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ANGULAR-DEPENDENT OPTICAL PROPERTIES OF LOW-E AND SOLAR CONTROL WINDOWS—SIMULATIONS VERSUS MEASUREMENTS

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Abstract—The angular-dependent optical properties of low-e and solar control glazings have been investigated in a European project, ADOPT, within the Standards Measurements and Testing programme. The object of the project has been to identify reliable ways of predicting the angular dependency without having to perform measurements or detailed calculations. Two new predictive algorithms have been developed and validated. For the investigated coatings the accuracy of these predictive algorithms is mostly within 1% of the value obtained by measurements or Fresnel calculations. This is an improvement over previously used algorithms, which have failed to distinguish between different types of coatings. The improved accuracy is of importance in energy simulation of buildings and makes improved product specification possible.

1. INTRODUCTION

Over the last few years the market has seen an increasing interest in energy efficient windows all over the world. Modern coating technology has led to the introduction of a large number of coated glazing products on the market; products which allow the builders and architects to control the energy flow through the windows in a more efficient way than was previously possible. Several types of solar control coatings can be deposited on standard float glass and the solar and light transmittance through the glass together with the thermal emittance of the coated surface can be varied within wide limits (Johnson, 1991; Arnaud, 1997). Such a coated glass pane in a double or triple pane configuration, sometimes with two coated panes, can form a very efficient window. With U-values below 1.0 W/m^2 K and a total solar energy transmittance[1] ranging from very low values to as high as close to 0.8, a properly designed window can contribute to reduce energy consumption for the heating and/or cooling of a building. In a heating dominated climate a high solar factor and a low U-value are desired. In a cooling dominated climate the solar factor should be low with a high, or at least moderate, light transmittance.[2]

For the user this has led to a situation where choosing the window not only means choosing between different frames, but also between different types of glazing. In order to make the best choice of windows with respect to heating and cooling demands, it becomes necessary to make an estimation of the energy balance of the window. The energy evaluation should be made separately for the heating and cooling seasons and only the energy flow of significance for the building's energy consumption for the heating and cooling systems should be considered. In order to calculate the correct amount of solar energy transmitted through the window, the total solar energy transmittance of the glazing needs to be known for all angles of incidence of the solar

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[1]The total solar energy transmittance, also called solar factor, is denoted g in ISO and CEN standards. In American notation this is identical to the solar heat gain coefficient. In the literature it is frequently referred to as the 'g-value'.

[2]The light transmittance is frequently also called luminous transmittance or visible transmittance.

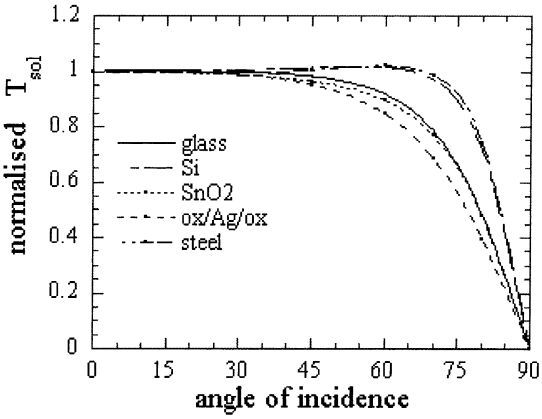

Fig. 1. Angular dependence of the direct total solar transmittance (normalised) for the coated glazings as indicated.

irradiation (Karlsson *et al.*, 2000a). For coated glazings the angular variation function is different for different categories of the materials used in the coatings. Moreover, it turns out that the most typical angles of incidence for solar irradiation are in the range 45–75 degrees which coincides exactly with the angle of incidence range where the difference between different coatings is largest. This is illustrated in Fig. 1, which shows the angle dependence of the solar direct transmittance of some coated glazings. It can be seen that the difference between different coatings is considerable for angles greater than 45 degrees.

Within a Ph.D. programme of research (Powles, 1999) various algorithms for the angular dependence and their impact on building energy simulation results have been investigated. This programme was carried out in collaboration between University of Sydney and Lawrence Berkeley National Laboratory. Powles investigated a simplified Fresnel approach where the actual coating was replaced by either a single equivalent substrate, or by a film with a simplified composition on a substrate (Rubin *et al.*, 1999). In all cases the optical constants of the model sample were calculated so as to reproduce the measured optical properties of the real sample at normal incidence. Using these optical constants Fresnel calculations were then applied to calculate the angular variation. This approach is very similar to one of the models studied within the ADOPT project presented in this paper.

2. THE ADOPT PROJECT

In the European collaborative project, ADOPT (*Angular dependent optical properties of coated glass and glazing products — Measurement procedures and validation of associated predictive methods*), sponsored within the 4th Framework Programme — Standards Measurements and Testing, the optical properties versus angle of incidence have been investigated for a number of low-e and solar control glazings. The total solar energy transmittance includes absorbed, re-emitted radiation and cannot be measured directly with a spectrophotometer. It has to be calculated from the optical properties of the individual panes using the ISO 9050 or EN 410 standards. These standards are only specified for near normal incidence, although they can be used for oblique incidence. It must be realised, however, that in such a case the optical properties of the panes have to be known for *p* and *s* states of polarisation for all relevant angles of incidence. Furthermore, the required properties include the reflectance of both the coated and uncoated side of the pane as well as the transmittance. All of this leads to an unreasonable amount of data, and considering the difficulties involved in performing measurements at oblique angles of incidence the accuracy of available data is in general limited and the final results become unreliable. For practical reasons approximate methods would be preferred. The simplest possible method is to use the near normal value of the optical properties for all angles of incidence, but this is clearly too inaccurate as can be seen in Fig. 1. Another simple way, which is used by window simulation tools, such as Window and Vision, is to assume the same angular variation profile as that of uncoated glass. This is not a bad approximation for some coated glazings but it fails for some of the most common types of coatings. This method of predicting the angular variation is used as a reference method in this paper and we simply call it 'the clear glass model'. It is obvious that any new predictive algorithm has to be more accurate than the clear glass model in order to be justified. Whenever used, the results of the clear glass model have been obtained by correctly considering single, double or triple glazed units.

