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ANGULAR DEPENDENT SOLAR GAIN FOR INSULATING GLASSES FROM EXPERIMENTAL OPTICAL AND THERMAL DATA

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ABSTRACT

An experimental determination of the angular dependent solar gain factor (or total solar energy transmittance, $g(\varphi)$) of complete insulating glasses has been developed and tested for two-glass units. The method is based on the optically measured angular dependent solar absorptance $\alpha(\varphi)$ and the determination of the heat flows q_e and q_i from the outer and inner surfaces of the insulating glass to the ambient under simulated solar radiation.

INTRODUCTION

The solar gain factor g (or total solar energy transmittance) of an insulating glass (IG) is an important factor for calculating the internal heat load or making dynamical temperature simulations for buildings. For realistic simulations g must be known as a function of the light incidence angle φ. Factor g is given by

$$g = \tau_e + q_i$$

where τ_e and q_i are the solar direct transmittance and the secondary internal heat transfer factor, respectively[1].

The secondary internal heat transfer q_i can be *calculated* for normal light incidence provided the following parameters are known: spectral transmittance, spectral reflectance and spectral absorptance of all individual components (glass panes and if present polymeric membranes including its optical coatings) of the IG along with the thermal conductance coefficients between adjacent pairs of components. Spectral transmittance, reflectance and absorptance must be known for both light propagation directions through the IG. Due to its complexity this procedure can hardly be applied routinely. An alternative approach has been suggested in order to predict angular dependency without having to perform measurements or detailed calculations[2]. Manufacturers of IGs give solar gain factors only for perpendicular light incidence and angular dependent values are generally not available.

A direct and efficient experimental method has been developed in order to determine the angular dependent solar gain $g(\varphi)$. The present method is based on the precise knowledge of the angular dependent solar direct absorptance $\alpha(\varphi)$ that is obtained from a complete optical characterization of insulating glass units that has been described in a previous work[3].

$g(\varphi)$-EXPERIMENT

Method

The method is based on the following simple idea: since we know the solar direct transmittance $\tau(\varphi)$ and the solar direct absorptance $\alpha(\varphi)$ the only missing information is how the solar absorptance is split into the heat flows q_e and q_i from the outer and the inner glass panes' surfaces to the ambient since the following equation is valid in the steady state

$$\alpha = q_e + q_i$$

In the present method q_e and q_i are determined experimentally in a solar simulator that irradiates the IG with radiation close to the solar spectrum (see below for experimental details) by measuring the outer and inner surface temperatures of the IG. The temperature increments are related to the heat flows from the surfaces towards the ambient in the quiescent air according to heat transport theory for free convection flows at vertical plates known for about a century. We do not reproduce here this theory that can be found in numerous textbooks and special literature (see e.g. ref. [4]). Figure 1 shows the total surface heat transfer coefficient h_{tot} for free convection and its contributions, a conductive term from free convection h_{cond} and radiation h_{rad}:

$$h_{tot} = h_{cond} + h_{rad}$$

h_{rad} is computed by assuming an emissivity of crown glass of $\varepsilon = 0.837$[1,5]. The relation $h_{tot}(T)$ yields directly absolute *heat flows* (in W/m^2) at the outer and inner glass panes' surfaces denoted as $\bar{q}_e$ and $\bar{q}_i$ in the following.

