GONIOSPECTROPHOTOMETRIC CHARACTERISATION OF ADVANCED DAYLIGHTING MATERIALS

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ABSTRACT

Advanced daylighting strategies and systems can considerably reduce a building's electricity consumption and also significantly improve the quality of light in an indoor environment. The prediction of these improvements requires good models of glazing properties such as visual solar transmittance or solar heat gain coefficient (g-coefficient). Although well-defined for planar transparent glazing under normal incidence, measurements of these coefficients are more difficult for typical non-homogeneous and complex materials. In this latter case, the knowledge of these parameters under variable angle of incidence would be of keen interest.

This paper presents the development of a measuring methodology, which aims to measure regular samples under variable angle of incidence. It allows the calculation of some optical factors such as luminous and solar direct transmittance and reflectance. The apparatus used is a commercial spectrophotometer equipped with a fully automated angular accessory. The obtained results were compared with experimental or theoretical previous results, among which the results of the ADOPT Project interlaboratory comparison.

Keywords
Goniospectrophotometry, advanced glazing, angular characterisation.

INTRODUCTION

In a world newly concerned about carbon emissions and global warming, the introduction of advanced daylighting strategies and systems can considerably reduce a building's electricity consumption and also significantly improve the quality of light in an indoor environment. Solar energy properties of these systems are derived from reflectance and transmittance spectra obtained with a spectrophotometer. For the sake of simplicity, daylight and solar energy properties of glazing are commonly specified for normal incidence only. In the case of directional optical properties of these materials, things get more complicated. Nevertheless, there is a growing need for data on directional optical properties of glazing, especially where architects rely on the accuracy of simulation tools to predict the energy balance of buildings in design.

Belgian Building Research Institute (BBRI) owns a quite new measuring device. It is a commercial spectrophotometer equipped with an angular accessory. The accessory makes it possible to measure spectral properties of glazings under variable angle of incidence. Through a fully automated mechanism, it is possible to modify the incidence angle of the beam on the sample and/or the observation angle of the reflected or transmitted beam. This angular accessory is therefore well-suited to the study of advanced glazing, the measuring methodology of which is here presented and validated through appropriate experimental comparisons.

ADVANCED GLAZINGS

One can distinguish three main functions of advanced glazing systems: solar control, insulation and angular selectivity.

Solar control glazing

Solar control is a general term, which includes control of solar factor (g) and/or control of light transmittance and/or reflectance factors (τ_v, ρ_v). A clear glass of 4mm thickness has a solar factor g of 0,87 and a light transmittance factor τ_v of 0,90. These characteristics are not very interesting, for example in the case of a building situated in a tempered area in the summer. In this case, one may desire a lower solar factor in order to reduce cooling loads.

Some advanced strategies aim to reduce these factors in order to confer optimal properties to the glazing. Body-tinted glazing makes it possible to reduce both light transmittance and solar factors. Glazings with reflective coatings are more effective because of their better spectral selectivity and lower rise in temperature. The most promising solar control strategy is achieved by chromogenic materials. These materials are characterised by two distinct states of high and low transmittances. The change of state may be controlled actively by the temperature (thermotropic glazing, Raicu et al, 2001, Georg et al, 1998) or the ultraviolet radiation (photochromic, Lampert, 1999), or directly by the operator with the help of a switch: electrochromic windows (Macrelli, 1998), liquid crystal windows (Lampert, 1999) or gasochromic windows (Georg et al, 1998). Chromogenic materials are promising because of their adaptability to the climate and to the time of the day or the year.

Insulating glazing

By reducing or eliminating one or more sources of thermal losses (conduction, convection or radiation loss), one can considerably improve the thermal efficiency of a facade. All the efficient insulating systems are based on a multiple layer structure. One or more of these layers may be covered by special coating, e.g. low-emissivity coating. Most advanced of these systems can lower the thermal coefficient (U-coefficient) of the glazing under 1 W/m_K, for example evacuated glazing (Griffiths et al, 1998) or aerogel glazing (Reim et al, 2000).

