FENESTRATION PEAK SOLAR HEAT GAIN: A REVIEW OF THE CLOUDLESS DAY CONDITION AS CONSERVATIVE HYPOTHESIS

by

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Peak solar heat gain through fenestration, particularly for clear and cloudy day conditions, was estimated, using an approach based on the ASHRAE methodology and considering the correlation between hourly clearness index k_T and diffuse ratio of the total radiation. Hourly SHG_{CLEAR} and SHG_{CLOUDY} values for surfaces facing the basic cardinal orientations and the horizontal surface, at different latitudes, on the 21st day of each month, have been computed and compared. Results show that in many cases solar heat gain for cloudy day may exceed that for clear day. For wall exposures near the north the clear day condition could not be the most conservative condition for the peak solar heat gain evaluation.

Keywords: *peak solar heat gain, cloudy day*

Introduction

Usually, the cloudless day is considered as reference to evaluate the peak solar heat gain (SHG) through fenestrations. Examples of this procedure are provided by ASHRAE [1] and Carrier [2] methods.

Li *et al*. [3], basing on extensive global solar radiation data measured at the City University of Hong Kong, found that values of peak SHG for horizontal surfaces occurred in condition of cloudy day and were higher than those indicated by ASHRAE [1] for clear day. On the base of this climatic data, they developed an approach to evaluate peak SHG on subtropical regions.

Also for Mediterranean regions the hypothesis of clear day could not be the most conservative condition, as it has been observed by the authors while testing the performance of an heating, ventilation, and air conditioning plant in Rome for particular orientations of the building surfaces, although not for horizontal ones.

In general, the value of solar irradiance for a surface facing the sun can increase for the simultaneous presence of direct beam and diffuse radiation and it may occur when there are few clouds that leave large areas of clear sky, fig. (1).

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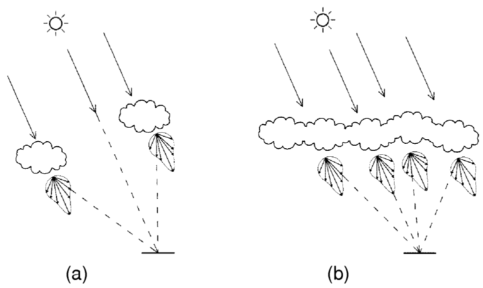

Figure1. (a) Partially cloudy sky; (b) Overcast sky

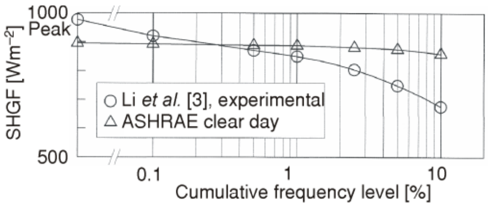

Figure 2. Comparison from experimental data [3] and ASHRAE

But this situation is statistically rare, verifying only for particular locations and for a short time. Figure 2 shows the frequency of experimental SHG, extrapolated from measured data [3], compared to the SHG valued by ASHRAE for a clear day. Only for a 0.25% the former is higher than the latter.

Conversely, the situation that normal occurs is when the sky is overcast and the beam of radiant energy emerging from the clouds is more attenuated than on a clear day and largely spread in all directions, as indicated in fig. 1(b). However, as will be shown below, even in a cloudy day, for particular expositions, the total radiation reaching a surface can be greater than for a clear day.

Indeed, the total radiation I_S reaching a surface can be expressed as [1]:

$$I_S = I_B \cos\Theta_S + I_D F_{SS} + \rho_G F_{SG} (I_B \cos\Theta_H + I_D) \tag{1}$$

where I_S is the total radiation, I_B – the beam radiation, I_D – the diffuse hourly radiation on a horizontal surface, ρ_G – the ground reflecting coefficient, Θ_S – the angle of incidence respect the normal to the surface, Θ_H – the angle of incidence relative to the normal to the ground, F_{SS} – the angle factor between sky and surface, and F_{SG} – the angle factor between ground and surface.

In eq. (1), $\cos\Theta_S$ and $\cos\Theta_H$ are strongly dependent on the incoming solar rays direction; on the other hand the values of F_{SS} and F_{SG} are barely influenced by beam direction. Considering that on a cloudy day the total radiation decreases while the diffuse fraction increases, for small values of $\cos\Theta_S$ and $\cos\Theta_H$ the incremental variation of the diffuse component can prevail on the reduction of the beam component, carrying out an increase of the total radiation I_S.