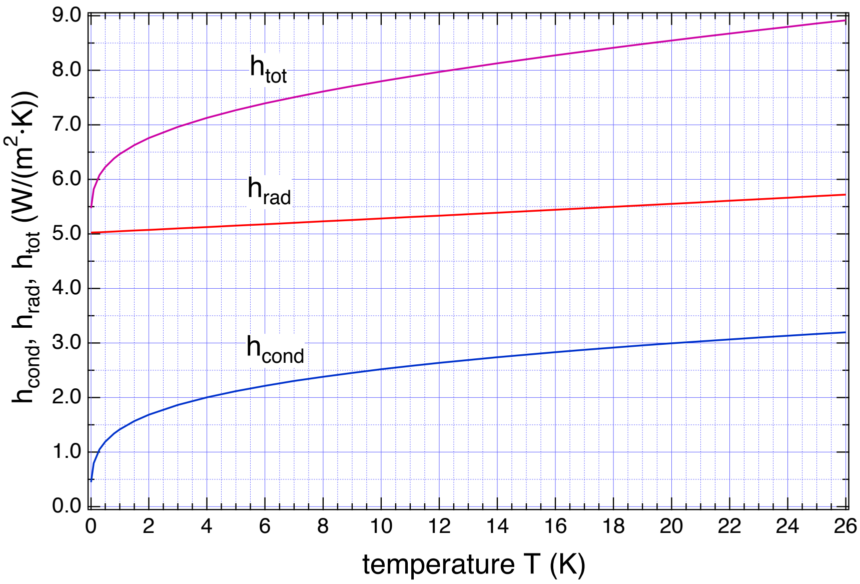

Figure 1: Surface heat transfer coefficient for free convection h_{tot} and its contributions from free convection h_{cond} and radiation h_{rad} as a function of T (surface temperature with respect to ambient)

The secondary internal heat transfer factor q_i depends on the external and internal heat transfer coefficients h_e and h_i, respectively that are fixed in standards such as EN 410, an European standard[1] to $h_e = 23$ W/(m^{2}K) and $h_i = 8$ W/(m^{2}K). Since we are not performing the experiment under these conditions (that would require a forced convection of the order of 4 m/s at the outer surface and an internal surface temperature increment of 12 K with respect to ambient, see fig. 1) we have to *compute* q_i for standard conditions. An advantage of the present procedure is the ability to compute q_i for *any* conditions of interest, which may deviate considerably from standard conditions such as for IGs in vehicles (busses, railroad cars).

Figure 2 shows the scheme used for the transformation of heat flows determined in the experiment, $\bar{q}_e$ and $\bar{q}_i$, to the corresponding values for standard conditions $\bar{q}_{e,N}$ and $\bar{q}_{i,N}$. The ambient temperatures have been set to $T_{e,\infty} = 0$ and $T_{i,\infty} = 0$. R_e and R_i represent the external and internal reciprocal surface heat transfer coefficients, respectively, and R_L is the reciprocal heat conductance coefficient of the IG excluding the outer and inner surface heat transition, $1/\Lambda_{int}$.

$\bar{q}_1$ and $\bar{q}_2$ represent again *heat flows* (in W/m^2) now originating from the absorption of solar radiation in the two glass panes. The sum of $\bar{q}_1$ and $\bar{q}_2$ is known in our experiment

$$\bar{q}_1 + \bar{q}_2 = S \cdot \alpha(0)$$

where S represents the intensity of the incident radiation. $\bar{q}_1$ and $\bar{q}_2$ can be calculated:

$$\bar{q}_1 = \bar{q}_e + \frac{(T_e - T_i)}{R_L} \qquad \text{and} \qquad \bar{q}_2 = \bar{q}_i - \frac{(T_e - T_i)}{R_L} \tag{1}$$

An interesting test has to be mentioned here: the sum of $\bar{q}_1$ and $\bar{q}_2$ has to be equal to the amount of absorbed intensity, $S \cdot \alpha(0)$, S being the intensity of the incident radiation that is measured with a thermopile in our experiment. This test yields direct information on the quantitative reliability of the above discussed relation $h_{tot}(T)$.

From $\bar{q}_1$ and $\bar{q}_2$ the corresponding parameters for standard conditions are obtained

$$\bar{q}_{e,N} = \frac{\bar{q}_1 \cdot R_L + \bar{q}_1 \cdot R_{i,N} + \bar{q}_2 \cdot R_{i,N}}{R_L + R_{i,N} + R_{e,N}} \qquad \text{and} \tag{2a}$$

$$\bar{q}_{i,N} = \frac{\bar{q}_1 \cdot R_{e,N} + \bar{q}_2 \cdot R_L + \bar{q}_2 \cdot R_{e,N}}{R_L + R_{i,N} + R_{e,N}} \tag{2b}$$

Finally, the angular dependent $q_i(\varphi)$ is obtained via the knowledge of the angular dependent solar direct absorptance $\alpha(\varphi)$

$$q_i(\varphi) = \frac{\bar{q}_{i,N} \cdot \alpha(\varphi)}{\bar{q}_{e,N} + \bar{q}_{i,N}} \qquad \text{and for the solar gain factor} \tag{3}$$

$$g(\varphi) = \tau_e(\varphi) + \frac{\bar{q}_{i,N} \cdot \alpha(\varphi)}{\bar{q}_{e,N} + \bar{q}_{i,N}} \tag{4}$$

