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EXPERIMENTAL DETERMINATION OF SPECTRAL AND ANGULAR DEPENDENT OPTICAL PROPERTIES OF INSULATING GLASSES

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ABSTRACT

An experimental set-up has been built in order to determine the performance of spectral and angular dependent optical properties of insulating glass units by transmittance and reflectance measurements. The present experimental method contrasts with the common approach in which the relevant data of the individual components of the insulating glasses (such as coated glass panes and membranes) are obtained by spectral and angular dependent measurements, which are used to *calculate* the properties of an insulating glass unit. Along with the knowledge of the secondary internal heat transfer factor the present experimental method represents an efficient way to obtain a complete and precise data set in order to perform dynamic in-door temperature calculations for a building during a given climatic episode.

INTRODUCTION

Physical properties of insulating glasses (IG) play a key role in energy issues of buildings both for heating and cooling, in-house climate comfort and aesthetic appearance. In the case of highly glazed façades the choice of an IG has a great influence on the energy management of the building especially in summertime when extreme heat loads by solar radiation may occur. However, the optimal evaluation of commercial insulating glasses is hindered by a lack of knowledge of *complete optical and thermal properties* of products available on the market. In particular, manufacturers give optical properties such as transmittance and reflectance data and solar gain figures only for normal light incidence, a situation that is almost never relevant in practice.

Therefore, an optical experimental set-up has been designed and realized in order to characterize completely IGs consisting of two or more glass panes or glass panes combined with coated polymeric membranes. The equipment enables fast spectral measurements of both the direct transmittance and reflectance at angles φ starting from 0° and 15°, respectively, up to 75° in the wavelength range from 350 nm to (currently) 1650 nm.

EXPERIMENTAL SET-UP

The experimental set-up shown in fig. 1 consists of a special light source, a revolving support carrying the IG, a receiver collimator either positioned in the main axes of the light source or at various angles φ for measuring the optical transmittance and reflectance, respectively (*T collimator* and *R collimator* in fig. 1). In the collimator the light is focused to the front entrance of a quartz fiber bundle that transmits the radiation to diode array spectrometers in order to determine spectral intensities in the near UV, visible and near infrared wavelength range. Reflectance measurements are performed for normal and inverse light propagation direction in the IGs. The absorptance as a function of φ is the basis for the determination of an angle dependent solar gain value, g[1].

Light source

The front diffusor plate of the light source provides a rectangular area (25 x 38 cm^2) of homogeneous diffuse radiation in the near UV, visible and near infrared wavelength range. Two types of lamps are used: a matrix of 25 quartz tungsten halogen lamps (35 Watts) with integral aluminum coated reflectors and two UV fluorescence lamps (20 Watts, length 40 cm). A homogeneous intensity distribution over the front diffusor plate is required in order to account correctly the radiation passing the IG indirectly by one or several internal reflections between the glass panes. The relative horizontal homogeneity over a distance of 30 cm amounts ±0.02. This has been realized by several means: the arrangements of the lamps, special diaphragms in front of the fluorescence lamps, an internal and a front diffusor plate and the interior walls of the light source housing consist of highly reflecting aluminum mirrors which generate virtually an infinite lateral extension of the light source interior. A high temporal stability of the radiation intensity over the time period of the measurements of one IG is obtained by making use of stabilized DC power supplies.