In the following sections, a general analytical approach to calculate the solar heat gain for several weather conditions and latitudes and to evaluate the impact of SHG peak on the conditioning plants design has been developed by the authors.

Assumptions and preliminary analysis

An approximate analysis can be done using the available equations for the estimation of the diffuse fraction of total radiation.

Liu *et al*. [4] first found a correlation, not dependent from latitude and elevation, between the diffuse fraction H_D/H of daily radiation and a "daily clearness index" K_T, defined as $K_T = H/H_0$, where H is the daily radiation on a horizontal surface, H_0 – the daily extraterrestrial radiation on a horizontal surface, and H_D – the diffuse daily radiation on a horizontal surface.

Other correlations were obtained by Orgill *et al.* [5] (data from Canadian measuring stations), Erbs *et al.* [6] (data from USA and Australia), and Reindl *et al.* [7] (data from USA and Europe) for hourly radiation. They found I_D/I *vs.* k_T correlations, where k_T is the I/I_0 "hourly clearness index", Φ_D – the I_D/I "diffuse ratio", I – the hourly radiation on a horizontal surface, I_0 – the hourly extraterrestrial radiation on a horizontal surface, and I_D – the diffuse hourly radiation on a horizontal surface.

This three correlations are shown in fig. 3. They are substantially identical.

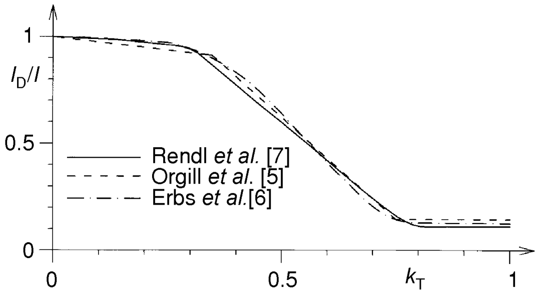

Figure 3. I_D/I *vs.* k_T correlations

The Orgill and Hollands correlation, that has been widely used, is given by the following equations:

$$\Phi_D(k_T) = \begin{cases} 1-0.249k_T & \text{for } 0 \le k_T 0.35 \\ 1.557-1.184k_T & \text{for } 0.35 \le k_T \le 0.75 \\ 0.177 & \text{for } k_T > 0.75 \end{cases} \tag{2}$$

Using eq. (2) the total radiation reaching a surface is expressed as follows:

$$I_S^{\text{cloudy}}(k_T) = I_{T0}k_T \left\{ [1-\Phi(k_T)]\frac{\cos\theta_S}{\cos\theta_H} + \Phi(k_T)F_{SS} + \rho_G F_{SG} \right\} \tag{3}$$

For vertical surfaces, with free sky view and flat surrounding ground, it is assumed that the angles factors are:

$$F_{SS} \cong 0.5 \quad \text{and} \quad F_{SG} \cong 0.5$$

Figure 4 shows the resulting plot of the ratio $R_{CL} = I_S^{\text{cloudy}}(k_T)/I_S^{\text{clear}}(k_T)$ *vs.* k_T for several values of $\cos\theta_S/\cos\theta_H$ and for ρ_G = 0 and 0.2.

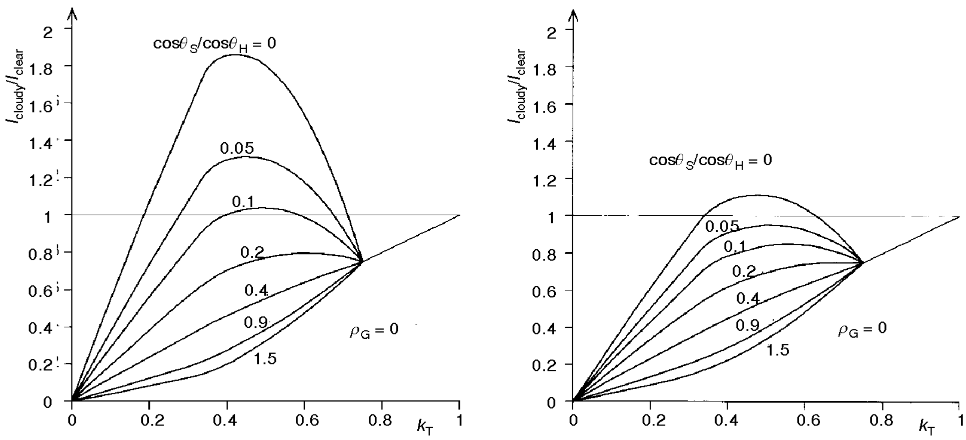

Figure 4. Plot of the ratio $R_{CL} = I_S^{\text{cloudy}}(k_T)/I_S^{\text{clear}}(k_T)$ *vs.* k_T for several values of $\cos\theta_S/\cos\theta_H$ and for ρ_G = 0 and 0.2

