A methodology for the calculation of solar gain in buildings through selective glazed surfaces for the application of building energy saving

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Abstract

A more accurate calculation methodology is proposed of the total solar energy transmittance g of glazed surfaces based upon the determination of solar factors in visible, infrared and ultraviolet bands. The method uses measured values of solar radiation and spectral optical properties of glazed surfaces calculated with the WIS code. This code implements the calculation procedure of optical parameters of EN 410 Specification, which uses a standard spectral distribution of global solar radiation. The investigation, referring to glazed surfaces with different optical properties, permits the highlighting of solar factor variability in the entire solar band and in the three bands which are characteristic of the spectrum, varying recorded solar energy, and the limits of the Standard procedure which assigns constant values to such coefficients. The results obtained are interesting, above all for the characterisation of glass with different optical properties in infrared and visible bands.

1. Introduction

The glazed components of the building shell act as solar radiation capturers and contribute significantly to the energy balance of environments both in winter heating and summer cooling. Thermal solar gains by means of such components are evaluated by the total solar energy transmittance g for normal incidence [1] whose determination is obtained following the EN 410 standard method [2]. The Specification uses a standard spectral distribution of global solar radiation corresponding to a condition of clear skies with relative air mass m=1, to evaluate the optical parameters of glazing for normal incidence in each wavelength interval and in the entire solar band. Solar factor g depends on the thermal and optical properties of the single layers of the glazed system, which can result as being very different if selective surface coatings are used [3], and on the spectral distribution of incident radiation. For a better characterisation of thermal solar gain, it can be useful to know the energy transmitted in the three bands which characterise the solar spectrum: ultraviolet, infrared and visible bands, as well as the energy transmitted by the entire solar band. The global radiation fractions which fall within the three spectral bands depend on the state of the atmosphere, and from the solar elevation angle which determines the relative air mass value.

In order to control solar gain, the market renders selective glazing systems available whose optical properties permit better thermal comfort and luminosity within environments. Generally, such surfaces result as being slightly transmissive in the infrared solar band, and highly transmissive in the visible band. Selective glazed surfaces are used, not only in the field of construction, but also in systems which require control of spectral distribution of entering radiation, such as photovoltaic cells and transparent greenhouse shells. In order to evaluate the solar gains in the three characteristic bands, it is necessary to know the relative coefficients for transmittance τ, for absorption α and the corresponding solar radiation fractions. In this work, an accurate calculation method is proposed for the evaluation of solar gain in the three bands which are characteristic of the solar spectrum. The optical and thermal properties of glazed surfaces are determined by means of the WIS code [4] which provides the transmission and absorption coefficient values for different wavelengths and angles of incidence, with reference to standard spectral distribution. The calculation procedure used is that of selected ordinates, proposed by Wiebelt and Henderson [5], also adopted by EN 410. The code supplies the values for thermal transmittance calculated according to the EN 673 Standard [6]. For solar radiation values, the hourly and daily values measured at the actinometric station of the Department of Mechanics, University of Calabria, were used.

The investigation, carried out considering glazed surfaces with different optical and thermal properties, permits the highlighting of the total solar energy transmittance with varying solar radiation, which can depend upon clearness index k, ratio between hourly or daily energy on the ground and the corresponding extra-atmospheric energy. Furthermore, solar factor variability in the three characteristic bands, compared to the reference values calculated according to the standard procedure using the WIS code, were evaluated. The analysis was developed with reference to the daily data of the energy on the horizontal plane, and successively widened to include hourly data to highlight the effective variability of the total solar energy transmittance.

2. Solar radiation measurement in three bands characteristic of the spectrum

For the solar radiation survey, three Eplab precision pyranometers respectively screened with a WG295 filter, for the measurement of global radiation ($275 \leq \lambda \leq 2500$ nm), with a GG395 filter, for the measurement of radiation in visible and infrared bands ($350 \leq \lambda \leq 2500$ nm), and with a RG780 filter for the measurement of the solar infrared band ($760 \leq \lambda \leq 2500$ nm). The latter pyranometer directly supplies solar infrared radiation, while the difference in measurements between $\lambda \geq 350$ nm and $\lambda \geq 760$ nm allows for the evaluation of radiation in the visible band. Finally, the difference between the measurement with WG295 and that with GG395 supplies radiation in the ultraviolet band. In table 1, the characteristics of the pyranometers used are reported.