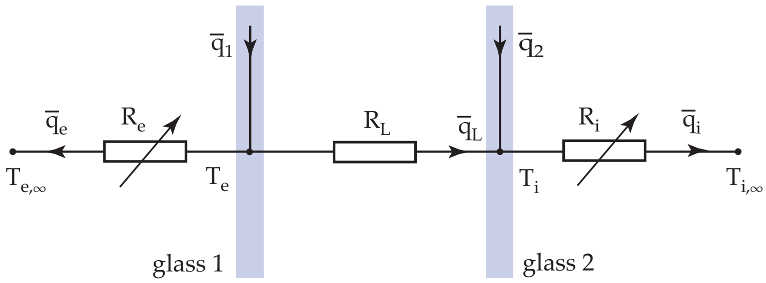

Figure 2: schematic illustration of heat flows and temperatures in the two-glass IG (see text)

Experimental set-up

Figure 3 shows the experimental set-up. The light source consists of a water-cooled xenon high-pressure arc lamp (1000 W) with an elliptical aluminum reflector. Filters improve the spectral distribution of the radiation in order to achieve a close match to solar radiation. Figure 4 shows a spectral comparison of natural solar radiation with the radiation of the solar simulator. The spectra have been measured with spectrometers described in ref. 3 that are not calibrated with respect to spectral sensitivity. Considering the fact that the relevant solar spectrum for the evaluation of solar gain factor, $S_\lambda(\lambda)$[1,3], has its main maximum shifted to smaller wavelengths as compared to the suns' spectrum, we note a fairly high spectral fidelity of our solar simulator. In addition, the spectral quality can be checked in a crucial test: the solar direct transmittance measured with a thermopile (Kipp & Zonen, CA1), $\tau_{e,therm}$, has to be close to the optically determined $\tau_e(\varphi = 0)$[3], which is indeed the case. For the commercial IG presented below we obtain the following ratios that describe the spectral quality:

$\tau_{e,therm}/\tau_e = 0.332/0.351 = 0.946$ determined with filter 1
$\tau_{e,therm}/\tau_e = 0.360/0.351 = 1.026$ determined with filter 2.

The distance between the light source and the IG (width: 60 cm, height: 120 cm) is of the order of 5 to 7 m. The central light intensity measured close to the IG is some 200 W/m^2 and a circular light spot with a diameter of about 60 cm is obtained. This light spot is positioned with its center 30 cm underneath the top of the IG.

Temperatures T_{ext} and T_{int} are measured by means of thermocouples (type K, diameter 0.1 mm) glued to the glass surface by means of Araldit® Cristal (Forbo CTU, Switzerland) as a function of time along with two ambient temperatures, T_1 positioned centrally underneath of the IG and T_2 representing the room temperature more remote from the IG (see fig.3). The experiment is located in a large room (360 m^3) without (changing) heat load by direct solar light that minimizes the long-term drifts of ambient temperature during the experiment.

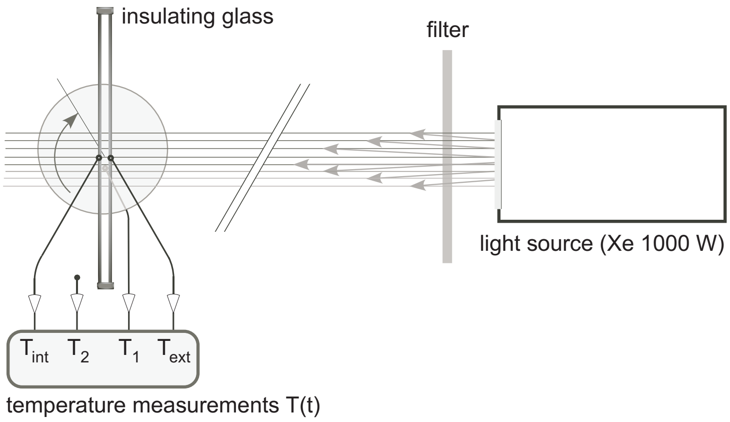

Figure 3: Experimental set-up for the determination of total solar energy transmittance g(φ) consisting of solar simulator light source, matching filter and temperature measurement.