As illustrated in fig. 4, values of $R_{CL} > 1$ can occur for $k_T < 1$ when weather conditions may not represent a clear sky. This effect is considerable for low values of $\cos\Theta_S/\cos\Theta_H$ when, generally, the direct component of solar radiation on the given surface is far from the maximum value I_B. Furthermore, the maximum value of R_{CL} goes up with the decrease of ρ_G. Note that if $k_T = 1$ (clear day) $R_{CL}=1$ for any value of $\cos\theta_S/\cos\theta_H$.

To investigate in more detail this situation, in the following section has been calculated the hourly SHG through real fenestration, in relationship with the wall orientation, the day of the year and the hour in the day. The numerical calculation of SHG for clear and cloudy day have been made by using eqs. (1) and (3). All terms in the equations have been calculated strictly following the method and data given in [1] as better specified in the following section.

Numerical calculation of SHG for clear and cloudy day

All calculations have been made hourly (from 6 a. m. to 6 p. m.), on the 21st day of the month with the procedure reported in the appendix.

Clear day

Solar radiation data are given in tab. 1 from [1].

Table 1. Solar radiation data

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
A_{SI} [Wm^{-2}]	1230	1215	1186	1136	1104	1088	1085	1107	1151	1192	1221	1233
B air mass-1	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C, [–]	0.058	0.06	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

A_{SI} is the apparent normal solar irradiation at air mass 0; B the atmospheric extinction coefficient, and C the diffuse radiance factor for clear day.

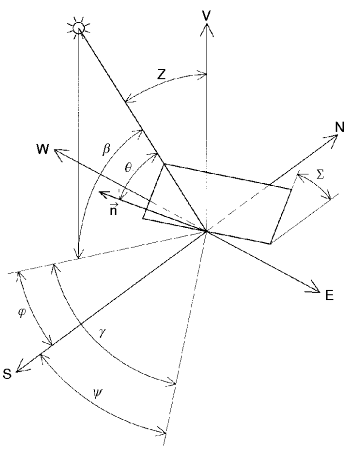

Figure 5. Solar angles

It has also, referring to fig. 5:

– solar declination δ *vs.* day of the year n_D:

$$\delta = 23.45\sin\left[360\frac{284+n_D}{365}\right] \tag{4}$$

– hour angle H_A vs. apparent solar time A_{ST}:

$$H_A = 15(A_{ST} - 12) \tag{5}$$

– direct normal irradiance I_{DN} *vs.* solar altitude β:

$$I_{DN} = \frac{A_{SI}}{e^{B/\sin\beta}} \quad \text{if } \beta \le \text{then } I_{DN} = 0 \tag{6}$$

– sun-wall azimuth γ *vs.* wall azimuth ψ and solar azimuth f (y and f from south, positive toward east):

$$\gamma = \Psi - \text{f} \tag{7a}$$

The following equations relate the solar altitude β, the latitude L, the declination δ, the hour angle H_A, the solar azimuth ϕ, the angle of incidence of the beam radiation on the wall Θ, and the tilt angle on the wall Σ [1]:

$$\sin\beta = \cos L \cos\delta \cos H_A + \sin L \sin\delta \quad (7b)$$

$$\sin\phi = \frac{\cos\delta \sin H_A}{\cos\beta} \quad (7c)$$

$$\cos\Theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma \quad (7d)$$

Direct (beam) irradiance and diffuse irradiance

Beam radiation on the wall I_B:

- If $\cos\Theta > 0$ then $I_B = I_{DN}\cos\Theta$; otherwise $I_B = 0$
- Diffuse irradiance on the horizontal surface: $I_{DH} = I_{DN}C$
- Sky diffuse irradiance on vertical surface: $I_{DSV} = I_{DN}CY$
- Ground reflected diffuse irradiance on vertical surface:

$$I_{DVG} = (I_{DH} + I_{DN}\cos\Theta_H)\rho_G F_{SG} = I_{DN}(C + \cos\Theta_H)\rho_G F_{SG} \quad (8)$$

It is assumed $F_{SG} = 0.5$ (ground horizontal, reflected radiation isotropic).
In the ASHRAE model, the total diffuse irradiance on vertical surface is given by:

$$I_{DV} = I_{DSV} + I_{DGV} = I_{DN}[CY + (C + \cos\Theta_H)\rho_G F_{SG}] \quad (9)$$

where Y is the ratio of sky diffuse irradiance on vertical surface to sky diffuse irradiance on horizontal surface and for clear day may be evaluated as:

$$\text{If } \cos\Theta > -0.2 \text{ then } Y = 0.55 + 0.437\cos\Theta + 0.313\cos^2\Theta \quad (10)$$

Otherwise $Y = 0.45$.

