittance and reflectance of both upper and rear lamella surfaces (at normal incidence)
- lamellas geometry: thickness, wideness, distances, and CURVATURE

The output are the broad band transmittance and reflectance for the system of Venetian blinds - considered as equivalent to a single vertical surface - as function of the profile angle, \(-75 \leq \alpha_p \leq +80\).

\[
\tau_{x/y,shd}(\alpha_p) \text{ and } \rho_{x/y,shd}(\alpha_p)
\]

**Diffuse properties** Deduction of geometrical coefficients for profile angle symmetry:

We present here a derivation of the diffuse properties of a device (Venetian blinds) which is endowed of symmetry with respect to the profile angle in analogy with the previous common derivation for device showing symmetry with respect to the incidence angle. We always consider a vertical facade but now we choose a system of polar coordinates such that in the hemisphere of incident radiation:
In this case the diffuse to hemispherical value of a certain optical property \( Y \) (\( Y \) can be spectral or broad band transmittance, reflectance or absorption of the shading device) is given by

\[
Y_{\text{dif}} \equiv \frac{\int_{\text{hemisph.}} Y(\theta_z, \tilde{\gamma}) \tilde{I}(\theta_z, \tilde{\gamma}) \cdot \vec{n} d\Omega}{\int_{\text{hemisph.}} \tilde{I} \cdot \vec{n} d\Omega} \quad d\Omega = \sin \theta_z d\theta_z d\tilde{\gamma} \tag{6.16}
\]

where \( \tilde{I} \) represents an isotropic incidence radiation (\( W/m^2 \cdot \text{sterad} \)), \( \vec{n} \) is the normal to the surface, and \( Y(\theta_z, \tilde{\gamma}) \) represents as usual direct to hemispherical angular values of \( Y \). Then we make a first change of variable:

\[
0 \leq \theta_z \leq \pi \quad -\frac{\pi}{2} \leq \tilde{\gamma} \leq \frac{\pi}{2}
\]

\[
\alpha_s = \frac{\pi}{2} - \theta_z
\]

and obtain

\[
Y_{\text{dif}} = \frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} Y(\alpha_s, \tilde{\gamma}) \tilde{I}(\alpha_s, \tilde{\gamma}) \cdot \vec{n} \cos \alpha_s \cos \alpha_s d\alpha_s d\tilde{\gamma}}{\int_{\text{hemisph.}} \tilde{I} \cdot \vec{n} d\Omega}
\]

\[
= \frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} Y(\alpha_s, \tilde{\gamma}) | \tilde{I} | \cos^2 \alpha_s \cos \tilde{\gamma} d\alpha_s d\gamma}{\pi | \tilde{I} |}
\]

\[
= \frac{1}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} Y(\alpha_s, \tilde{\gamma}) \cos^2 \alpha_s \cos \tilde{\gamma} d\alpha_s d\tilde{\gamma}
\]

(6.17)

(6.18)

where \( \cos \alpha_s \cos \tilde{\gamma} \) is the view factor between the unit area in the incidence direction and the vertical surface.

Now due to geometrical structure of the blinds system we assume that the optical properties depend only on the profile angle \( Y(\alpha_p) = Y(\alpha_p(\theta_z, \tilde{\gamma})) \). Then we make a second change in the variables of integration

\[
-\frac{\pi}{2} \leq \alpha_s \leq +\frac{\pi}{2} \quad -\frac{\pi}{2} \leq \alpha_p \leq +\frac{\pi}{2}
\]

\[
\alpha_p = \arctan \left( \frac{\tan \alpha_s}{\cos \tilde{\gamma}} \right)
\]

which gives

\[
\frac{\partial \alpha_s}{\partial \alpha_p} = \frac{1}{1 + \tan^2 \alpha_p \cos^2 \tilde{\gamma}} \cdot \frac{\cos \tilde{\gamma}}{\cos^2 \alpha_p}
\]

\[
\cos^2 \alpha_s = \frac{1}{1 + \tan^2 \alpha_p \cos^2 \tilde{\gamma}}
\]

and we finally obtain

\[
Y_{\text{dif}} = \frac{1}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\alpha_p \frac{Y(\alpha_p)}{\cos^2 \alpha_p} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\tilde{\gamma} \left( \frac{1}{1 + \tan^2 \alpha_p \cos^2 \tilde{\gamma}} \right)^2 \cos^2 \tilde{\gamma}
\]