The scope of the ADOPT project has been to find improved approximate methods for the prediction of the optical properties of glazings and to validate these methods by comparison with both Fresnel calculations and accurate measurements. To do this, two sets of customised samples were prepared. The first set consisted of dielectric coatings on glass. The second set contained more realistic coatings similar to the ones found in commercial products, but without diffusion barriers or adhesion layers. In order to obtain the values of the optical constants and film thickness of the coatings, these two sets were characterised by optical spectroscopy, ellipsometry as well as by X-ray and neutron reflectometry. As an example, the results obtained on some samples using some of these techniques are reported in (Battaglin *et al*., 1999,2000). The transmittance and reflectance spectra measured at different angles of incidence could then be compared with calculated spectra.

The optical properties of interest for energy simulations are the spectrally integrated values for the light transmittance, T_{vis}, and total solar energy transmittance, g. The solar direct transmittance, T_{sol}, is normally of less importance and differs only marginally from g in its angular variation profile. In this report mainly the g-value is considered but exactly the same strategy can be used for light transmittance and reflectance. Since the visible wavelength region is narrower than the solar range, more extreme variations can be seen when integrating over only the visible range. This is for example manifested in a maximum in the light transmittance around the Brewster angle for some coatings. For g this maximum is suppressed due to the averaging effect of the wider wavelength range.

3. PREDICTIVE MODELS

The angular dependence of coated glazings can be obtained in different ways. Measurements and Fresnel calculations are the most precise, but are also the most difficult ways and are not suitable for routine work. Approximate methods have to be able to predict the angular dependence of different coatings in order to outperform the clear glass model as defined in Section 2 above. Three different approaches have thus been tested in this project. One approach uses exact Fresnel calculations on a highly simplified substrate model, one uses approximate Fresnel-like calculations on a 'moderately' simplified substrate and one approach is purely empirical. The second approach was not fully evaluated at the time the project ended and is therefore not included in this report. It is reported elsewhere (van Nijnatten, 1999a). The other two approaches are presented briefly in the subsections below. They differ in the way in which the angular variation function is calculated and they require different input data.

3.1. Hybrid equivalent model

The hybrid equivalent model approach is similar to the bulk model approach described by Rubin *et al*. (1999). It approximates the coated pane with a bulk uncoated substrate, which is divided into two or three layers, all of a thickness making the Fresnel calculations incoherent. At least one of the layers is non-absorbing and at least one of the others is absorbing (Montecchi *et al*., 1999,2001). A special case is set up for antireflective coatings. This model requires spectral data files for all the panes in the window. The correct equivalent configuration needs to be selected depending on the optical data of the chosen panes. This is done automatically in the software packet developed for the model. The approach is then to calculate 'equivalent optical constants' for a bulk sample having the same reflectance and transmittance as the coated pane. This leads to optical constants which may be 'unphysical', but they are nevertheless used to calculate the spectral optical properties of the panes versus angle of incidence. The next step is to calculate the spectral transmittance and reflectance of the complete window using EN 410 and then, finally, to calculate the integrated solar factor. This method has turned out to yield accurate results for a collection of tested coatings. The method is illustrated in the flow chart in Fig. 2. It requires fairly complex computations and the equivalent optical constants have to be extracted from the data files in a correct way. All calculations are performed spectrally and for the angle dependence an extended version of the EN 410 standard has to be employed since the standard does not include the angle dependence. Mathematically, however, the standard is as exact for oblique angles of incidence as it is for near normal incidence, provided the transmittance and reflectance are separated into s- and p-polarised components for the complete procedure and that the average is taken at the end for the complete window.

It is obvious from Fig. 2 that the procedure can be seen as a modification of EN 410. All steps of the standard have to be performed in a correct sequence together with the Fresnel computations. The computations are quite complex, and the user must have access to the appropriate software. When this is the case the user does not necessarily need to know exactly how the calculations are being performed, and the procedure becomes similar to performing the EN 410 calculations.

3.2. Empirical model

The second method takes account of the fact that the angular profiles in Fig. 1 can all be simulated by a simple polynomial. Such a polynomial must cross the points (0°,1) and (90°,0) and multiplied by the normal incidence value, g_o, it generates the angular g-value:

1) Obtain spectral data files for near normal incidence for all window panes

2) Calculate equivalent optical constants that give the same spectral transmittance and reflectance for the equivalent substrates as for the selected window panes (For the uncoated pane(s) this is trivial).

3) Apply standard Fresnel formalism to calculate $R_{s,p}$ and $T_{s,p}$ versus angle of incidence for the window panes using these equivalent optical constants. Subscript s and p represent s and p polarisation, respectively

4) Apply CEN410 procedure to calculate spectral $R_{s,p}$ and $T_{s,p}$ versus angle of incidence for the window.

5) Take average of s and p polarisation results to obtain R and T spectra for unpolarised light versus angle of incidence for the window

6) Integrate spectra to obtain g, Tsol or Tvis versus angle of incidence.