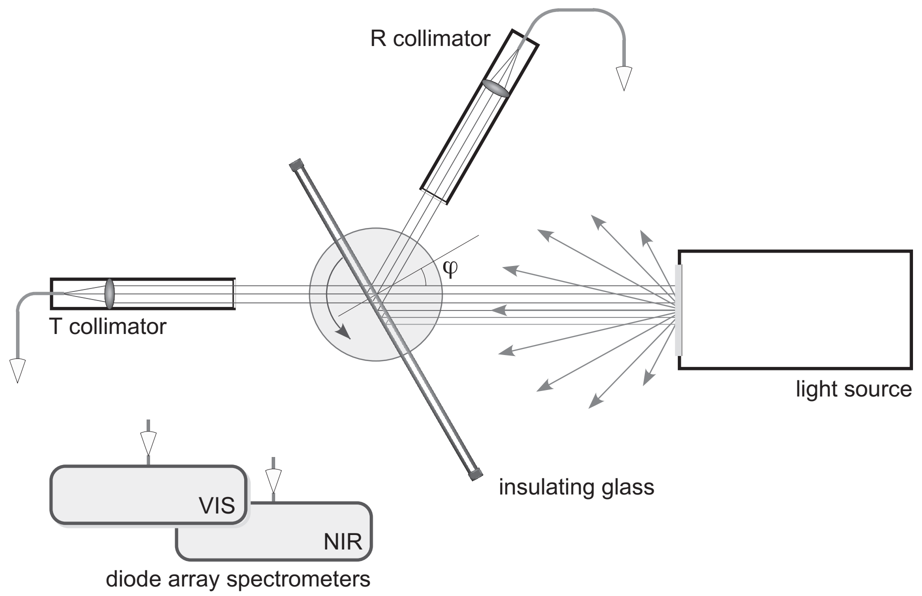

Figure 1: Experimental set-up for spectral optical, angular dependent measurements of both the direct transmittance and reflectance in the near UV, visible and near infrared wavelength range.

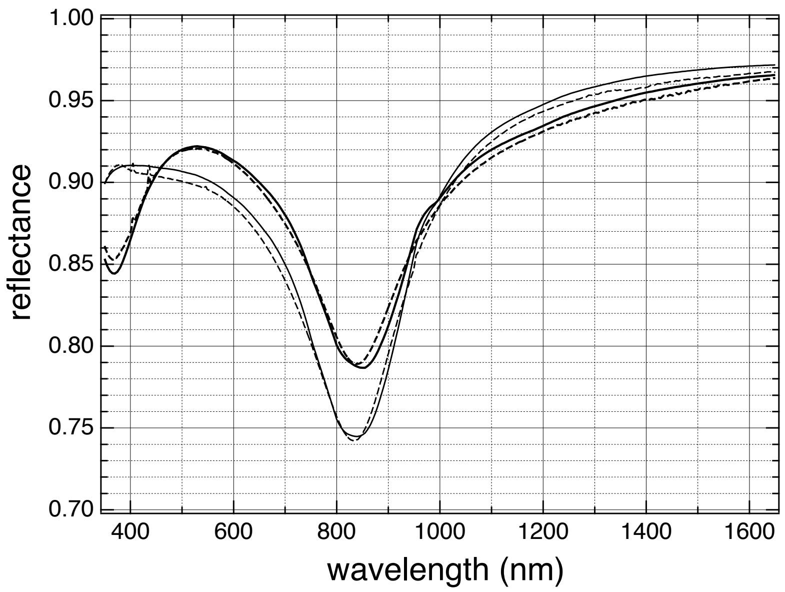

Figure 2: Reflectance of the calibration mirror determined at two angles φ of light incidence, 15° (thicker lines) and 60° (thinner lines). Full and dashed lines represent data obtained via ellipsometric and direct reflectivity measurements, respectively.

Receiver collimator

The receiver collimator defines the direction of the transmitted or reflected bundle of parallel radiation, which contributes to the transmittance and reflectance measurements. It consists of a quartz lens with an aperture of 28 mm and a focal length of 76 mm. The incoming radiation is focused to the entrance area of a y-shaped quartz fiber bundle, which enables a permanent connection to two diode array spectrometers.

Diode array spectrometers
Fast data acquisition is realized by two diode array spectrometers MCS 501/UV/VIS/NIR and MCS 511/NIR (Zeiss, Jena, Germany) equipped with 1024 Si and 128 InGaAs diodes, respectively. One spectrum is typically measured within a few seconds. In the present set-up the upper wavelength is limited to 1650 nm. However, according to general standards[2] the wavelength range in order to calculate one-figure values (e.g. the solar direct transmittance $\tau_e(\varphi)$) is 300 nm $\leq \lambda \leq$ 2500 nm. The error resulting from the missing data for $\lambda >$ 1650 nm is minimized by extrapolating the spectral data by the constant value obtained at 1650 nm to 2500 nm.