(6.20)
Assuming the availability of a discrete angular characterization at $2N + 1$ equally spaced profile angles (extremes included) we can approximate 6.20 with:

$$Y_{dif} = \sum_{i=-N}^{N} b_i \cdot Y(i \frac{\pi}{2N})$$

\[
\begin{align*}
    b_i &= b_{-i} = \frac{2}{\pi} \int_{(2i-1) \frac{\pi}{2N}}^{(2i+2) \frac{\pi}{2N}} \frac{1}{1+\tan^{2} \gamma} \frac{1}{\cos^{2} \gamma} d\gamma \\
    b_N &= b_{-N} = (1 - \sum_{i=1-N}^{N-1} b_i) / 2
\end{align*}
\]

In the following table we report numerical results for $b_i$ coefficients in case of $N = 6$.

<table>
<thead>
<tr>
<th>profile angles</th>
<th>0°</th>
<th>±15°</th>
<th>±30°</th>
<th>±45°</th>
<th>±60°</th>
<th>±75°</th>
<th>±90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight coefficients</td>
<td>0.130</td>
<td>0.126</td>
<td>0.113</td>
<td>0.092</td>
<td>0.065</td>
<td>0.034</td>
<td>0.005</td>
</tr>
</tbody>
</table>

### 6.3 Model validation

#### 6.3.1 Description of the case study

The window system considered in all this chapter is composed of the "Solar Control A" glazing already presented in Chapter 3 in combination with an internal Venetian blinds typically used in daylighting application.

**The glazing** In the following tables we report the broad band properties of the double glass unit Solar Control A and comparison with the results of angular characterization using ASHRAE model or the proposed extension of the empirical model to the optical properties:

<table>
<thead>
<tr>
<th>Solar Control A</th>
<th>$\tau_e(60^\circ)$</th>
<th>$\tau_{UV-e}(60^\circ)$</th>
<th>$\tau_{VIS-e}(60^\circ)$</th>
<th>$\tau_{NIR-e}(60^\circ)$</th>
<th>$\tau_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.193</td>
<td>0.032</td>
<td>0.314</td>
<td>0.030</td>
<td>0.412</td>
</tr>
<tr>
<td>ASHRAE model</td>
<td>0.214</td>
<td>0.055</td>
<td>0.350</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>Empiric extended</td>
<td>0.202</td>
<td>0.044</td>
<td>0.330</td>
<td>0.032</td>
<td>0.406</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solar Control A</th>
<th>$\rho'_e(60^\circ)$</th>
<th>$\rho'_{UV-e}(60^\circ)$</th>
<th>$\rho'_{VIS-e}(60^\circ)$</th>
<th>$\rho'_{NIR-e}(60^\circ)$</th>
<th>$\rho'_v(60^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.428</td>
<td>0.159</td>
<td>0.328</td>
<td>0.597</td>
<td>0.288</td>
</tr>
<tr>
<td>ASHRAE model</td>
<td>0.412</td>
<td>0.199</td>
<td>0.294</td>
<td>0.600</td>
<td></td>
</tr>
<tr>
<td>Empiric extended</td>
<td>0.441</td>
<td>0.159</td>
<td>0.306</td>
<td>0.623</td>
<td>0.302</td>
</tr>
</tbody>
</table>

The results show that the straightforward extension of the empirical model to the optical transmittance is even more accurate than ASHRAE predictions. While the proposed extension for the back reflectance gives even better results with relative errors around 5%.
The shading system  The lamellas of the Venetian blinds have concave curvature, the upward surface is mirror finished, while the downward surface is diffusive. This kind of device is suitable for daylighting applications since when the blinds are open they redirect the light to the ceiling of the room.