Peak solar heat gain

- Transmitted component:

$$SHG_T = I_B\tau(\Theta) + I_D\bar{\tau} \quad (11)$$

- Absorbed component:

$$SHG_A = I_B a(\Theta) + I_D\bar{a} \quad (12)$$

$\tau(\Theta)$ and $a(\Theta)$ are the transmission and absorption coefficients of the fenestration as a function of Θ; $\bar{\tau}$ and $\bar{a}$ are the average values: $\tau(\Theta)$ and $a(\Theta)$ may be expressed in polynomial form as [1]:

$$\tau(\Theta) = \Sigma_{J=0}^{5} t_J \cos^J\Theta \quad \bar{\tau} = 2\sum_{J=0}^{5}\frac{t_J}{J+2} \quad (13)$$

and

$$a(\Theta) = \Sigma_{J=0}^{5} t_J \cos^J\Theta \quad \bar{a} = 2\sum_{J=0}^{5}\frac{a_J}{J+2} \quad (14)$$

Table 2. ASHRAE standard double glass coefficients for eqs. (13) and (14)

J	t_J	a_J
0	–0.00885	0.01154
1	2.71235	0.77674
2	–0.62062	–3.94657
3	–7.07329	8.57881
4	9.75995	–8.38135
5	–3.89922	3.01188

For an ASHRAE standard double glass the coefficients t_J an a_J for the polynomial expressions are given in tab. 2.

The SHG factor in clear day is finally given by:

$$SHG_{CLEAR} = SHG_T = NSHG_D \tag{15}$$

where N is the inward flowing fraction of the absorbed radiation. Here it has been assumed $N = 0.3$.

Cloudy day

Equations (4)-(7) and the nomenclature given in section 3.1 remain the same. To calculate the beam and diffuse components the Orgill and Hollands correlation was used. It was slightly modified to obtain that *in clear day condition* $F_D(k_T)$ values in the Orgill and Hollands correlation were the same that in the ASHRAE model in the same month and hour.

For the ASHRAE model the hourly clearness index in clear day $k_T^{clear}(m,h)$ is given by:

$$k_T^{clear}(m,h) = \frac{I_{DN}(C + \cos\Theta_H)}{A\cos\Theta_H} \tag{16}$$

and the corresponding $\Theta_D(k_T)$ value:

$$\Phi_D^{clear}(m,h) = \frac{I_{DN}C}{I_{DN}(C + \cos\Theta_H)} \tag{17}$$

Using (16) and (17), the new correlation $\Phi_{DN}(k_T)$ can be expressed as:

$$\Phi_D(k_T) = \begin{cases} 1 - 0.249k_T & \text{for } 0 \le k_T \le 0.35 \text{ and } k_T^{clear} > 0.35 \\ 0.913 + \dfrac{\Phi_D^{clear} - 0.913}{k_T^{clear} - 0.35}(k_T - 0.35) & \text{for } 0.35 \le k_T 0.75 \text{ and } k_T^{clear} > 0.35 \\ \Phi_D^{clear} & \text{for } k_T > 0.75 \text{ or } k_T \ge k_T^{clear} \end{cases} \tag{18}$$

The solar heat gain was then calculated with the procedure given in appendix A.

Results

SHG_{CLOUDY} values were calculated on the 21st day of each month, for latitudes between 35° and 55° north, for surfaces facing the eight cardinal orientations and the horizontal surface. For example, results for latitude of 48° north are given in tabs. 3 and 4. Data carried out from model were formatted in the same manner of that presented in [1] for each month, hour and orientation, for clear and cloudy conditions. Calculations were made for $\rho_G = 0.1$ (bituminous parking lot) and $\rho_G = 0.2$ (green grass) as suggested by Threlkeld [8].