Angular selective glazing

A third important function that may be complied by some advanced glazings is the angular selectivity. Angular selectivity means that glazing modulates the transmitted radiation in function of the incident direction of the beam. For example, one may block the direct solar radiation but transmit the diffuse skylight. The key objectives are reduced energy consumption and reduced glare. Angular selectivity can also be obtained by redirection of transmitted light. For instance, the transmitted light may be redirected towards the ceiling of the room in order to provide an acceptable level of lighting more deeply in the building.

One approach is to utilise a special class of thin film coating (Smith et al, 1998). This coating allows control of both angular and spectral properties of the transmitted radiation. Another approach is to use the internal physical structure in the glazing element (Fusco et al, 1999). Most of these require polymer glazing panels, including laser-cut panels (Reppel et al, 1998).

GONIOSPECTROPHOTOMETRY

Measurements under variable angle of incidence are not as simple as under normal incidence, not only for a question of measuring device, but also because particular aspects must be taken into account in this case.

Multiple reflections

Influence of multiple reflections may be evaluated by means of geometrical considerations. Let us consider a simple glass sheet (Figure 1). A parallel beam reaches this panel under an angle of incidence θ_1. At the first air/dielectric interface, the beam is partially reflected and transmitted (refracted). At the second interface dielectric/air, the transmitted beam splits in reflected and transmitted parts again. One can easily imagine that this phenomenon will reproduce itself infinitely.

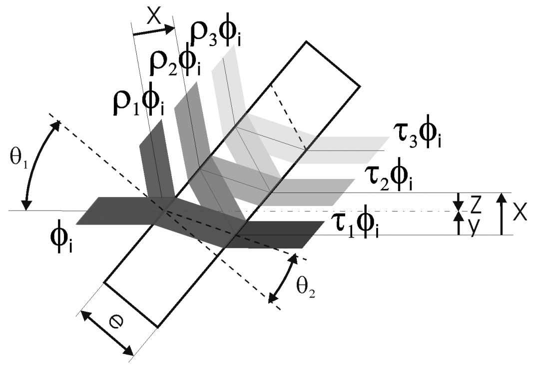

Figure 1: Multiple reflections in a simple glass sheet

The total transmitted and reflected fluxes are

$$\tau\phi_i = \tau_1\phi_i + \tau_2\phi_i + \tau_3\phi_i + \ldots \qquad \rho\phi_i = \rho_1\phi_i + \rho_2\phi_i + \rho_3\phi_i + \ldots$$

where ϕ_i is the incident flux, τ_1, τ_2, …, are the multiple transmission factors and ρ_1, ρ_2, …, the multiple reflection factors.

Now, let us consider the influence of the incidence angle on the shift between the different beams. By means of simple trigonometric operations, we find

$$\frac{x}{e} = 2\cos(\theta_1)\tan(\theta_2)$$

$$\frac{y}{e} = \sin(\theta_1) - \sin(\theta_2)\cos(\theta_1)$$

$$z = y - x$$

where θ_2 is the refraction angle of the incident beam, e is the thickness of the sheet, x the shift between two successive transmitted or reflected beams, y the shift between the first transmitted beam and the incidence direction and z the shift between the second transmitted beam and the incidence direction. Figure 2(a) illustrates the variations of the relative beam shifts in function of the angle of incidence while Figure 2(b) illustrates the amplitude of multiple components in function of the same angle of incidence. One can observe that in transmission, multiple components are of importance only at high angles of incidence.

However, at that point, the shift between two successive components is quite low (x-value) and positionning the measuring head at the first transmittance component (τ_1) output leads to measure in one step all components of importance (τ_2 and τ_3). In reflection, one can always manage to measure separately the two principal components (ρ_1 and ρ_2).