Input data for the ray-tracing simulation with TAURO are:

- Lamella broad band optical properties at normal incidence:

<table>
<thead>
<tr>
<th>lamella opt. prop.</th>
<th>( \rho_{\text{tot,front}} )</th>
<th>( \rho_{\text{tot,rear}} )</th>
<th>( \rho_{\text{diff,front}} )</th>
<th>( \rho_{\text{diff,rear}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>0.848</td>
<td>0.304</td>
<td>0.030</td>
<td>0.295</td>
</tr>
<tr>
<td>Solar</td>
<td>0.855</td>
<td>0.279</td>
<td>0.032</td>
<td>0.268</td>
</tr>
<tr>
<td>UV-e</td>
<td>0.672</td>
<td>0.074</td>
<td>0.052</td>
<td>0.065</td>
</tr>
<tr>
<td>VIS-e</td>
<td>0.839</td>
<td>0.287</td>
<td>0.030</td>
<td>0.278</td>
</tr>
<tr>
<td>NIR-e</td>
<td>0.894</td>
<td>0.285</td>
<td>0.033</td>
<td>0.272</td>
</tr>
</tbody>
</table>

- Geometry of the lamella:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>wideness</td>
<td>50 mm</td>
</tr>
<tr>
<td>thickness</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>distances</td>
<td>29 mm</td>
</tr>
<tr>
<td>ray of curvature</td>
<td>68 mm</td>
</tr>
</tbody>
</table>

In Figure 6.1 and 6.2 we show two results of the ray-tracing simulation with TAURO. To underline the importance of the curvature we also show a comparison with flat lamella assumption. It turns out that the slope of the cut off is much sharper with curved lamellas, and the start of the sharp slope of the function is shifted on the profile angle axis.
Figure 6.1: Transmittance and reflectance of the Venetian blinds with slat angle 0° simulated with TAURO. Lamella are concave, gray and mirror finished on the upper side. For comparison we include also results for flat lamella (*).

Figure 6.2: Transmittance and reflectance of the Venetian blinds with slat angle 45° simulated with TAURO. Lamellas are concave, gray and mirror finished on the upper side. For comparison we include also results for flat lamella (*).
6.3.2 Measurements

In the following table we report the results of the direct measurements of the solar factor for our window system case study for different blinds tilt angles and different incidences of the solar radiation. All the measurements have been done at Fraunhofer ISE using the Solar Simulator and the Calorimeter, which is described in Appendix B.

<table>
<thead>
<tr>
<th>solar altitude</th>
<th>relative azimuth</th>
<th>slat angle</th>
<th>incidence angle</th>
<th>profile angle</th>
<th>g value</th>
<th>U value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>0°</td>
<td>0° ± 5°</td>
<td>45°</td>
<td>45°</td>
<td>0.25 ± 0.03</td>
<td>1.20 ± 0.1</td>
</tr>
<tr>
<td>60°</td>
<td>0°</td>
<td>0°</td>
<td>60°</td>
<td>60°</td>
<td>0.21 ± 0.03(+)</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>0°</td>
<td>30° ± 5°</td>
<td>0°</td>
<td>0°</td>
<td>0.28 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>0°</td>
<td>30°</td>
<td>30°</td>
<td>30°</td>
<td>0.25 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td>0°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>0.22 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>0°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0.19 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>45°</td>
<td>52°</td>
<td>39°</td>
<td>39°</td>
<td>0.23 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td>45°</td>
<td>60°</td>
<td>55°</td>
<td>55°</td>
<td>0.21 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>0°</td>
<td>45° ± 5°</td>
<td>0°</td>
<td>0°</td>
<td>0.26 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>0°</td>
<td>30°</td>
<td>30°</td>
<td>30°</td>
<td>0.24 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td>0°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>0.20 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>0°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0.13 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>45°</td>
<td>52°</td>
<td>39°</td>
<td>39°</td>
<td>0.21 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>0°</td>
<td>66° ± 5°</td>
<td>0°</td>
<td>0°</td>
<td>0.25 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td>0°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>0.14 ± 0.03</td>
<td></td>
</tr>
</tbody>
</table>

The value of the angle at which the slats are tilted is non exactly the same for all the slats since real Venetian blinds system slats are not perfectly parallel. Typically at the bottom the tilt angle is lower than at the top. In the preparation of the measurement the tilt angle has been set for slats in middle position to the mean value reported, but variation up to 5° have been found for slats in the lower and upper part. The errors rang have been determined by Fraunhofer ISE as a feature of the measurement instrument.
6.3.3 Models comparison

We present and discuss a comparison of different formulation for a fixed $\kappa$ deduced according to Formulas 6.5 and 6.8.