The tables carry out the SHG_{CLOUDY} values in relationship with different format. Precisely:

- if $1 < SHG_{CLOUDY}/SHG_{CLEAR} \le 1.25$ underscored
- if $1.25 < SHG_{CLOUDY}/SHG_{CLEAR} \le 1.5$ italic
- if $1.5 < SHG_{CLOUDY}/SHG_{CLEAR}$ bold italic

The results reveal that:

– Comparisons between SHG_{CLOUDY} and SHG_{CLEAR} shown that the values of the former often exceed the latter, particularly for the smaller values of the ground albedo. The increment between respective hourly values was often a tenth percent but in some case was twice and more. Nevertheless, for all considered expositions, excluding north exposition, the maximum daily value occurs for clear condition so the clear day remains the conservative condition for computing the peak solar heat gain.
– For north exposure the behavior is different. Indeed SHG_{CLOUDY} is never lower and in nearly every case, notably in peak condition, greater than SHG_{CLEAR}. Figure 6 shows the evolution of SHG_{CLOUDY} and SHG_{CLEAR} for the month of June, at different times of day. As it can be noted, for SHG_{CLOUDY} the peak value occurs at noon while SHG_{CLEAR} has the maximum values at early morning or in last hour of the evening, *i. e.* when the conditioning plant is off. For this reason the difference between the peak values occurring during the seasonal period of operation of the conditioning plant can reach 70-90 W/m^2. The time range shown in fig. 6 corresponds with the typical working time of an office building, from 08.00 to 17.00.

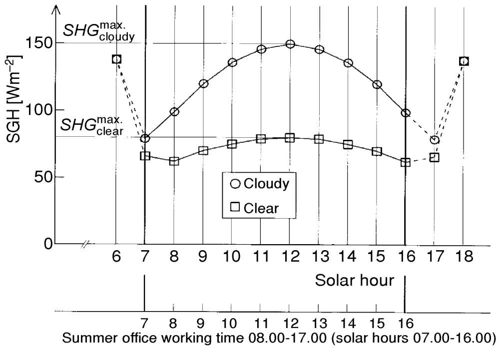

Figure 6. Evolution of $SGH^{max.}$ for clear and cloudy day for the month of June, for a wall facing north

Therefore, for north exposition, if the value of fenestration heat gain is a valuable part of the total sensible heat gain, the assumption of clear day cannot be a conservative condition.

A better representation of the situation described above can be made plotting the values of the maximum difference between $SGH^{max.}_{cloudy} - SGH^{max.}_{clear}$ as a function of the latitude and the exposition, as shown in the following figures.

Figure 7 describes $SGH^{max.}_{cloudy} - SGH^{max.}_{clear}$ distributions for latitudes range between 0 and 60°, with exposition purely north. It is observed that this difference is small for low latitudes while is more pronounced for latitudes between 20° and 35°, decreasing gradually for high latitude values until to 60°.

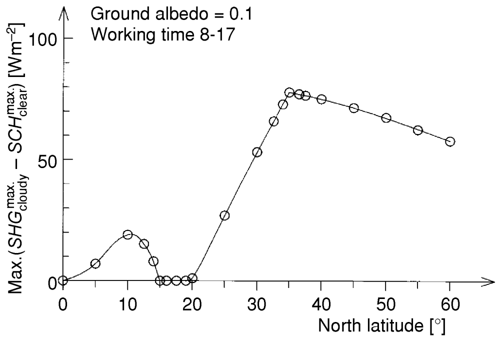

Figure 7. Evolution of $SGH^{max.}_{cloudy} - SGH^{max.}_{clear}$ of a wall facing north

In fig. 8 is presented the maximum deviation from north exposure so that the difference $SGH^{max.}_{clear} - SGH^{max.}_{cloudy}$ is positive, for different latitudes. At low latitudes the difference $SGH^{max.}_{cloudy} - SGH^{max.}_{clear}$ is small and only for exposure close to the north. At major latitudes, it is noted that this difference increases with the angular distance from north, until to 32° W or 13° E. The different behavior shown for west and east expositions is due to the choice of an asymmetric working time respect to the noon (fig. 6).