Fig. 2. Point by point description of the hybrid equivalent model to predict the angular variation of the optical properties of windows.

$$g = g_o(1 - az^{\alpha} - bz^{\beta} - cz^{\gamma}), \quad (1)$$

where $a + b + c = 1$ and we use a normalised angle of incidence $z = \theta/90°$. The coefficients a, b and c together with the exponents α, β, and γ can be chosen so that Eq. (1) fits the shape of the curves in Fig. 1. When fitting to the angular variation profile of the solar factor, g, for different types of windows, it was found that Eq. (1) gives a good fit for all the tested windows with the following coefficients and exponents

$$\begin{aligned} a &= 8 \\ b &= 0.25/q, \\ c &= (1 - a - b), \\ \alpha &= 5.2 + 0.7q \\ \beta &= 2 \\ \gamma &= (5.26 + 0.06p) + (0.73 + 0.04p)q \end{aligned} \quad (2)$$

The model is purely empirical and the parameters a, b, c, α, β, and γ have no physical interpretation. In Eq. (2), the parameters, p and q, are introduced. The parameter p is equal to the number of panes in the window configuration ($p = 1 - 3$) and q represents the material 'category' of the coating, which has been given values between 1 and 10 depending on the type of coating. The parameter q recognises the fact that different categories of materials have different angular profiles as shown in Fig. 1. This parameter has to be determined for different categories. The parameter p affects the angular profile in an unambiguous way and does not present any problem. Adding more panes, coated or uncoated, to the window tends to push the inflection point in the angular variation curves from angles near 90 degrees towards lower angles, thus reducing the solar factor at high angles of incidence. It is assumed that the user always knows the number of panes.

The procedure using the empirical approach is illustrated in Fig. 3. It is different from the hybrid equivalent model approach since no spectral data

1) Find g-value of window
2) Apply empirical algorithm to obtain g (Tsol or Tvis) versus angle of incidence

Fig. 3. Point by point description of the empirical model to predict the angular variation of the optical properties of windows.

Table 1. Values of the category parameter *q*, obtained by fitting Eq. (1) to the corresponding experimental functions

Glazing (coating) type	*q*-value
Absorbing electrochromic	1
Double silver	1
Absorbing, 'grey' or 'green' glass	2
Single silver (thick or thin)	2.5
SnO_2, SnO_2/SiO_2	3.5
Antireflection glass (SiO)	3.5
Clear glass	4
a-Si/SiO_2	4.5
Titanium oxide	6
Titanium nitride (TiN)	10
Stainless steel (SS)	10
TiN/SS	10
a-Si	10

are required. The only required input data is the total solar energy transmittance, *g*, at normal incidence for the complete window. For a given product, this is usually provided by the manufacturer for a selection of recommended window configurations. In case the near normal solar factor is unknown, the EN 410 standard has to be applied and then the spectral data files are of course required for the panes of the window in accordance with the standard. In order to apply the polynomial function defined by Eqs. (1) and (2), the category parameter, *q*, also needs to be known. Table 1 lists the *q*-parameter for a selection of common low-e and solar control coatings available on the market today. The values listed in Table 1 have been validated by comparing predictions using Eqs. (1) and (2) with both Fresnel calculations and with measurements (Karlsson and Roos, 2000). The listed categories cover a large fraction of the marketed products, but is obviously not 100% complete.

In order to fit the angular variation of the direct solar transmittance or the light transmittance, slightly different values of a, b, c, α, β and γ need to be chosen. This is, however, only a mathematical process. The polynomial as defined in Eq. (1) can readily reproduce also curves having a maximum in transmittance at the (pseudo) Brewster angle, as is the case for the light transmittance. The solar direct transmittance is averaged over the same spectral range as the solar factor and the shape of the angular variation curve is very similar. In fact the parameter values defined in Eq. (2) work well for the solar direct transmittance of single glazings.

4. SAMPLE SELECTION

A large part of the ADOPT project entailed performing measurements of reflectance and transmittance versus angle of incidence. The object was to identify reliable measurement procedures in order to validate the predictive algorithms. Three sets of samples were identified as being of interest to the project.

1. *Dielectric single and double layers on glass substrates:* such coatings are well known, relatively easy to prepare and to characterise. They are frequently used in a number of commercial coatings. Optical constants and film thickness of the coatings can be obtained by ellipsometry and X-ray diffraction, as well as by optical reflectance and transmittance spectroscopy. The measured optical spectra can thus be compared with spectra obtained by Fresnel calculations.
2. *Thin films of the actual materials used in low-e and solar control coatings:* these coatings include metallic, semiconducting and dielectric coatings. The chosen materials can readily be produced in a laboratory type sputter unit and the resulting coatings are reproducible and homogeneous. Samples can be prepared as single films, which makes characterisation and evaluation of the results easy and straightforward. These samples were chosen to cover a range of different materials having optical properties with different angular dependence as illustrated in Fig. 1.
3. *Commercial coatings:* such coatings are the ones the algorithms for the angular dependence are intended for. It is obvious that they have to be included in the project and studied in connection with the algorithms. A selection of commercial coatings were therefore used in an industrial round robin, which was conducted as an important part of the project (Hutchins *et al*., 2000). These coatings were chosen to represent some typical coated glazings on the market, but it was not the intention to cover every kind of coating. The coatings were judged suitable to be sent to the participants of the round robin. Since silver-based coatings were included, all samples were packed and shipped in plastic boxes containing a desiccant.

The first two categories of coatings were mainly intended as test coatings for the evaluation of the measurements and as reference materials for the comparisons of measurements, Fresnel calculations and algorithms. Only if good agreements were achieved between the results obtained by the different methods for the first two categories of coatings, the results would be reliable when the actual commercial coatings were being studied.