Influence of different formulations In all the comparisons we find the following ordering relation $g_{e/v-fit} < g_{e/3band-emp.} < g_{3band-ashrae}$. Where:

- $g_{e/v-fit}$ is calculated according to Formula 6.2, using the extension of the empirical model in glazing characterization.
- $g_{e/3band-emp.}$ is calculated according to Formula 6.4, using the extension of the empirical model in glazing characterization.
- $g_{3band-ashrae}$ is calculated according to Formula 6.4, using ASHRAE model in glazing characterization.

The first ordering relation between "solar/light" and "three bands" is explained by the way in which they account for the radiation that is directly transmitted out through the glazing after reflection on the binds. In the "solar/light" formulation this "effective" glazing transmittance has been chosen equal to the light transmittance, because of assumption that glazing spectral selectivity has already filtered out the incoming NIR radiation. This simplification produce two small but systematic overestimation of the effective transmittance since light transmittance ($\tau_v$) is larger than the solar direct transmittance in the visual range ($\tau_{VIS-e}$), and the NIR radiation is not completely filtered. We expect that the "Three bands" formulation takes in better account spectral properties, and the results show that "solar/light" simplification can affect the prediction of the total solar factor with a maximal underestimation of about 10% when blinds are closed.

The second "<" sign was expected since we know that ASHRAE angular algorithm overestimate the solar factor of this glazing. In fact larger discrepancies are observed for azimuth zero and solar altitude $> 45^\circ$ (which means incidence angle $> 45^\circ$) while discrepancy reduce when the slats are more closed, i.e. blind reflection becomes more important.

Measurements and models predictions The comparisons show that all model formulations give a small but systematic overestimation of the solar factor measured with the calorimeter, when incident angle is smaller than $60^\circ$ (that means for relative azimuth equal to $45^\circ$, solar altitude smaller than $45^\circ$). For larger incidence angle, on the contrary, measurements give results higher than predictions. A systematic problem could affect present calorimetric measurements for incidences larger than $60^\circ$, since they have not been fully validated over that angular range yet.
Figure 6.3: Measurements and models predictions for slats in horizontal position: "solar-light" formulation, and three bands versions implemented with ASHRAE or extended empirical model. \( q = 1 \) and \( \kappa = 68\% \)

Figure 6.4: Measurements and models predictions for slats tilted at 30\(^\circ\): "solar-light" formulation, and three bands versions implemented with ASHRAE or extended empirical model. \( q = 1 \) and \( \kappa = 68\% \)
Figure 6.5: Measurements and models predictions for slats tilted at 45°: "solar/light" formulation, and three bands versions implemented with ASHRAE or extended empirical model. \( q = 1 \) and \( \varkappa = 68\% \)

Figure 6.6: Measurements and models predictions for slats closed: "solar/light" formulation, and three bands versions implemented with ASHRAE or extended empirical model. \( q = 1 \) and \( \varkappa = 68\% \)
Figure 6.7: Measurements and models predictions for slats tilted at 30°: "solar-light" formulation, and three bands versions implemented with ASHRAE or extended empirical model. $[q = 1 \text{ and } \kappa = 68\%]$

Figure 6.8: Measurements and models predictions for slats tilted at 45°: "solar-light" formulation, and three bands versions implemented with ASHRAE or extended empirical model. $[q = 1 \text{ and } \kappa = 68\%]$
6.3.4 Sensitivity analysis

Model sensitivity to slat angle  We see that all formulation of the model predict a "cut off" (i.e. quickly decreasing function of the solar altitude) as result of blinds reflectance which became important when $\alpha_p(\alpha_s, \tilde{\gamma}) \approx 90^\circ - \beta_k$.

As we have shown with OPTICAD ray tracing characterization of the blinds, the shape off the cut off is determined by their specular properties and curvature.

In Figure 6.3.5 we show that around the "cut off" position models results are very sensitive to the slat angle. A difference of a few degree in the determination of the slat angle produce a shift of the same entity in the cut off position and very large differences of the solar factor. Indeed far from the cut off the influence on the slat angle is very small. These results together with the intrinsic deviation of the slat angle recommend to be very careful when comparing model predictions with measurements for positions close to the cut off, even if the good agreement in figure 6.3.5 suggests that there might be a compensations of errors between the behavior at the bottom and the top of the Venetian blinds.
**Model sensitivity to $q$-parameter**  Form comparison done in Chapter 3 we know that $q = 1$ is not the best choice for all the glazing with double silver coating, as it is generally prescribed by the empirical model [?]. We have confirmed that $q = 1$ works very well for the glazing that we have named *Solar Control A* and we have further used in our facade system case study. But we have also found that for another double silver coated glazing provided by a different company the angular dependency would fit better a $q = 2$. Unfortunately it is still a question how to predict this behavior. So at present in a predictive approach we should consider $1 \leq q \leq 2$ and its consequent range of indetermination for the $g$ value of the whole system.