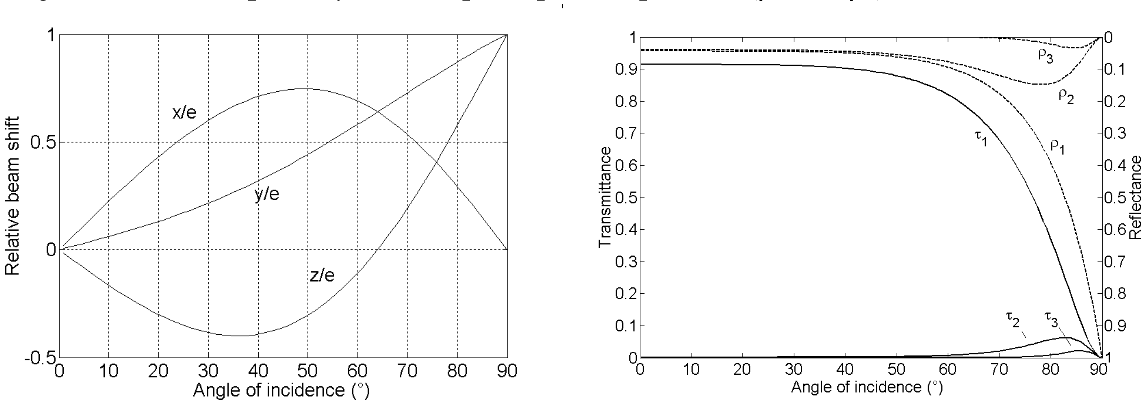

Figure 2: (a) relative beam shifts in function of incidence angle, (b) amplitude of multiple components in function of incidence angle.

Polarisation

Contrary to the case of normal incidence, light polarisation must be considered under oblique incidence because of the polarisation dependence of the optical glass properties. In our case, there would not be any problem if the incident beam was perfectly unpolarised. However, a perfect unpolarised beam is difficult to obtain with this kind of spectrophotometer. Thus it is recommended to carry out two measures with light respectively completely p-polarised and completely s-polarised, and then to calculate the average of both measures. Failing to do so, entails the risk to have an unacceptable error on the searched parameters (between 1% and 3% depending on the glass structure).

MEASURING METHODOLOGY

Apparatus

The apparatus used is a Perkin-Elmer model Lambda 900, double beam spectrophotometer with a spectral range from 175 to 3300 nm. It is equipped with an angular accessory, model PELA 1030. The accessory includes two symmetric mirror paths for reference and measurement beams. These beams are collected in a small integrating sphere through small apertures, one on the top of the sphere (for the reference beam) and the other on the side of the sphere (for the measurement beam). The sample is mounted on a rotary turntable, the movement of which is independent of the one of the sphere. The sample position can be varied from 0° to 360° while the sphere position can be varied between 180° (direction of incidence beam) and 20° (near-normal reflectance, as illustrated on Figure 3). The polarizer is of a Glan-Thompson type. It has been placed at the entrance of the measurement beam in the accessory for a question of bulk but it could have been placed in whatever position in the path of the measurement beam before this latter reaches the sample.

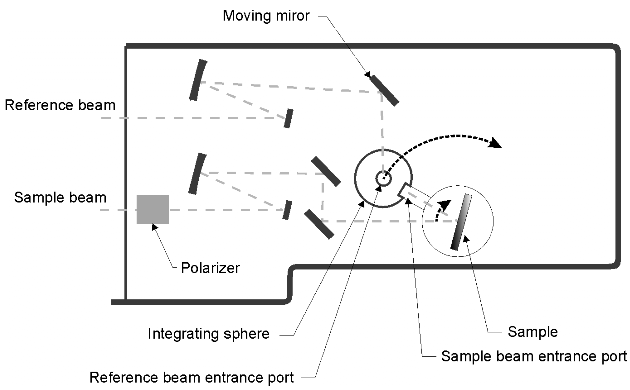

Figure 3: Angular accessory principle.