The samples were prepared by Saint Gobain Recherce and distributed to the participants. The

Table 2. First set of samples for evaluation in the ADOPT project

Sample	Description
1:1	TiO_2/glass (~150 nm)
1:2	TiO_2/glass (~300 nm)
1:3	SiO_2/TiO_2/glass
1:4	Antireflective single sided
1:5	Clear uncoated glass
1:6	Antireflective double sided

commercial coatings were selected from the Saint Gobain market products except the Amiran sample, which is produced by Schott. The three sets of samples are presented in Tables 2–4.

5. RESULTS AND DISCUSSION

5.1. Determination of required accuracy for algorithms

It is a complex task to determine the required limit for accuracy. It is a function of how the results are going to be used and it is a function of the accuracy of other relevant parameters. It has been shown that two different kinds of solar control windows having identical *U*-value and solar factor at normal incidence can differ substantially at high angles of incidence and that the annual amount of energy calculated per unit window area can therefore differ by as much as 10% (Pfrommer *et al*., 1994). The error caused by applying an incorrect angular dependence function for the investigated window depends on the angular distribution of the irradiation against the window. The error is low for the angular interval 0–45 degrees and has its maximum around 60–70 degrees. For many windows more than 50% of the incident solar irradiation falls within an angle interval of 45–90 degrees and for these cases it is obvious that the error when performing building energy simulations can be significant.

The required accuracy must also be seen in relation to the accuracy of the validation process. It is generally assumed that the position of a certain coating in the window does not influence the shape of the angular variation function of that window. However, a detailed analysis reveals that there is indeed a small variation at high angles of incidence. This is due to the secondary heat transfer of absorbed solar radiation. The variation is only a few tenths of a percentage point of transmittance, but nevertheless influences the accuracy. This is demonstrated in Fig. 4 for a triple glazed window with a silicon-based solar control coating. The difference is most pronounced for this type of coating having fairly high absorption. For coatings with low absorption the corresponding differences are negligible.

Other factors that may influence the accuracy of the predictive methods are variations of the thicknesses and refractive indices of the coatings. Production tolerances must allow for small variations in these values. The float glass used as the substrate also varies slightly from batch to batch, and aging and handling during transport, both before and after deposition, may influence the

Table 4. Third set of samples for evaluation in the ADOPT project and for the industrial round robin

Sample	Description	Trade name
3:1	Pyrolytic TiO_2	Antelio Argent
3:2	Dipcoated antireflective	Amiran
3:3	Uncoated low-iron glass	Diamond
3:4	Double silver solar control	Coolite
3:5	Single silver low-e	Planitherm

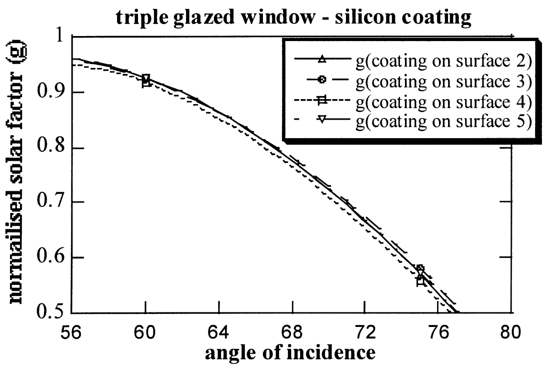

Fig. 4. Normalised solar factor versus angle of incidence calculated for four different positions of the coating in a triple glazed window. Calculations performed according to the EN 410 standard adapted to oblique incidence by separating the two polarisation states.

Table 3. Second set of samples for evaluation in the ADOPT project

Sample	Description
2:1–3	SnO_2/NiCr/Ag/SnO_2/glass (three different Ag-thicknesses)
2:4	Si/glass
2:5	TiN/glass
2:6	TiO_2/TiN/TiO_2/glass
2:7	SnO_2/glass
2:8	ITO (indium tin oxide)/glass
2:9–11	Ti/glass (three different thicknesses)

quality of the coatings. Since the methods used in this investigation are approximate by nature, they cannot possibly include all these variations. It has been shown previously, however, that the influence on the angular variation function of the solar factor is very limited when the coating thickness is varied or when the optical constants of the coatings are varied within reasonable limits (Roos, 1997). The results of the hybrid equivalent model have been tested for different assumed thicknesses of the equivalent substrate and the results are almost completely insensitive to variation in substrate thickness (Montecchi *et al*., 1999). Variations in the optical constants and actual coating thickness are automatically taken care of in this model, provided the corresponding variations in the recorded spectra are correctly reproduced.

Another limit is the more obvious limit of experimental accuracy. At the end of the day the algorithms have to be compared to experimental results. Experience shows that an experimental accuracy of better than 1% can be obtained only if the greatest care is taken during the measurements, especially for high angles of incidence. During the ADOPT project a systematic study of all possible errors specific for spectrophotometric measurements at oblique angles of incidence have been identified and evaluated (van Nijnatten, 1999b). The most problematic angles of incidence to measure accurately are around 50 degrees where the side shift of the beam has a maximum, and the angles where the derivative $dT/d\Theta$ is large for which the angular setting of the accessory becomes critical. This is outside the (pseudo) Brewster angle, usually around 70–85 degrees (cf. Fig. 1). For transparent float glass substrates with a thickness of typically 3–6 mm, it is absolutely crucial that the side shift of the beam and multiply reflected components are correctly detected. All such possible systematic errors must be eliminated and an average over more than one scan should be taken for the highest accuracy. It is then possible to obtain accuracies better than 1% also for high angles of incidence.