Table 1. Characteristics of the pyranometers used for measurements.

Sensitivity (V W^{-1} m^2)	WG295	3,88 10^{-6}
	GG395	9,70 10^{-6}
	RG780	9,38 10^{-6}
Temperature dependance	± 1% (-20 ÷ 40 °C)	
Linearity	± 0,5% (0÷2800 W m^{-2})	
Response Time Cosine	± 1% (0° ÷ 70° Zenith angle)	
	± 3% (70° ÷ 80° Zenith angle)	

The evaluation of the measurement error introduced by the non ideal characteristics of the filters used, showed that the values of radiation obtained in the ultraviolet band are not sufficiently accurate to be used. Whereas, for infrared and visible bands the errors are completely acceptable. Taking into account the characteristics of the sensors and of the uncertainties introduced by the presence of filters, due to the total measurement errors, the following values were obtained: global radiation 3.3%, infrared radiation 3.8%, visible radiation 6.4%, ultraviolet radiation 50% [7].

The solar radiation data used relate to a year of observation. In figure 1, for a clear day (clearness index k=0.733), global solar radiation, visible and infrared band radiation values and the relative fractions referring to global radiation are reported. In figure 2, the values relative to a day with cloudy skies (clearness index k=0.155) are reported. The trends highlight that in clear sky conditions the division of global solar radiation in the two bands is hardly variable at different times, while for cloudy skies, due to greater absorption due to atmospheric components, fractions which fall into infrared and visible bands vary and, generally, an increase of the fraction in the visible band corresponds to a reduction in the infrared band.

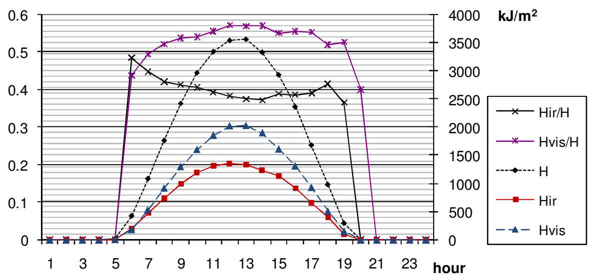

Figure 1. Hourly trend of global solar radiation H, visible H_{vis} and infrared H_{ir}, and fractions of the solar spectrum contained in the two bands H_{vis}/H and H_{ir}/H. Clearness index k=0.733.

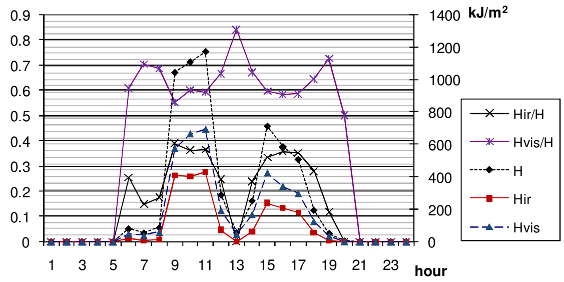

Figure 2. Hourly trend of global solar radiation H, visible H_{vis} and infrared H_{ir}, and fractions of the solar spectrum contained in the two bands H_{vis}/H and H_{ir}/H. Clearness index k=0.155.

3. Solar gain coefficients in the three spectral bands

Given the optical spectral properties of the glazed system $\tau_{\lambda(i)}$, $\rho_{\lambda(i)}$, $\alpha_{\lambda(i)}$, and the spectral distribution of solar radiation $I_{\lambda(i)}$, for a particular angle of incidence (i), the transmission coefficient $\tau_{(i)}$ in the solar band, is given by the following relation:

$$\tau(i) = \frac{\int_{300}^{2500} I_\lambda(i)\,\tau_\lambda(i)\,d\lambda}{\int_{300}^{2500} I_\lambda(i)\,d\lambda} \tag{1}$$