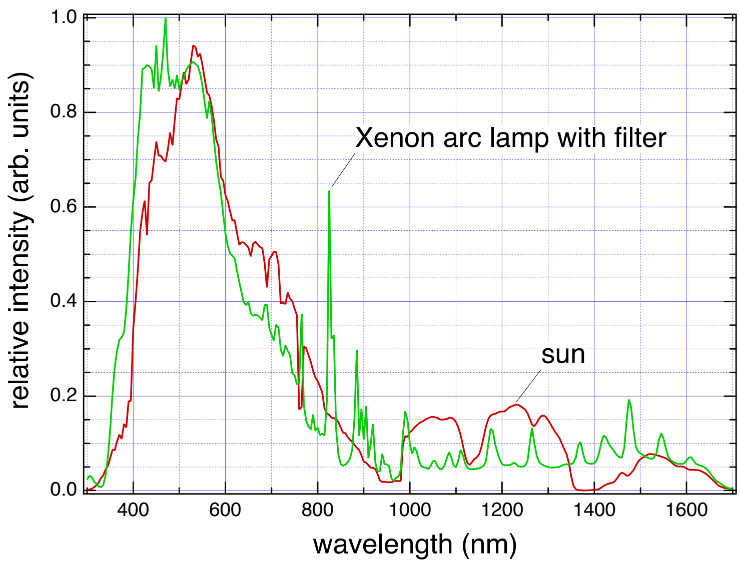

Figure 4: Spectral comparison of xenon arc lamp solar simulator equipped with filter 1 and measured natural solar radiation (Basel, February 4, 2005, 14:15 p.m.). Spectra have been obtained by using identical spectrometers (uncalibrated with respect to spectral sensitivity)

RESULTS

Figure 5 shows the temperature measurements ($T_{ext}(t)$, $T_{int}(t)$ and $T_1(t)$) performed at a sun protection glass (SPG) *Pilkington Insulight™ Sun Neutral 68/34*[6]. Data shown in this section have been obtained with filter 1. Measurements are typically performed for both light propagation directions, corresponding to normal mount (NM) and reverse mount (RM, inside of IG out). The temperature increments amount

$T_e = 8.39$ K and $T_i = 2.07$ K for NM and
$T'_e = 3.93$ K and $T'_i = 4.84$ K for RM.

Temperature trace $T_1(t)$ representing the air temperature underneath the IG shows more fluctuations as compared to the glass surface temperatures due to the lack of a pronounced heat capacity. Nevertheless, $T_1(t)$ is used to compensate long term drifts in ambient temperature which are however marginal in the present case.

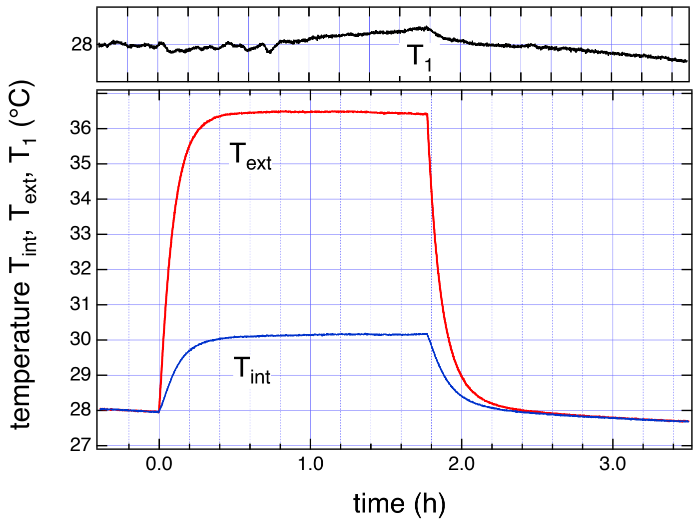

Figure 5: Surface temperature measurements at the sun protection glass Pilkington Insulight™ Sun Neutral 68/34[6]

From the above values for T_e, T_i and T'_e, T'_i we obtain for the heat transfer coefficients

$h_e = 7.65$ W/(m^{2}K) and $h_i = 6.77$ W/(m^{2}K) for NM and
$h'_e = 7.12$ W/(m^{2}K) and $h'_i = 7.25$ W/(m^{2}K) for RM.