Looking at the 'maximum possible error' defined as the difference between the two most extreme types of coatings (represented by the upper and lower curves in Fig. 1), we can understand that it is quite large. At angles of incidence larger than 45 degrees, the difference is as large as 10–30 percentage points. It also turns out that the maximum moves to lower angles when more panes are added.

Another important issue is the extent to which the thermal emittance value of the coating affects the result. It is quite possible that different coatings of the same category can have different values of thermal emittance (indeed, this is today a sales argument used by the manufacturers of silver-based coatings for which the emittance value varies between around 0.1 and 0.04). To test this the emittance of the coating was varied within extremely large limits, much larger than that physically feasible. In spite of this there was no difference in the resulting shape of the normalised angular variation curve. The actual value differs, which is to be expected, but the shape is the same.

To summarise this section we can say that an obvious target is to achieve a higher accuracy than we get for the clear glass model (i.e. assuming the same angular variation as for clear uncoated glass). For extreme coatings the difference in solar factor at high angles of incidence can be as high as 10–30 percentage points using this model. Considering all systematic errors and variations of the coatings and the angular variation function not accounted for by the models, an accuracy of better than 3% is a reasonable target. By definition the error is always zero for normal incidence and also in the limit when the incidence angle approaches 90 degrees. Somewhere in between the error has a maximum, usually in the interval 60–80 degrees. A mean error can be defined for 0–90 degrees and a weighing procedure could be applied depending on which angle of incidence interval is the most relevant. For our discussions the maximum error is the most relevant.

5.2. Algorithms versus experiments and Fresnel calculations

The hybrid equivalent model and the empirical model have been developed, tested and evaluated by different research groups and the evaluation procedures have not been the same. The results are therefore partly presented in different forms. Moreover, the empirical model is more completely documented in published papers, and therefore there are more results available for this model. The details of the models are presented in the references and in this summary report we only give some examples of the results.

5.2.1. Results of the empirical model. As described above, the error must be much smaller than is achieved by the clear glass model. In Fig. 5 the results are shown for the empirical algorithm applied to double glazed windows made up

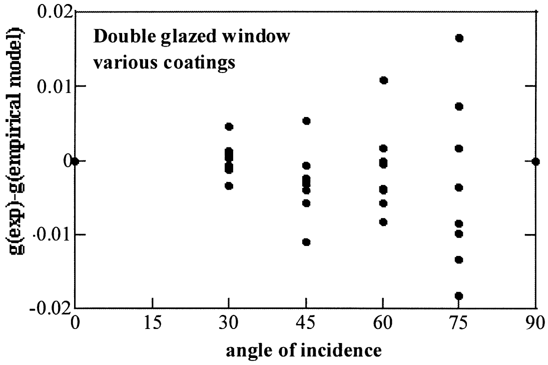

Fig. 5. Solar factor difference obtained from experimental spectra and the empirical model for a double glazed window.

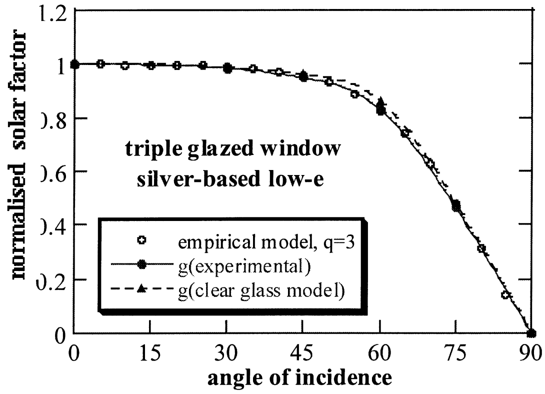

Fig. 7. Normalised solar factor versus angle of incidence for a triple glazed window with one silver-based low-e coating. The graph shows a comparison between the empirical model, the clear glass model and experimental results.

from the samples of set 2 combined with a clear float glass pane. The algorithm is compared to the experimental values of the solar factor obtained by applying the EN 410 standard to the experimental spectra. Most of the data points are within the limit ±1% and only a few at the highest angles of incidence are outside this limit. Similar results are obtained if the comparison is made between the algorithm and results of Fresnel calculations. In this case the optical constants and film thickness values obtained from the ellipsometric and neutron reflectometry analysis were used to generate calculated spectra, which were then used to obtain the calculated solar factors. Some of these results are shown in Fig. 6. As can be seen the results are quite similar to those in Fig. 5. According to the discussion about accuracy limitations in Section 5.1, we cannot expect to reach much further with an approximate algorithm. We have to remember that a certain fraction of the discrepancies as presented in Figs. 5 and 6 may be due to experimental inaccuracies or errors in the optical constants used for the Fresnel calculations. It is not the intention in these two figures to show which type of film gives the highest or lowest error, but only to demonstrate the overall agreement for many types of film. This is why the same plot symbol is used for all samples. In Figs. 5 and 6 we have chosen to present the absolute value $\Delta g = g(\text{exp/Fresnel}) - g(\text{algorithm})$ rather than the relative error $\Delta g/g$. This is because for low values of g, the value of $\Delta g/g$ can be quite large even for low values of the absolute error. For most solar energy applications it is the error in relation to the solar irradiation which is significant, not the error in relation to g. It is therefore more relevant to look at the error Δg, expressed in percentage points.

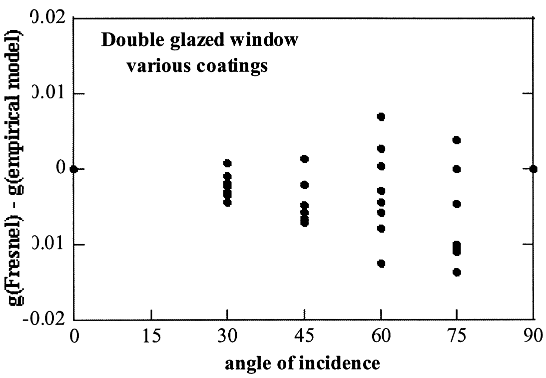

Fig. 6. Solar factor difference obtained from Fresnel calculations and the empirical model for a double glazed window.