The value $q = 4$ corresponds to double clear float glass angular dependency, and it would be the default choice if no knowledge about the coating was available. 

In Figure 6.3.4 we see that the choice of the $q$-parameter in the empirical model can affect the prediction of the solar factor of about one or two deviation with respect to measured values and their declared error bar. This happens of course at large incidence angles and with blinds relatively opened, i.e. before the cut off. After the cut off even for large incidence angles we see in Figure 6.3.4 that the effect of glazing angular dependency is less important. All the predictions differs for less than one deviation with respect to the measurements.

**Model sensitivity to $\kappa$-parameter**  In Figures 6.3.4 and 6.3.4 we show the range of influence of $\kappa$ on the solar factor. In the first case according to the original model formulation [30] $0 \leq \kappa \leq 1$ is considered as a free parameter that can be determined by comparison with a measured value. On the other in the predictive approach $kappa$ has a more precise physical interpretation and according to Formula 6.5 its physical range is associated to $0 \leq \chi \leq 1$.

Anyway we see that the possible range of variation of $\kappa$ is not sufficient to allow the predicted solar factor to exactly match measured values for solar altitudes before the cut off position. At these angles model sensitivity to $\kappa$ is very small, while for larger angles, after the cut off position, since blinds reflectance is high, it is much more important, and the choice of $\kappa$ determines the agreement with measured values.
Figure 6.10: q-sensitivity in three bands formulation [$\kappa = 68\%$]

Figure 6.11: q-sensitivity in three band formulation [$\kappa = 68\%$]
Figure 6.12: $\kappa$-sensitivity in three bands formulation [$q = 1$]

Figure 6.13: $\kappa$-sensitivity in solar/light formulation [$q = 1$]
Figure 6.14: Model comparison with WIS simulation and simplified formula in standard [26]. REMARK: (*) = simulation for diffuse flat lamella, (**) = implemented with ASHRAE algorithm for glazing angular dependency.

### 6.3.5 Comparison with WIS simulations and standards

We present here a comparison with the simplified method in EN13363-1 and a simulation with WIS 2.01.

According to EN13363-1 the optical properties of the blinds system for slats tilted at 45° are given by formula 2.16, that applied to our case study give the following results.

<table>
<thead>
<tr>
<th>EN13363-1</th>
<th>$\tau_{shd,e}$</th>
<th>$\rho_{shd,e}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>slat angle 45</td>
<td>0.13</td>
<td>0.64</td>
</tr>
</tbody>
</table>

This simplified method has been proposed only for normal incidence radiation, since does not take into account angular dependency of $\tau_{shd}$ & $\rho_{shd}$. We extend formula 2.14, which gives the solar factor at normal incidence according to prEN13363-1, to off normal incidences, assuming constant values for $\tau_{shd}$ & $\rho_{shd}$ and using ASHRAE model for glazing angular dependency as follow:

$$g_{tot}(\theta) = g_{glz,ashrare}(\theta)(1 - g_{glz,ashrare}(\theta)\rho_{e,shd} - \alpha_{e,shd}\frac{G}{G_2})$$  \hspace{1cm} (6.22)

WIS simulation has been carried out using lamella and individual panes optical spectral data as input. In present version only a "default" (not specialized) algorithm for coated glass angular dependency and option for modelling diffuse lamella are available.
6.4 Conclusions

A fully predictive reformulation of the model introduced in [30] to derive the solar factor of a Window system including internal Venetian blinds has been developed and validated.

It needs spectral properties at normal incidence for the glazing and the lamella (since three bands values are generally not directly available), instead of visual and solar broad band values. The capability to be predictive is based on the empirical model categories ([13]) and a simple formula introduced to estimate the secondary heat transfer of the glazing in presence of internal blinds. In this context an extension of the empirical model has been introduced to derive the angular dependency of the back reflectance of the glazing. Moreover an exact derivation of diffuse properties for horizontal blinds systems, i.e. with profile angle symmetry, has been presented.