Similar relations can be used for the calculation of $\rho_{(i)}$ e $\alpha_{(i)}$. The previous relation can even be written subdividing the solar spectrum into three characteristic bands in such a way as to obtain the corresponding transmission coefficients:

$$\tau(i) = \frac{\int_{300}^{380} \tau_\lambda(i) I_\lambda(i) d\lambda}{\int_{300}^{380} I_\lambda(i) d\lambda} \frac{\int_{300}^{380} I_\lambda(i) d\lambda}{\int_{300}^{2500} I_\lambda(i) d\lambda} + \frac{\int_{380}^{780} \tau_\lambda(i) I_\lambda(i) d\lambda}{\int_{380}^{780} I_\lambda(i) d\lambda} \frac{\int_{380}^{780} I_\lambda(i) d\lambda}{\int_{300}^{2500} I_\lambda(i) d\lambda} + \frac{\int_{780}^{2500} \tau_\lambda(i) I_\lambda(i) d\lambda}{\int_{780}^{2500} I_\lambda(i) d\lambda} \frac{\int_{780}^{2500} I_\lambda(i) d\lambda}{\int_{300}^{2500} I_\lambda(i) d\lambda} \tag{2}$$

With, τ_{uv}, τ_{vis}, τ_{ir}, indicating the ultraviolet, visible and infrared band coefficient value, and with f_{uv}, f_{vis} and f_{ir} the energy fractions which fall within the three bands, the relation (2) assumes the form:

$$\tau_{(i)} = \tau_{uv}\, f_{uv} + \tau_{vis}\, f_{vis} + \tau_{ir}\, f_{ir} \tag{3}$$

Similar relations can be used to determine the absorption coefficient $\alpha(i)$. Energy fractions in the three bands are calculated from the EN 410 Specification with reference to standard distribution, and assume values of $f_{uv} = 0.034$, $f_{vis} = 0.570$, $f_{ir} = 0.396$. The solar factor is evaluated considering the normally incident solar radiation and calculated with the relation:

$$g = \tau + q_i \tag{4}$$

with q_i secondary thermal exchange factor towards the inside inwards which for single glazing assumes the form:

$$q_i = \alpha \frac{U}{h_e} \tag{5}$$

U is thermal transmittance and h_e is the external surface thermal exchange coefficient, calculated with definite boundary conditions [6]. Subdividing the solar spectrum into three characteristic bands, the solar factor can be calculated as

$$g = g_{uv} + g_{vis} + g_{ir} \tag{6}$$

with

$$g_{uv} = (\tau_{uv} + \alpha_{uv} \frac{U}{h_e}) f_{uv} \qquad g_{vis} = (\tau_{vis} + \alpha_{vis} \frac{U}{h_e}) f_{vis} \qquad g_{ir} = (\tau_{ir} + \alpha_{ir} \frac{U}{h_e}) f_{ir} \qquad (7)$$

Using the previous relations, with reference to different glazed surfaces, total solar energy transmittance values in the three bands were determined. Coefficients τ and α relative to the three bands were determined with the WIS code using reference spectral distribution, while the fractions f were determined using measured solar radiation values. For the ultraviolet band, whose contribution is greatly reduced, since the measured radiation values are affected by excessive errors, the solar factor g_{uv} was presumed to be equal to that supplied by the Standard. Four glass systems with and without selective coatings were considered, whose optical and thermal properties, determined with the WIS code according to Standard procedure, are reported in table 2.

Table 2. Total solar energy transmittance evaluated according to EN 410 and thermal transmittance values for the glass considered, (s= thickness, ε emissivity in far- infrared).

	g_{uv}	g_{vis}	g_{ir}	g	U (W/m^2 K)	ε_i	ε_e	s (mm)
Clear glass	0.023	0.509	0.332	0.864	5.80	0.837	0.837	4
Selective glass	0.009	0.422	0.051	0.482	5.73	0.837	0.040	6
Low-emitting glass	0.006	0.415	0.060	0.481	3.22	0.037	0.837	4
Solar control glass	0.007	0.118	0.056	0.181	5.67	0.837	0.375	8

4. Solar factor daily variability

Using the measured values of solar radiation on the horizontal, the variability of solar factor g in the solar, visible and infrared bands, in relation to sky conditions characterised by clearness index k, were investigated. The data used relate to an entire year. If global radiation on the ground is known, but the fractions which fall in the visible and infrared window are not known, it is possible to refer to an empirical model which supplies the relation between infrared band energy H_{ir}, visible H_{vis} and global extra-atmospheric energy H_{ex} in relation to the daily clearness index k [7]. In figure 3, for clear glass, the total solar energy transmittance relative to the entire solar band is reported, using measured solar fractions and the reference value provided by the Standard in relation to clearness index k. Figure 4 reports the results obtained for selective glass. Both for clear and selective glass, a dependence on clearness index k was highlighted, with deviations compared to the value provided by the Standard, which for clear glass does not exceed 5%, and for selective glass reaches 15% in cloudy sky conditions. Similar results were obtained for other considered glass types.