The results for triple glazed windows are similar. In Fig. 7 an example of these results is shown as a plot of g versus the angle of incidence. The clear glass model results are also included for comparison. The example shown in Fig. 7 is for a silver-based coating. It can be seen that the algorithm performs better than the clear glass model for this example, although the difference in this case is not very large. It is typical for silver-based coatings that the angular variation function is below that of clear glass. The value of $q = 3$ used in Fig. 7 is in good agreement with the value of 2.5 as presented in Table 1. This value ($q = 2.5$) has been obtained by investigating several calculated spectra as well as a few different commercial coatings of another origin than the ones used here (Karlsson and Roos, 2000).

5.2.2. Results of the hybrid equivalent model. The hybrid equivalent model has been evaluated independently of the empirical algorithm and the choice of coatings used for the evaluation is slightly different. Nevertheless, the results show

Table 5. $\Delta g = g_{sol}(\text{Fresnel}) - g_{sol}(\text{hybrid equivalent model})$ for different kinds of coating (“twin” means that both surfaces of the glass are coated)

Sample	Δg_{max} (%)		Δg_{mean} (%)	
	2 panes	3 panes	2 panes	3 panes
a:Si	0.6	0.5	0.1	0.1
SnO_2(F)	1.1	0.9	0.6	0.5
3(SiO_2/TiO_2) (twin)	1.6	1.5	0.7	0.6
Si	0.1	0.2	0.1	0.1
TiN	0.3	0.2	0.1	0.1
TiO_2/TiN/TiO_2	1.0	1.3	0.4	0.6
SnO_2 (dielectric)	0.3	0.3	0.1	0.1
ITO (indium tin oxide)	0.5	0.5	0.3	0.2
TiO_2 [a]	0.3	0.2	0.1	0.1
SiO_2/TiO_2	2.2	2.2	0.8	0.7
3(SiO_2/TiO_2)	0.8	1.0	0.4	0.4
Cr+Fe oxides	0.3	0.2	0.2	0.1
SnO_x/SiO_2	1.2	1.2	0.4	0.4
IrO_x/Steel/IrO_x	1.6	1.4	0.7	0.7
Metal oxides (twin)	0.8	0.7	0.3	0.2
Cr+Fe oxides	0.3	0.2	0.1	0.1
TiNO	0.4	0.5	0.2	0.2
TiNO/Steel	1.0	0.8	0.3	0.2
TiO_2 [b]	0.4	0.4	0.2	0.1
$SiO_2+TiO_2+Na_2O$ (twin)	4.0	2.8	1.6	1.1
Double silver	9.1	7.7	3.4	2.9
Single silver	9.2	8.0	3.2	2.8

[a] Produced in the laboratory.
[b] Industrial production.

that the equivalent model algorithm seems to work for a large number of different coatings (Montecchi *et al*., 2001). The results are presented in Table 5 for a number of single glazings. Since these calculations are for single glazing, the solar direct transmittance was used instead of the solar factor, and the ΔT value was taken as the difference between the hybrid equivalent model and Fresnel calculations. The mean value is taken as the mean value for all the angles between zero and 90 degrees and the max value is the maximum deviation, which usually occurs around 60–80 degrees. It can be seen that the max deviation is always less than three percentage points, except for the last three samples: for silver-based coatings the results so far are not as good as for other types of coating, and further tests are underway. This model has been tested for both light transmittance and solar direct transmittance and has been shown to work well for both, excluding again silver-based coatings. These results are similar to the results shown in Figs. 5–7 for the empirical model.

5.2.3. Comparison of empirical and hybrid equivalent models. The validation process has been carried out on a number of different samples and by comparing the two models with experimental results and Fresnel calculations. It is not necessary to perform all possible tests on both models provided it can be shown that the two models themselves agree when applied to different types of windows. In Figs. 8 and 9 the results of both algorithms are shown together with Fresnel calculations and the clear glass model. For most of the coatings commonly used as solar control coatings, the clear glass model fails, while there is excellent agreement between the Fresnel calculations, the hybrid equivalent model and the empirical model. This is clearly seen for the two

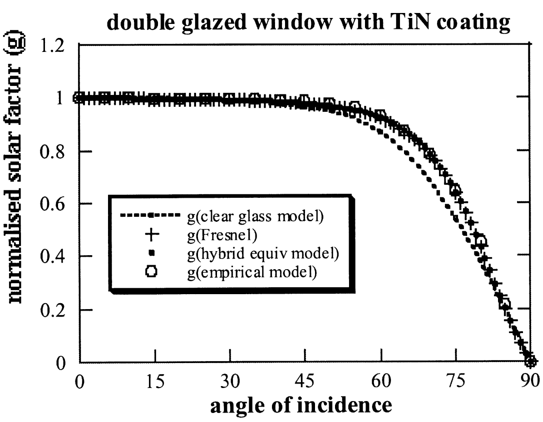

Fig. 8. Normalised solar factor versus angle of incidence for a double glazed window with one titanium nitride-based coating. Values calculated according to the empirical model, the hybrid equivalent model and Fresnel calculations. Also shown for comparison is the result of the clear glass model.