Calibration procedure for reflectance measurements
Absolute reflectance data are obtained by using a SiO_2 coated aluminum calibration mirror (10 x 16 cm^2) with known spectral and angular dependent reflectivity determined by two independent methods: *(i)* direct measurement of the angular dependent spectral reflectivity by using the set-up shown in fig. 1, and *(ii)* by determining ellipsometrically the thicknesses of the Al_2O_3 and SiO_2 surface layers and calculating the optical reflectance by using literature data for the optical constants of Al, Al_2O_3 and SiO_2 [3]. The deviations of the data obtained by the two methods are $< 10^{-2}$ in the entire wavelength range. Figure 2 shows the reflectivity data for two angles of incidence determined by the two methods.

Data accuracy
The reproducibility of the experimental spectral transmittance and reflectance data is of the order $\pm 3 \cdot 10^{-3}$. The absolute accuracies of the spectral transmittance and reflectance values amounts $\pm 7.5 \cdot 10^{-3}$ and $\pm 1.5 \cdot 10^{-2}$, respectively. The absolute error of derived one-figure values (see below) amounts $< 10^{-2}$.

EXPERIMENTAL RESULTS

Spectral data
Figure 3 and 4 show transmittance and reflectance measurements of the commercial sun protection insulating glass *Pilkington Insulight™ Sun Neutral 68/34*[4] obtained at angles of incidence φ between 0° and 75°. Reflectance measurements have been performed for both light propagation directions (corresponding to both mounting possibilities, IG outside to the exterior denoted as normal mount, NM, and IG outside to the interior of the building denoted as reverse mount, RM, in the following) in order to calculate the absorption $\alpha(\varphi)$ and the solar gain factor $g(\varphi)$[1] as well for both light propagation directions. The reflectance shown in fig. 4 corresponds to NM.

Derived optical data
The transmittance and reflectance spectra obtained at different angles φ of incidence are used in order to determine (among others) the following parameters as a function of φ (all calculations and spectral distribution functions according to European Standard *'Glass in Building'*[2]): solar direct transmittance $\tau_e(\varphi)$, light transmittance $\tau_v(\varphi)$, solar direct reflectance $\rho_e(\varphi)$, light reflectance $\rho_v(\varphi)$, and direct solar absorptance $\alpha_e(\varphi)$. Except for the transmittance related parameters all functions are determined for both light propagation directions.

Figure 5 shows the functions $\tau_e(\varphi)$, $\tau_v(\varphi)$, $\rho_e(\varphi)$ and $\alpha_e(\varphi)$. Crosses represent experimental data points obtained at the above mentioned angles φ whereas the full lines show a fit of an analytical function which is required whenever model calculations of the heat load of a building is performed. A type of sigmoid function has been found very well suited for this problem since it allows a flat plateau at small angles and even an inflexion point at high angles. The latter is sometimes required for a satisfactory fit. The present sigmoid function is given by

$$f(\varphi) = k_0 + k_1 \cdot \varphi + \frac{k_2}{exp\left(\frac{\varphi - k_3}{k_4}\right) + k_5} \qquad (1)$$

The six coefficients $(k_0, k_1, k_2, k_3, k_4, k_5)$ for the three functions $\tau_e(\varphi)$, $\tau_v(\varphi)$ and $\alpha_e(\varphi)$ for the present IG are (angle in degree)

(-0.10056, -0.0002864, 0.64589, 75.623, 11.022, 1.4292)
(-0.19211, -0.00029654, 0.87668, 78.962, 10.011, 0.99621)
(-0.71348, 0.00059268, 1.0323, 92.837, 5.4995, 0.96671).