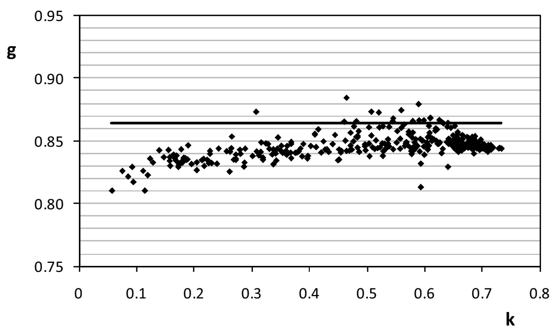

Figure 3. Clear glass. Annual trend of daily solar factor g values in relation to clearness index k.

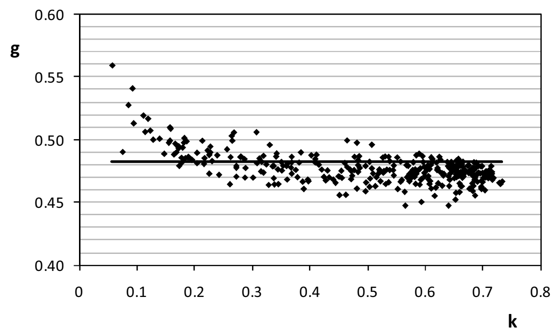

Figure 4. Selective glass. Annual trend of daily solar factor g values in relation to clearness index k.

Figures 5-8 illustrate fraction variability in visible g_{vis}/g and infrared g_{ir}/g bands for clear glass. The graphics highlight a more marked dependence on the clearness index: while the fraction of solar gain in the infrared band g_{ir}/g increases with index k, the visible fraction g_{vis}/g reduces. The relation g_{ir}/g calculated with the procedure results as being equal to 0.385, while the calculated values result as being comprised between 0.26 and 0.43 in January, and between 0.34 e 0.39 in July. Greater variances are recorded for k values of less than 0.3, corresponding to a cloudy sky, and in January reach 32.4% and in July 12.4%. The relation g_{vis}/g results as being more faithful to the standard value, and registers a variable deviation between -21% for cloudy winter skies (k=0.094) and 8,4% for clear winter skies (k=0.652). In summer, the maximum deviation is -10% in correspondence with a clearness index of 0.155.

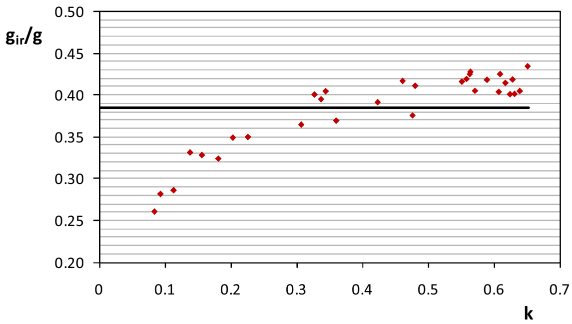

Figure 5. Clear glass. Daily values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for January.

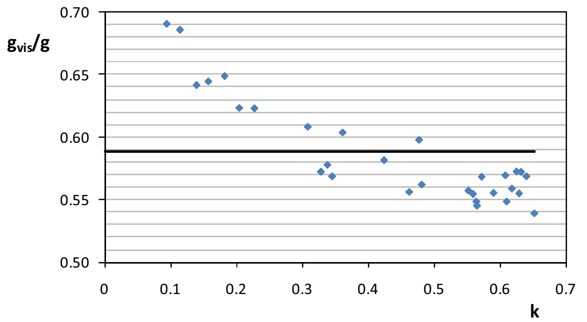

Figure 6. Clear glass. Daily values of the fraction in the visible band g_{vis}/g in relation to clearness index k for January

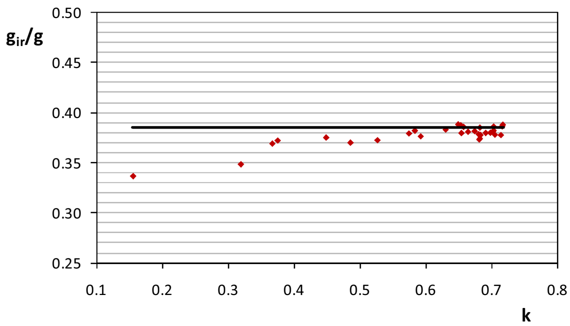

Figure 7. Clear glass. Daily values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for July.