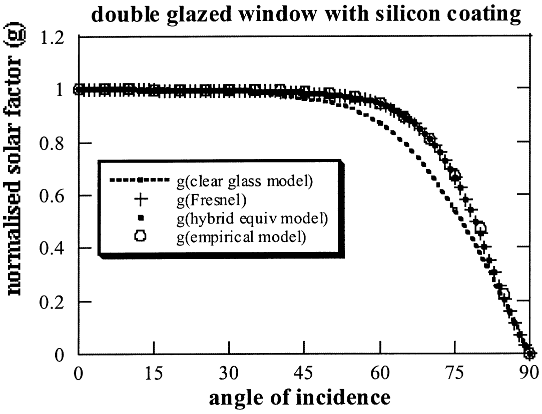

Fig. 9. Normalised solar factor versus angle of incidence for a double glazed window with one silicon-based coating. Values calculated according to the empirical model, the hybrid equivalent model and Fresnel calculations. Also shown for comparison is the result of the clear glass model.

examples reported in Figs. 8 and 9 and the results are equally good for all other tested samples.

5.3. Validation of the empirical model on commercial products and windows

The results presented in the previous section show that both models accurately predict the angular variation of most coatings used for solar control purposes. However, so far only the results for specially customised samples have been presented. For the industrial round robin some commercially available coatings were chosen. These samples were measured by several laboratories at near normal and at 60 degrees angle of incidence. The complete results of the round robin are presented in a separate report and are not given here (Hutchins *et al.*, 2000). As an example, the results of calculations using the empirical model are shown together with the experimental results. The EN 410 standard was used to calculate the experimental values of the solar factor for a double glazed window at near normal incidence, and these values were then used as input for the empirical model calculations. The results are shown in Fig. 10a–e. The data points at 60 degrees angle of incidence in these graphs represent the measured results obtained by the participating laboratories. It is irrelevant for this evaluation to know which lab is which, and we can see that the results from the seven laboratories are in good agreement.

The results in Fig. 10 are very encouraging and show that the empirical algorithm accurately predicts the angular variation of the commercial samples selected for the industrial round robin. We can also see that the selection of samples

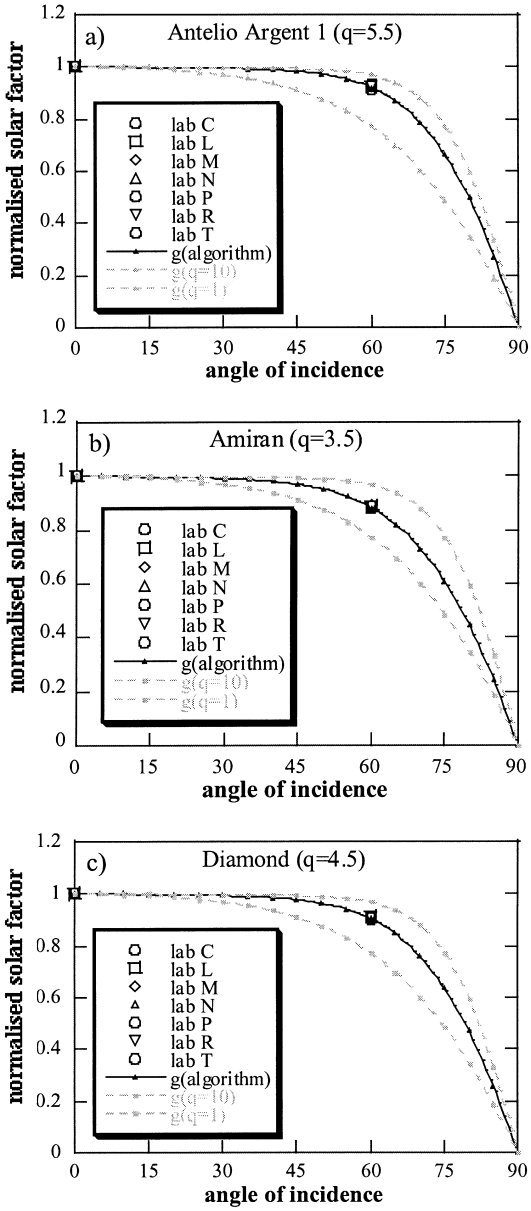

Fig. 10. Normalised solar factor for a double glazed window with one pane being the round robin sample and the other pane a standard clear float glass. Full line represents the prediction by the empirical model and symbol points at zero and 60 degrees indicate experimental values as measured by different laboratories. The dotted lines are included to indicate the borders for the most extreme possible coatings. Samples as indicated in the graphs.

represent coatings with an angular variation close to both extremes as well as in the middle. The values of the category parameter q were fitted to the experimental results at 60 degrees angle of incidence obtained by the participants of the round robin. We can see that these values are in excellent agreement with the values of q given in Table 1.

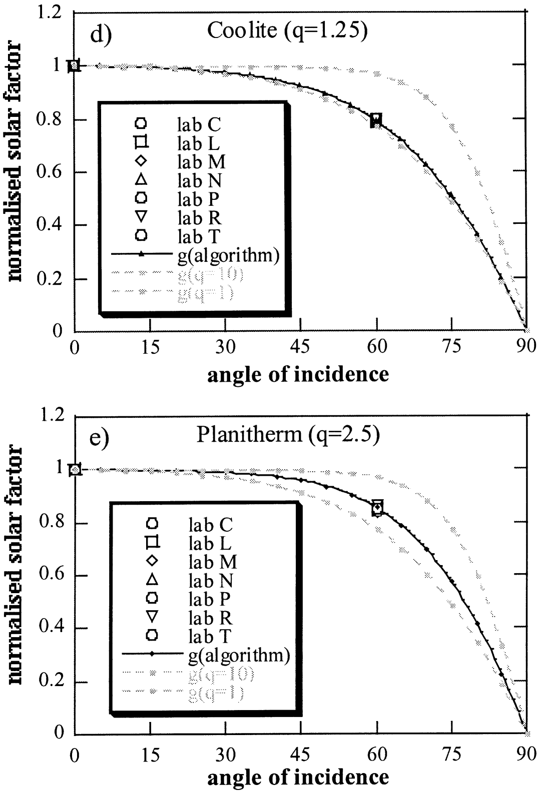

Fig. 10. (*continued*)