A wide experimental angular characterization of the solar factor for a facade system composed of a Solar Control glazing and internal Venetian blinds has been carried on to assess the validity of the proposed modelling approach.

The present work shows that the proposed changes to the original model formulation imply accuracy improvements that can be important in a fully predictive approach. And has been proven in this case study that this approach ensure a good agreement with measured values.

Moreover the results of the calorimetric measurements for azimuth values different from zero have permitted to validate the capability of the original and modified model to reproduce the complete angular dependency of the solar factor.
Chapter 7

Conclusions and perspectives

Different issues have been addressed in this thesis with respect to the angular characterization of energy and optical properties of window components and systems: evaluation of errors introduced by simplified calculations, experimental characterizations, angular dependency of properties of coated glasses and the modelling of the solar factor of a complex window system.

A three bands approach for glazing characterization has been introduced and its accuracy has been validated for a case study of advanced solar control and heat mirror glazing. It can be suitable also in the modelling of a combination of devices (glazing and shading) with different spectral properties, when spectral calculation is too time consuming or when simplified methods are necessary.

The influence of polarization effects in double glass units has been investigated by error analysis applied to the simplified calculation which does not takes into account these effects. The detailed analytical expansion of the error shows how the degree of polarization induced by single glasses can influence the results. It turns out that when the maximum level of polarization is induced by individual panes at different angles the combined effect is negligible. The expansion has been proven to be consistent, very accurate and useful also for estimating the error on the solar factor. It could be straightforwardly extended also to reflectance. It should be implemented with a physical investigation on the polarization effect introduced by different coatings in order to predict at which angles this effects are more relevant, thus to be able to discriminate whether experimental characterization of polarized properties at oblique incidence is really necessary.

Angular dependency of coated glass is still a critical issue. Two algorithms have been introduced and validated within the recent European project ADOPT ([14]), but
at present they have not been implemented in building simulation tools. They are in a certain way complementary since none of them is suitable to all cases. The Hybrid Equivalent Uncoated Model, introduced by Pietro Polato and others in [22], leads to systematic overestimation of the angular transmittance of glazing with silver based coatings. These coatings are very important in solar control applications since they achieve the highest performance in spectral selectivity. On the other hand the Empirical Model of Karlsson and Roos ([13]), even if is often very accurate in the prediction of the solar factor, in principle does not apply to the optical properties of the glazing. These information are also important in simulation algorithms and in the modelling of complex systems. It would be very useful to determine similar families of empirical functions for transmittance and reflectance angular dependency.

In this work a simple extension of the Empirical Model have been introduced in the context of the modelling of a complex window system including shading devices. For this case study the extension proposed is more accurate than ASHRAE reference algorithm, which is implemented in main simulation software.

Two experimental spectral and angular optical characterizations have been carried out: for the transmittance in different switching states of an electrochromic glazing and for components for shading devices. The latter has been part of IEA Solar Heating and Cooling Program - Task 27 in [25].

Finally a fully predictive reformulation of a model recently developed by Tilmann Kuhn ([30]) to derive the solar factor of a window system including internal Venetian blind has been developed and then validated through a wide angular experimental characterization. The original formulation required as an input two parameter whose values were deduced from an experimental off normal characterization of glazing and from a direct calorimeter measurement, while the modified version needs spectral properties of glazing (and lamellas) only at normal incidence. With this purpose a formula to estimate the heat transfer to the external environment due to the radiation reflected by the blinds and absorbed by the glazing has been proposed and validated.
Appendix A

Description of CATRAM apparatus at ENEA

CATRAM apparatus is an experimental facility, located at the ENEA Research Center in Casaccia (Rome), for the measurement of the spectral optical properties of advanced transparent materials. Its layout is schematically shown in Figure A.1 and Figure A.2. The complete features of the experimental apparatus are widely described in [11], the attention is focused on the measurements performed in this thesis.