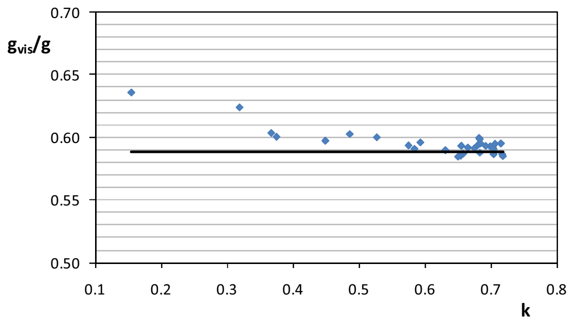

Figure 8. Clear glass. Daily values of the fraction in the visible band g_{vis}/g in relation to clearness index k for July.

For selective glass, the results obtained for January are reported in figures 9 and 10. In the visible band, no significant differences are highlighted compared to standard values. Greater deviations are recorded in the infrared band: in cloudy sky conditions, the variance compared to the standard, reaches 41%, while for high k the variance is -20%. For July, the results obtained are approximate to those of the standard. For low-emitting glass, deviations from the standard value in the visible band do not exceed -5% for low k values. Greater deviations are to be found in the infrared band with an overestimation of the ratio g_{ir}/g of 40.7% in January for a cloudy sky, and an underestimation of the ratio g_{ir}/g of -19% for a clear sky. In July, the overestimation of the standard does not exceed 17% in cloudy sky conditions, while for clear skies variances are not significant. For solar control glass the comparison of the standard value presents the same preceding trends, with significant deviations of the fraction in infrared and visible bands for cloudy winter skies.

5. Solar factor hourly variability

A more detailed analysis was obtained using the hourly radiation values which present a variability of the fractions in the visible and infrared bands with a varying clearness index. In figure 11 the solar factor g for clear glass obtained in January is reported, and in figure 12 those obtained for the month of July, prevalently characterised by clear skies.

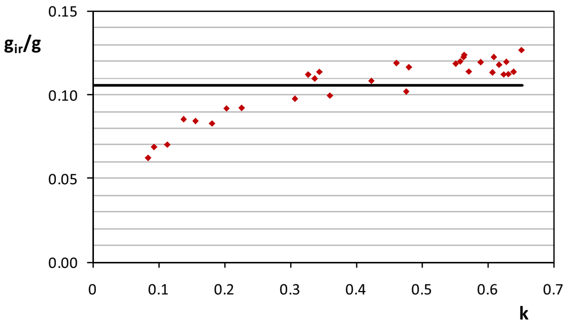

Figure 9. Selective glass. Daily values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for July.

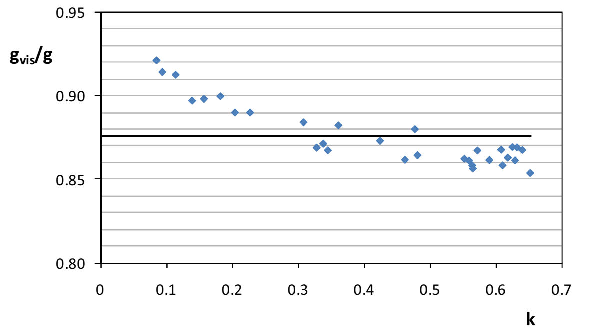

Figure 10. Selective glass. Daily values of the fraction in the visible band g_{vis}/g in relation to clearness index k for July.

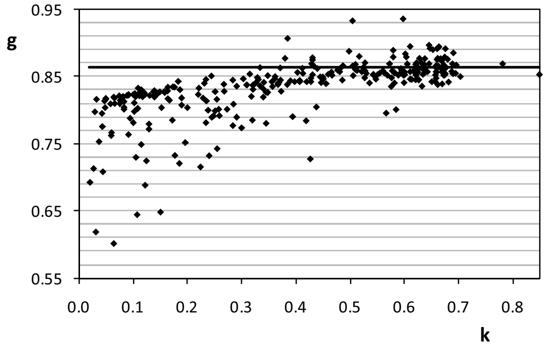

Figure 11. Clear glass. Hourly values of solar factor g in relation to clearness index k for January.