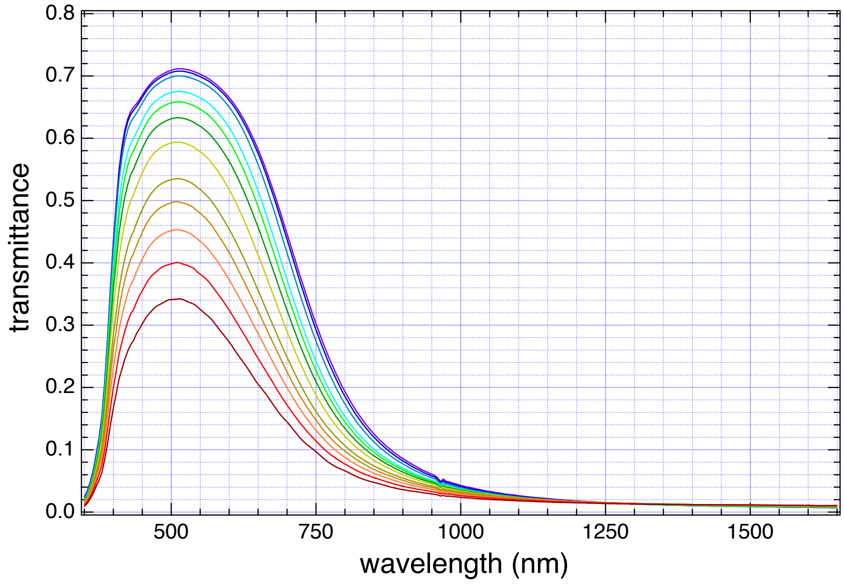

Figure 3: Spectral transmittance of the sun protection insulating glass Pilkington Insulight™ Sun Neutral 68/34. The spectra have been obtained at 12 different angles φ of incidence (in degrees from top to bottom): 0, 15, 30, 45, 50, 55, 60, 65, 67.5, 70, 72.5, and 75.

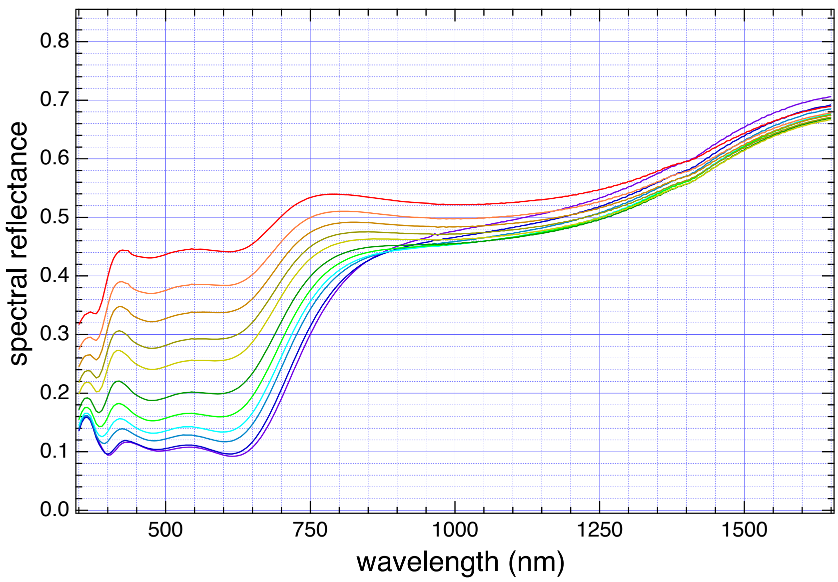

Figure 4: Spectral reflectance of the sun protection insulating glass Pilkington Insulight™ Sun Neutral 68/34. The spectra have been obtained at 11 different angles φ of incidence (in degrees from bottom to top in the range 350 nm < λ < 1650 nm): 15, 30, 45, 50, 55, 60, 65, 67.5, 70, 72.5, and 75.