A.1 The experimental set-up

The main component is the integrating sphere (made by LABSPHERE) having a 100 cm diameter. The sphere is made of aluminium with an inner coating of Spectrafloat (that is based on barium sulphate) having a reflectance coefficient greater than 0.97-0.98 in the visible range (400-800 nm) and greater than 0.80 in the whole solar range (up to 2500 nm). The sphere has several ports, necessaries for a proper execution of the measurements. Referring to A.2, P1 (7) is the sample port, through which the beam emitted from the light source is sent inside the sphere. At the bottom of the sphere the 2.5 cm detection port Pd1 (6) allows the detection system to collect the luminous energy present inside the sphere. The auxiliary port, P2 (8), is necessary to determine the substitution errors correction factors (see next paragraph). Diametrically opposite to the sample port, a light trap can be mounted on another 12.7 cm port (11) to perform reflectance and normal diffusing transmittance measurements. The sample port P1 can have different dimensions, with the diameter ranging from 12.7 up to 30 centimeters, in order to have the best configuration of the system according to the complexity of the sample and the measurement to be performed.
The light source is mounted on the rotatable arm (4) in order to allow off-normal transmittance measurements. The position of the beam can be adjusted using the three axis movement system supporting the light source. With this equipment it is possible to perform measurements at high angle of incidence for glazing having complex structure and thickness too. The mechanical structure supporting the sphere includes a movable sample holder (accepted sample size: 15x15 cm up to 100x100 cm) to insert and remove the glazing in quick and reliable way.

The detection system is not functioning at the moment, hence it was necessary to limit the scanned range from 350 to 1150 nanometers, which in any case covers the 80% of the solar energy. The measurement were performed with a 300 Watt Xenon arc lamp, equipped with very stable power supplies, the scanned range is from 350 to 1150 nanometers. The optical spectrum analyser has a silicon detector for visible and near infrared range. The entrance slit of the monochromator is directly coupled with the detector port by a tilted mirror. The wavelength steps generally used are 5 nanometers for the visible (up to 800 nanometers) and 10 nanometers for the near infrared range.

A.2 Measurements procedure

The following measurements were performed on the selected samples with the CATRAM facility:

- Spectral directional to hemispherical transmittance
- Spectral directional to hemispherical absorption

All measurements are performed with the single beam procedure, requiring two readings at each angle of incidence: the "reference" where the beam straight hits the sphere surface, and the "sample" where the beam hits the sample properly positioned depending on the optical parameter to be evaluated.

CATRAM also allows reflectance measurements on transparent not-diffusing components. In this work absorption and transmittance are performed, the reflectance values are calculated by subtraction.
A.2.1 Spectral directional to hemispherical transmittance

This kind of measurement is performed positioning the sample outside the sphere and close to the sample port. The beam emitted from the light source, positioned on the rotatable arm, passes through the glazing and goes inside the sphere through the sample port (reading \( E_s \)). In the reference measurement (\( E_x \)) the glazing is removed and the beam goes directly inside the sphere. The spectral directional hemispherical transmittance is given by

\[
\tau(\lambda, \theta) = \frac{E_s(\lambda, \theta)}{E_x(\lambda, \theta)} \cdot CF(\lambda) \tag{A.1}
\]

Where \( CF(\lambda) \) (spectral correction factor) compensates the variation of the mean reflectance of the sphere due to the positioning of the sample in front of the port. According to the auxiliary lamp method, when the lamp irradiates the sphere from the auxiliary port (P2), \( CF(\lambda) \) is the ratio of the signal obtained without sample \( E_x \) on the signal with the sample mounted in front of the sample port \( E_s \).

\[
CF(\lambda) = \frac{E_x(\lambda)}{E_s(\lambda)} \tag{A.2}
\]

A.2.2 Spectral directional to hemispherical absorption

In hemispherical absorption measurements the sample is located inside the sphere and is mounted on a telescopic support, which allows to set the proper incidence angle (see A.2). In the sample reading \( E_s \) the light source is on the normal to the sample port, the sample is rotated to have the chosen incidence angle and the detection system collects the light transmitted and reflected by the sample. In the reference reading \( E_x \) the beam crosses the sample port at 30° so that it directly hits the sphere wall. This measurement does not require the single beam correction factor because for both readings the sample is inside the sphere. When the beam hits the sample the detection system collects the light transmitted and reflected by the sample, the spectral absorption of the glazing is the complement to one of the ratio of sample signal on reference signal:

\[
\alpha(\lambda, \theta) = \frac{E_s(\lambda, \theta)}{E_x(\lambda, \theta)} \cdot CF(\lambda) \tag{A.3}
\]