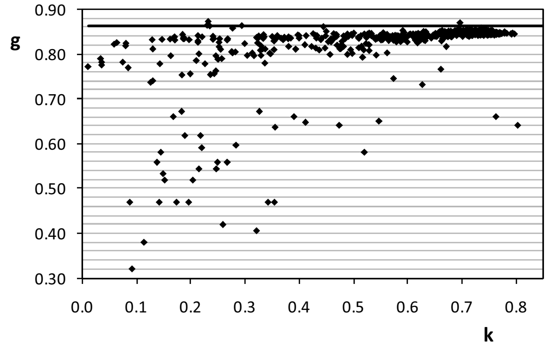

Figure 12. Clear glass. Hourly values of solar factor g in relation to clearness index k for July.

The graphics highlight the tendency of the Standard to overestimate solar gain with a diminishment of the clearness index for winter and summer skies, which is more contained in the latter. For selective glass, the results reported in figures 13 and 14, significantly highlight variable trends with index k. In particular, solar gain is reduced with an increase in k for winter skies, while for summer skies the Standard provides values which are sufficiently accurate for clear skies. Divergences from the standard value result as being variable between -40% and 22% in January, while for the summer month, in cloudy sky conditions, results as being between -30% and 40%. Similar results are obtained for low-emitting glass, while for solar control glass the g-value generally results as being overestimated, with divergences which do not exceed 20% in January and 10% in July. In figures 15 and 16 hourly trends of the g_{ir}/g and g_{vis}/g ratio are reported, in relation to the clearness index for January. Trends reported in figures 17 and 18 relate to July.

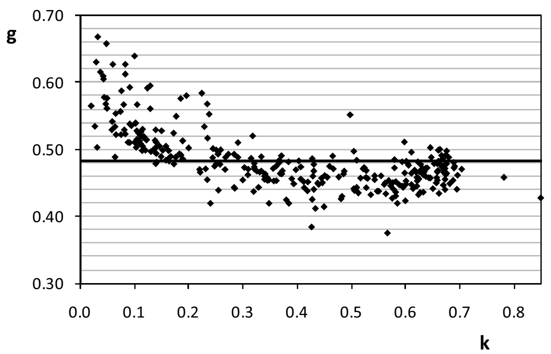

Figure 13. Selective glass. Hourly values of solar factor g in relation to clearness index k for January.

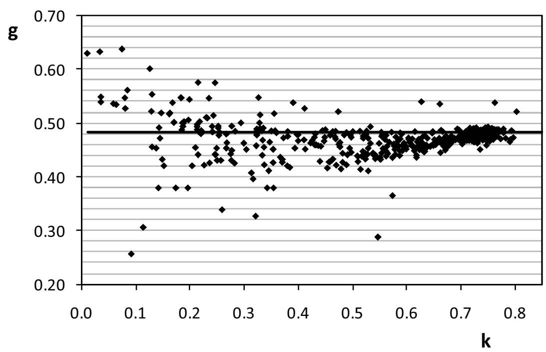

Figure 14. Selective glass. Hourly values of solar factor g in relation to clearness index k for July.

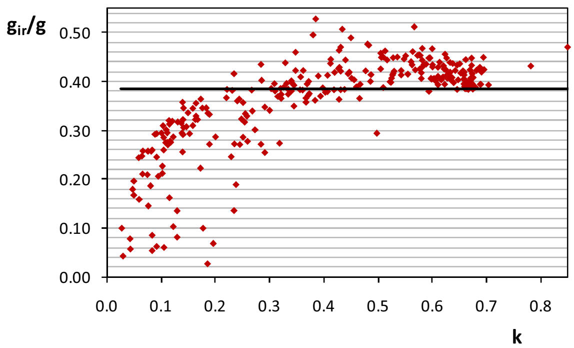

Figure 15. Clear glass. Hourly values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for January.