6. SUMMARY AND CONCLUSIONS

Two new algorithms have been presented in this paper. They are totally different in nature and require different inputs. One is very simple and the other quite complex. They both produce reliable results for a majority of the existing low-e and solar control coatings on the market. The validation process has been quite elaborate and entailed comparisons with both accurate measurements and Fresnel calculations. A selection of these results is presented in this paper, but for a more complete presentation the readers are referred to the references. Exactly to which extent the improved accuracy is needed remains to be established. It will depend on the application.

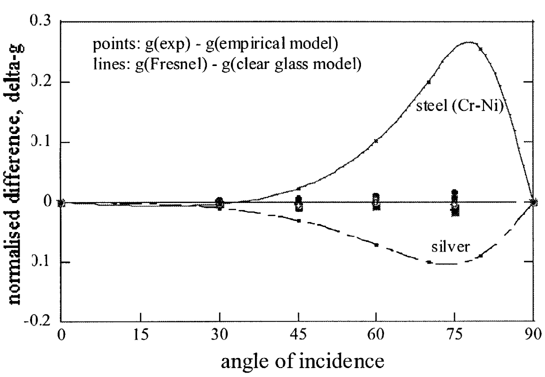

Fig. 11. Difference in solar factor between prediction and experiment/Fresnel calculation. Graph illustrates the improvement obtained by the empirical model compared to the clear glass model for the ‘worst cases’.

Going back to the discussion about accuracy in Section 5.1, we can see in Fig. 11 that the improvement compared to the clear glass model is quite considerable for the most extreme coatings when the new empirical algorithm is used. For some kinds of coatings, for instance conducting oxides such as ITO or fluorine doped tin oxide, the improvement is not as large. The clear glass model works well for all coatings with a category parameter close to $q=4$ in Table 1. The general conclusion is, however, that the new algorithms produce more reliable results.

The empirical model requires that the coating category is known, the category being basically determined by the material used for the coating. Other than that only the solar factor for the window needs to be known, information which is usually provided by the manufacturer according to the EN 410 standard. A very important advantage with the empirical model is that it can be added to existing standards as an appendix. Nothing at all needs to be changed in the current standard procedure. The algorithm is simply added at the end of the EN 410 (or, equivalently, the ISO 9050) standard. It can also be easily incorporated in any simulation software, since it only consists of one simple equation, Eq. (1). The category parameter is unambiguously determined by the materials used in the coatings, and is given for most coatings in Table 1. This is also information which can be easily provided by the manufacturers. In some cases where unusual combinations of materials are being used in the coating the category parameter may need to be determined by independent measurements. For this purpose only one oblique angle of incidence needs to be measured, say 60 degrees. By fitting the result at 60 degrees to Eq. (1), the value of q can be determined, and any other angle of incidence can then be accurately calculated from Eq. (1). For building simulations it is possible that the category parameter introduced for the empirical model can be reduced to fewer values, for instance ‘low’, ‘medium’ and ‘high’, depending on whether the angular variation function is below, about equal to or above that of uncoated glass. This is only speculation, though, and is left to be established in future work.

The hybrid equivalent model requires that the spectral reflectance and transmittance data files for all panes in the window are available for near normal incidence together with the thermal emittance of the coated pane(s). This is the same requirement as for the EN 410 and ISO 9050 standards. The model then requires that these data files are used to extract equivalent optical constants for all the panes of the window. This is a complex procedure and only experts in the field of optical properties are capable of doing this. Most users would require access to a software packet in order to perform the calculations. The algorithm is thus suitable for anyone who is used to work with standards EN 410 and ISO 9050. In fact a considerable part of the procedure is to perform these standard calculations. For a correct result the content of the standards would need to be modified and the calculation to extract the equivalent optical constants would have to be added together with a detailed description of how to calculate the optical properties of the window at oblique angles of incidence taking polarisation into account. At the present stage the accuracy of the algorithm is lower for silver-based coatings since it is an inherent property of the calculation procedure, which is less suitable for the modelling of materials with a very low refractive index and a high extinction coefficient (Karlsson *et al*., 2000a,b). This problem is currently under investigation.

The results of the ADOPT project have shown that simple predictive algorithms can accurately reproduce the angular variation function of windows with both coated and uncoated glazings. The agreement between the new algorithms and Fresnel calculations or experiments is for most coatings and angles of incidence better than one percentage point. Higher accuracy is difficult to achieve for the simple reason that the validation becomes uncertain. The improved accuracy obtained with these algorithms compared to previously used ones, such as the clear glass model, can directly improve the accuracy of building simulations since the total solar energy transmittance can be predicted with better accuracy than it was in common practice to date. Window energy simulations using a simple model for the calculation of annual energy balance (Karlsson and Roos, 2000) indicate an error of the order of 5–10% in annual energy performance for the window if an incorrect angular variation function of the solar factor is used. The error depends on the orientation of the building, climate and type of building. The most extreme cases are probably found closer to the equator where a higher fraction of the solar irradiation strikes the window at high angles of incidence. It is, however, far beyond the scope of this paper to evaluate these errors in detail.

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