A detailed description of the terminology used for the various detector readings is reported in the following table:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Sphere configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_s )</td>
<td>lamp pointed to P1 with sample mounted on P1</td>
</tr>
<tr>
<td>( E_s )</td>
<td>lamp pointed to P2 with sample mounted on P1</td>
</tr>
<tr>
<td>( E_x )</td>
<td>lamp pointed to P1 without sample</td>
</tr>
<tr>
<td>( E_x )</td>
<td>lamp pointed to P2 without sample</td>
</tr>
</tbody>
</table>
Figure A.1: CATRAM: layout for direct to hemispherical transmittance measurements
Figure A.2: CATRAM: layout for direct to hemispherical reflectance and absorption measurements
Appendix B

Description of the Calorimetric apparatus at Fraunhofer ISE

We include here only a very short description of the Calorimetric apparatus at Fraunhofer ISE (see also [15]).

B.1 Experimental set-up

The experimental apparatus is composed of a solar simulator, a cabin in which specified external condition are maintained, and the calorimetric box on which the test specimen is mounted.

The Solar simulator is provided with HMI 4000 lamps, whose spectral distribution correspond well but not perfectly to the standard solar spectrum (EN410). This small differences are corrected in the results with the gamma-model (Rosenfeld [5] and [6]). During the measurements the lamps irradiation on the is test specimen is between 500 $W/m^2$ and 800 $W/m^2$ at normal incidence.

The lamps are mounted on an arm that can be elevated and rotated to reproduce solar altitude between 0° and 60°.

A schematic drawing of the cabin is given in Figure B.1. Inside the cabin is placed the calorimetric box which reproduce the ”inside environment”. Glazing together with internal shading are mounted, on the front side of the box while the absorber is on the back (a picture is also given in Figure B.2). The edge of the glazing with the frame and the rest of the box are insulated. The box is mounted on a telescopc support that can be rotated to change the relative azimuth (with respect to the solar simulator).

On the front vertical surface of the sample a cross-flow ventilator reproduce wind condition that results in an external heat transfer coefficient $h_e = 23\pm 3 \frac{W}{(m^2K)}$. This corresponds to the external boundary condition defined in EN410 for the calculation of the solar factor.
B.2 Measurement procedure

We describe here the reference method, which has been used for the measurements reported in this thesis.

The principle of the calorimetric measurement of the solar factor is to irradiate the box on which test specimen is mounted and to measure the heat power extracted at the cooled absorber \( \phi(E) \). With appropriate corrections for heat loss by thermal transmission, when fluxes and temperatures reach stationarity, the extracted heat is proportional to the total solar energy transmitted through the test specimen.

\[
g = \frac{\phi(E(\alpha_s, \tilde{\gamma})) + \phi_{\text{thermal loss}}}{A \cdot E(\alpha_s, \tilde{\gamma})} \quad (B.1)
\]

where: \( A \) is the glazing area exposed and \( E(\alpha_s, \tilde{\gamma}) \) is the irradiance which is measured separately, without the sample but with a pyranometer that scans the intensity of the radiation produced by the solar simulator on the same surface of incidence.

The heat losses are evaluated by

\[
\phi_{\text{thermal loss}} = U_{\text{eff}}(T_{i,\text{eff}} - T_{e,\text{eff}}) \quad (B.2)
\]

where the \( T_{i,\text{eff}}, \) and \( T_{e,\text{eff}} \) are the internal (in the box) and external (in the cabin) effective temperatures. The \( U - value \) is measured separately with the sample mounted on the box, without solar irradiation and with a large temperature difference imposed between the absorber and the air in the cabin.

The calculation of effective indoor temperature, averaging internal air and radiant temperatures, is affected by errors due to uncertain values on the emissivity of the blinds system. This does not have large influence on the determination of the \( g - value \) since during the measurement of \( \phi(E) \) the setting of air and absorber temperatures is chosen to have small difference between internal and external temperatures.
Figure B.1: Schematic drawing of the calorimeter at the Fraunhofer Institute for Solar Energy System, Freiburg, Germany.
Figure B.2: The glazing, together with the blind, is mounted in front of the absorber of the calorimeter with the aid of a frame made of insulating material.
Bibliography


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[30] Tilmann Kuhn *Solar control: Two new systems and a general evaluation method for facades with venetian blinds or other solar control systems to be used ‘stand-alone’ or within building simulation programs* submitted to ”Energy and Buildings”

[31] http://www.ceere.org/task27


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