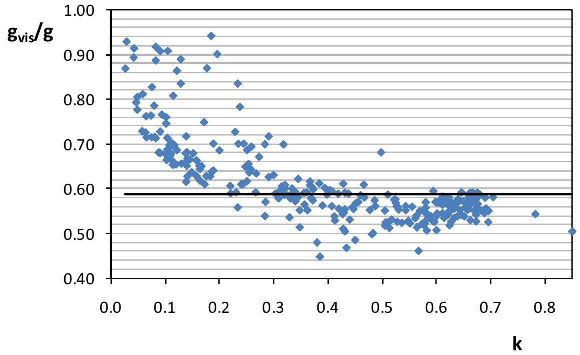

Figure 16. Clear glass. Hourly values of the fraction in the visible band g_{vis}/g in relation to clearness index k for January.

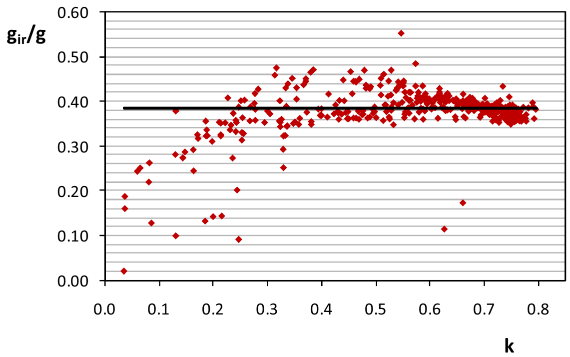

Figure 17. Clear glass. Hourly values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for July.

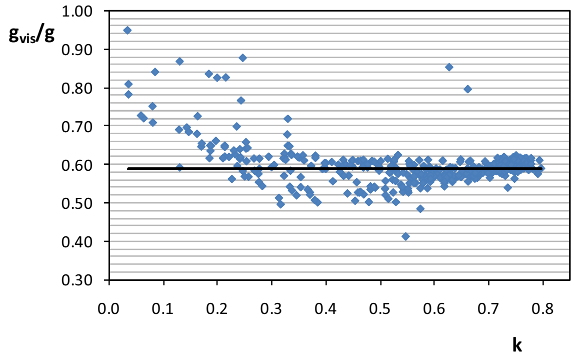

Figure 18. Clear glass. Hourly values of the fraction in the visible band g_{vis}/g in relation to clearness index k for July.

For January, the two fractions present a significant dependence on parameter k, in particular the infrared fraction increases with k, while the visible band fraction reduces with k, with significant variances compared to values provided by the Standard.

Deviations result as being averagely variable between 40% and -15% for the infrared fraction, and between -40% and 12% in the visible band with an increase in k. For July, the value provided by the Standard is representative of distribution of the obtained values. For glass with selective coating, in January, qualitative trends were obtained which were similar to previous ones, both for infrared and visible fractions, as shown in figures 19 and 20. Average deviations for the infrared fraction are between 40% and -20% with an increase in k, and for the visible fraction between -8% and 5%. In figures 21 and 22 the results obtained for July are reported.

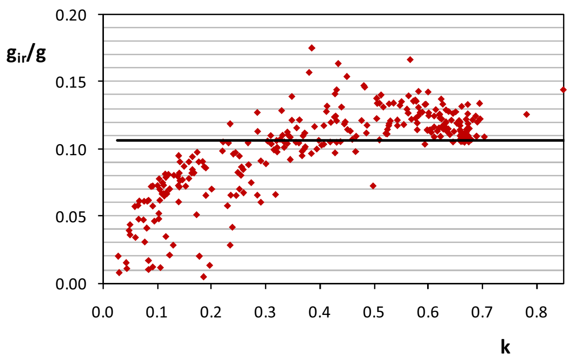

Figure 19. Selective glass. Hourly values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for January.

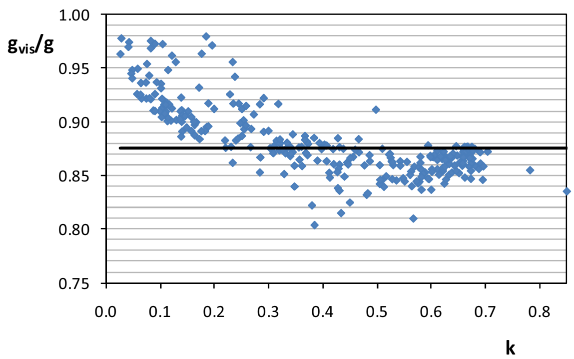

Figure 20. Selective glass. Hourly values of the fraction in the visible band g_{vis}/g in relation to clearness index k for January.