Measuring methodology

Figure 3 illustrates the measuring geometry for specular reflectance. The measurement of regular transmittance is simply obtained by positioning the sphere at 180° and the sample in the position required for the choosed incidence. We observed problems due to multiple reflections because of the shift appearing at high angles of incidence. The problem was notably due to the fact that one of the main (first or second) transmitted or reflected components reached the sphere out of the detecting aperture. We solved that problem by adding a lens at the front of the sample beam entrance port of the sphere (Figure 4).

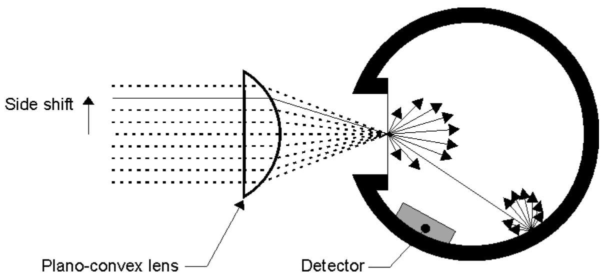

Figure 4: Positioning of plano-convex lens.

The measures obtained in the case of regular samples are simply the spectral transmittance or reflectance factors, $\tau(\lambda)$ and $\rho(\lambda)$.

EXPERIMENTAL RESULTS

An empirical model for angular properties predictions exists for simple clear or body-tinted glass (Rubin et al, 1998). We realised experimental measurements on such a sample and results were compared. This comparison is illustrated in Figure 5. One can observe the perfect correspondence between theory and experience.

As a second validation test, we compared our results with previous results of the European ADOPT Project, in the frame of which five commercial coated samples have been compared (Hutchins et al., 2001). We realised some tests on a part of these samples (kindly lent by Glaverbel, Belgium) and we compared the results with the mean of the European laboratories results. In all cases, the results were very similar (typical deviation lower than +/-1%). Figure 6 illustrates the comparison of the results obtained with an anti-reflective sample. It is important to note that no empirical model exists for such complex glazing.

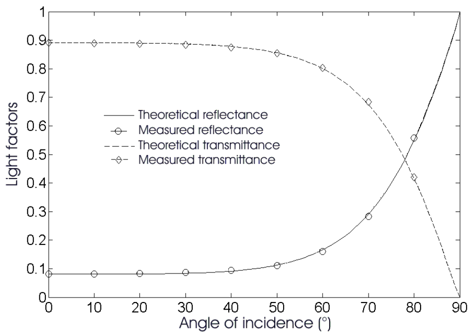

Figure 5: Comparison between theoretical model and experimental results for a clear glass.

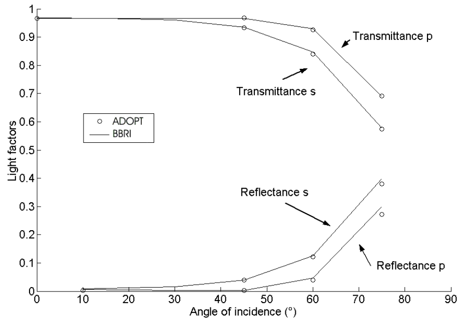

Figure 6: Comparison of light transmittance and reflectance factors between ADOPT Project and BBRI results.

CONCLUSIONS

The apparatus studied here has been adapted for angular characterisation of several advanced and complex glazings. Coated samples (e.g. low-emissivity glazings) can be perfectly studied. The sample thickness must not exceed a certain value in order to restrain the lateral shift of the beam. For this reason, measurement of multiple glazing cannot be realised as such, but properties can be deducted from the characteristics of each component. Angular-selective glazing can be measured as far as the "pattern" of the glazing is not too wide compared with the measuring beam area. Chromogenic glazing cannot be measured without adding an extra control device, for example a temperature regulator in the case of a thermotropic glazing.

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