From these values we obtain the heat flows under experimental conditions

$\bar{q}_e = T_e \cdot h_e = 64.2$ W/m^2 and $\bar{q}_i = T_i \cdot h_i = 14.0$ W/m^2 for NM and
$\bar{q}'_e = 28.0$ W/m^2 and $\bar{q}'_i = 35.1$ W/m^2 for RM.

Finally for the heat flows under standard conditions from equations (2a) and (2b) we obtain

$\bar{q}_{e,N} = 69.5$ W/m^2 and $\bar{q}_{i,N} = 8.7$ W/m^2 for NM and
$\bar{q}'_{e,N} = 30.2$ W/m^2 and $\bar{q}'_{i,N} = 32.8$ W/m^2 for RM.

For the solar gain factor we obtain by using $\alpha_e(0) = 0.363$, $\alpha'_e(0) = 0.286$, $\tau_e(0) = 0.351$[3] and for the thermal transmittance of the present IG $U = 1.1$ W/(m^{2}K)[6]

$\boldsymbol{g} = 0.351+0.038 = \mathbf{0.389}$ for NM and $\boldsymbol{g'} = 0.351+0.148 = \mathbf{0.499}$ for RM.

The values given by the manufacturer are $g = 0.37$ and $g' = 0.50$[6]. Regarding the U-value (according to EN 673[5]) taken from the manufacturers data sheet we note only a weak influence on the g-value: a reduction e.g. of U from 1.1 W/(m^{2}K) to 1.0 W/(m^{2}K) increases the g-value by from 0.389 to 0.391 for NM and from 0.499 to 0.500 for RM.

For the angular dependent solar gain factor $g(\varphi)$ we obtain according to equation (3) a function that is shown in figure 6. The comparison of $g(\varphi)$ with $\tau_e(\varphi)$ clearly reveals that $\tau_e(\varphi)$ represents the dominant contribution to $g(\varphi)$.

CONCLUSIONS

The present experimental method for g-value evaluation has been tested successfully for 2-glass-IGs. The experiment enables a fast and accurate determination of solar gain factors not only for sun protection glasses but IGs in general. At a first look, theory for free convection applied here including its relation between heat transfer coefficients and surface temperature increments appears to be a critical point in the present method since deviations from the relation shown in fig. 1 may occur when the experimental set-up and irradiation conditions deviate from the ideal theoretical assumptions. However, tests performed so far clearly reveal a close agreement between the resulting heat flows obtained from theory and the experimentally determined sum of absorption flows in the two glass panes. In addition, the experimental set-up can be used in order to determine the relation $h_{tot}(T)$ *experimentally* by measuring e.g. a single glass pane instead of an IG. In this case T_{ext} and T_{int} are equal and $h_{tot}(T)$ can be determined from known absorbed radiation intensities.

Future experimental tests will include IGs with more than two glass panes and combinations of glass panes with polymeric coated membranes. Results will be revealed in a forthcoming publication and in an internet-hosted database[7].

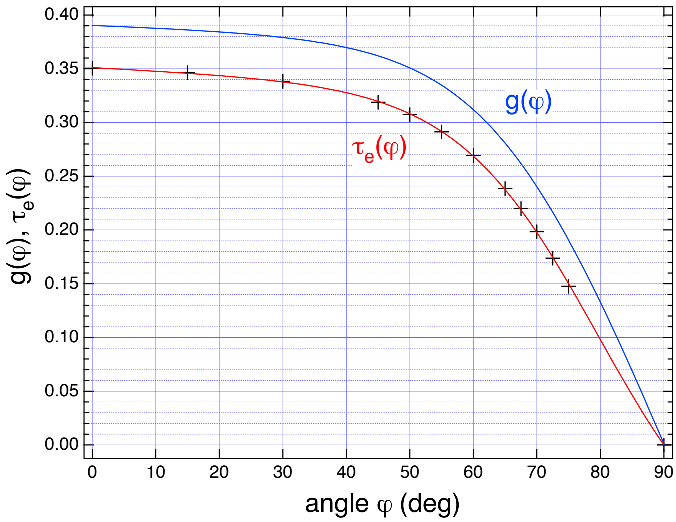

Figure 6: Solar gain factor g(φ) and solar transmittance $\tau_e(\varphi)$[3] of the sun protection glass Pilkington Insulight™ Sun Neutral 68/34[6]. Crosses represent data points; the full curve is obtained by fitting an analytical function (see [3])

Acknowledgement

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