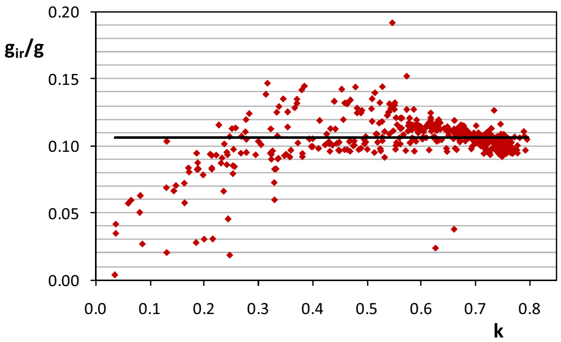

Figure 21. Selective glass. Hourly values of the fraction in the infrared band g_{ir}/g in relation to clearness index k for July.

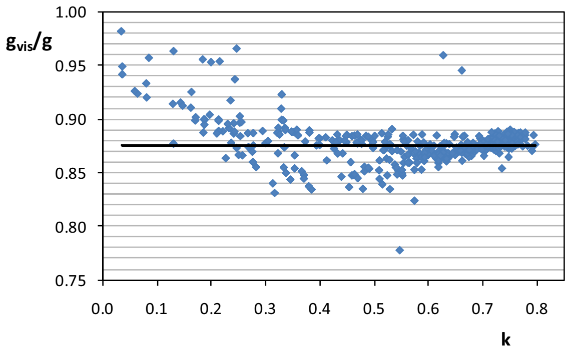

Figure 22. Selective glass. Hourly values of the fraction in the visible band g_{vis}/g in relation to clearness index k for July.

Qualitatively the trends do not differ from those obtained for clear glass. Similar results are obtained for low-emitting glass, while for solar control glazed surfaces high deviations are recorded compared to the standard value even in the visible band for which the fraction g_{vis}/g can result as being underestimated by 30% for k values lower than 0.3, and overestimated by 10% for high clearness indices.

6. Conclusions

The optical parameters used for the calculation of the total solar energy transmittance were evaluated by the EN 410 Standard considering a standard spectral distribution of solar radiation corresponding to an air mass value m=1 with clear skies. The investigation carried out considering glazed surfaces with different optical properties, solar radiation measured in the entire band, and in visible and infrared bands, for an entire year, permitted the highlighting of the field of variability of the corresponding solar factors, and the deviations compared to the constant values obtained applying the Standard. The results obtained can be summarised as follows:
a) solar factors vary in relation to the solar elevation angle and the clearness index which characterises sky conditions;
b) the total solar energy transmittance in the entire solar band calculated with reference to daily energy presents deviations compared to the standard value which can be held to be acceptable. In conditions of cloudy skies ($k < 0.2$) deviations can reach 15%;
c) If g_{vis}/g and g_{ir}/g fractions are considered, clearness index dependence is much more marked with deviations compared to standard values which are significant for cloudy winter skies, and more contained for cloudy summer skies;
d) the solar factor in the entire calculated band, with reference to hourly energy variances from the standard value in a significant way, with deviations that for selective glazing vary between -40% e + 22% for winter skies, and between -30% e + 40% for summer skies. Significant variances are also found for low-emitting glass and solar control glass;
e) The fractions g_{vis}/g e g_{ir}/g calculated on an hourly basis, for clear glass, present deviations for winter skies comprising between +40% and - 15% for the infrared band and between -40% e + 12% in the visible band, with increasing k. For summer skies the obtained values are approximate to the standard values. For selective glass and winter skies the previous trends are confirmed for the infrared fraction, while for the visible fraction the results obtained do not diverge from those obtained applying the Standard. For summer skies the results obtained for clear glass are confirmed. Finally, for solar control glass divergences are also found in the visible fraction with deviations which reach 30% for a sky with k<0.3.
The results obtained result as being of interest for the evaluation of solar gain in cases in which a control of the spectral properties of entering radiation is required. A possible application is the hourly evaluation of solar gains through glazed building surfaces, for which glazing with differing optical properties can be used in visible and infrared bands.

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