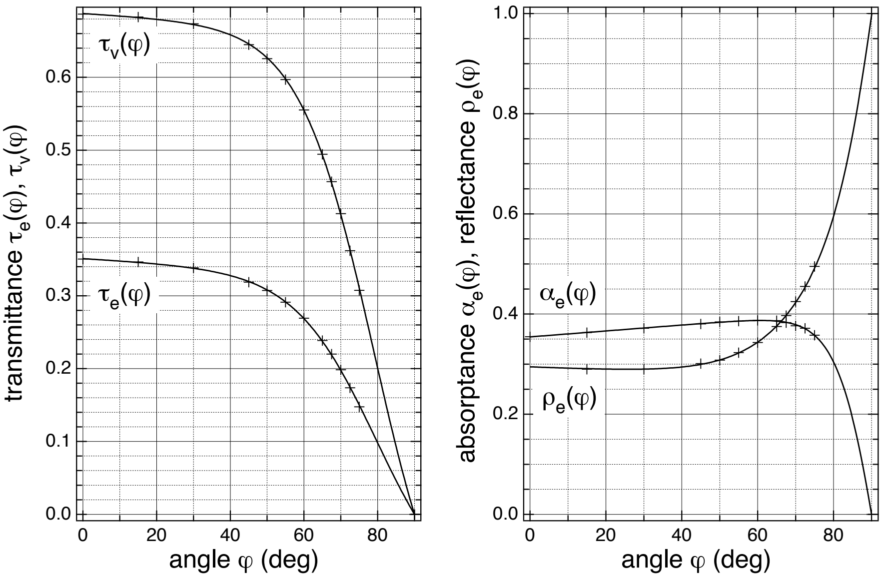

Figure 5: $\tau_e(\varphi)$, $\tau_v(\varphi)$, $\rho_e(\varphi)$ and $\alpha_e(\varphi)$ for the insulating glass Pilkington Insulight™ Sun Neutral 68/34. Crosses represent experimental data points whereas the full lines show a fit of a sigmoid function (see text).

The comparison with data given by the manufacturer for the present commercial sun protection glass looks as shown below. Parameters with a dash (e.g. ρ_e') correspond to reverse mount, RM of the IG). All values are given for normal light incidence:

parameter	*present measurements*	*manufacturer*
τ_e	0.351	0.34
τ_v	0.688	0.68
ρ_e	0.294	0.33
ρ_v	0.105	0.10
ρ_e'	0.368	0.37
ρ_v'	0.118	0.12
α_e	0.355	0.33
α_v	0.207	0.22
α_e'	0.281	0.29
α_v'	0.194	0.20
g [1]	0.389	0.37
g' [1]	0.499	0.50
τ_v/g	1.77	1.84
$(\tau_v/g)'$	1.38	1.36
R_a [2]	93.3	93

The absorptance values at $\varphi = 0$ have been obtained by linear extrapolation from the corresponding values at $\varphi = 15°$ and $\varphi = 30°$.

Characterization in terms of colors

The present experimental optical data are also analyzed in order to obtain a characterization of various color properties of the IG *as a function of the angle of light incidence* φ and assuming D_{65} standard daylight illumination[2]: *(i)* color of transmitted light, *(ii)* color of reflected light, *(iii)* color rendering of test colors and *(iv)* the general color rendering index R_a[2] (all data as a function of φ).

Angular dependent solar gain factor (total solar energy transmittance)

The total solar energy transmittance $g(\varphi)$ is given by

$$g(\varphi) = \tau_e(\varphi) + q_i(\varphi) \qquad (2)$$

$q_i(\varphi)$ represents the secondary heat transfer to the interior of the building due to the optical absorption of solar radiation in the IG, which causes a temperature rise of all elements with non-vanishing absorptance. The secondary heat transfer to the interior cannot be determined from the present optical measurements. A detailed optical characterization of all individual components of the IG would be required in order to calculate q_i[2]. However, the idea of the present method is to perform measurements on the complete IG in a non-destructive manner, a method that can also be applied to glazings manufactured years ago in order to characterize the performance IGs in existing buildings. Therefore, an experimental method has been developed in order to determine q_i of complete IGs[1].

CONCLUSION

The determination of accurate angular dependent optical properties of insulating glasses is a complex procedure. On one hand the parameters of the IGs are computed according to the method described e.g. in the European Standard[2] which requires the detailed knowledge of the angular dependent properties of the individual components of the IG. On the other hand methods have been suggested in order to predict angular dependency without having to perform measurements or detailed calculations[6,7].

The experimental method described here represents an efficient way to determine precisely all relevant optical data as a function of light incidence angle of complete IG units. Along with the experimental determination of the angular dependent solar gain factor (total solar energy transmittance) a full optical and (except for the thermal transmittance *U*) thermal characterization of IGs is available. The as determined data enable reliable dynamic simulations of indoor temperatures of buildings with highly glazed façades.

The data obtained by the present method in the authors' laboratory will be published in an internet-hosted database[5].

ACKNOWLEDGEMENT

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