Table 3 $r_g = 0.1; L = 48°$

Date	Solar time	Direct normal irradiaton	Solar heat gain factors, W/m²																		Solar time
			N		NE		E		SE		S		SW		W		NW		Hor		
	A.M.	W/m²	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy	P.M.
Jan 21	8	108	3	***5***	10	10	84	84	102	102	58	58	3	***5***	3	***5***	3	***5***	6	9	4
	9	582	18	***31***	18	***31***	365	365	548	548	400	400	21	*31*	18	***31***	18	***31***	78	78	3
	10	756	27	***49***	27	***49***	323	323	674	674	608	608	149	149	27	***49***	27	***49***	173	173	2
	11	825	31	***60***	31	***60***	153	153	646	646	724	724	353	353	31	***60***	31	***60***	243	243	1
	12	845	33	***64***	33	***64***	33	***64***	529	529	761	761	529	529	33	***64***	33	***64***	268	268	12
	8	557	18	***30***	104	104	455	455	511	511	252	252	18	***30***	18	***30***	18	***30***	74	74	4
	9	778	29	***54***	32	***54***	516	516	715	715	479	479	29	***54***	29	***54***	29	***54***	205	205	3
	10	869	36	***73***	36	***73***	397	397	750	750	640	640	115	115	36	***73***	36	***73***	326	326	2
	11	910	40	***85***	40	***85***	184	184	680	680	740	740	339	339	40	***85***	40	***85***	404	404	1
	12	921	42	***89***	42	***89***	42	***89***	538	538	774	774	538	538	42	***89***	42	***89***	431	431	12
Mar 21	7	471	17	***26***	241	241	444	444	376	376	61	61	17	***26***	17	***26***	17	***26***	61	61	5
	8	742	31	***55***	224	224	632	632	641	641	249	249	31	***55***	31	***55***	31	***55***	210	210	4
	9	854	41	***80***	76	90	592	592	739	739	436	436	41	***80***	41	***80***	41	***80***	368	368	3
	10	909	48	***99***	48	***99***	438	438	731	731	579	579	74	*105*	48	***99***	48	***99***	491	491	2
	11	935	51	***111***	51	***111***	206	212	642	642	669	669	275	275	51	***111***	51	***111***	567	567	1
	12	943	53	***115***	53	***115***	53	***115***	487	487	700	700	487	487	53	***115***	53	***115***	592	592	12
Apr 21	6	342	32	32	269	269	335	335	201	201	16	*22*	16	*22*	16	*22*	16	*22*	46	48	6
	7	649	34	*51*	409	409	621	621	461	461	39	*53*	34	*51*	34	*51*	34	*51*	190	190	5
	8	783	46	***79***	334	334	676	676	605	605	157	157	46	***79***	46	***79***	46	***79***	361	361	4
	9	851	55	***102***	168	178	601	601	660	660	314	314	55	***102***	55	***102***	55	***102***	510	510	3
	10	888	61	***120***	61	***120***	440	440	635	635	446	446	61	***120***	61	***120***	61	***120***	622	622	2
	11	907	65	***132***	65	***132***	214	233	542	542	529	529	187	217	65	***132***	65	***132***	693	693	1
	12	913	66	***135***	66	***135***	66	***135***	384	384	558	558	384	384	66	***135***	66	***135***	718	718	12
May 21	6	516	106	106	441	441	502	502	261	261	31	*40*	31	*40*	31	*40*	31	*40*	128	128	6
	7	695	51	*69*	488	488	658	658	436	436	46	*68*	46	*68*	46	*68*	46	*68*	291	291	5
	8	787	57	***94***	400	400	671	671	543	543	86	103	57	***94***	57	***94***	57	***94***	454	454	4
	9	839	65	***116***	234	236	587	587	580	580	216	221	65	***116***	65	***116***	65	***116***	591	591	3
	10	869	71	***133***	82	***135***	428	428	550	550	334	334	71	***133***	71	***133***	71	***133***	696	696	2
	11	884	75	***143***	75	***143***	215	243	454	454	413	413	121	*156*	75	***143***	75	***143***	763	763	1
	12	889	76	***147***	76	***147***	76	***147***	301	306	440	440	301	306	76	***147***	76	***147***	785	785	12
June 21	6	547	138	138	481	481	528	528	258	258	36	*47*	36	*47*	36	*47*	36	*47*	163	163	6
	7	697	66	79	508	508	655	655	413	413	51	*74*	51	*74*	51	*74*	51	*74*	326	326	5
	8	779	62	***99***	420	420	659	659	510	510	73	*102*	62	***99***	62	***99***	62	***99***	482	482	4
	9	826	70	***120***	259	259	575	575	542	542	180	199	70	***120***	70	***120***	70	***120***	614	614	3
	10	854	75	***136***	96	*142*	420	420	510	510	288	290	75	***136***	75	***136***	75	***136***	716	716	2
	11	869	79	***146***	79	***146***	214	245	416	416	363	363	107	*154*	79	***146***	79	***146***	780	780	1
	12	873	80	***150***	80	***150***	80	***150***	268	283	389	389	268	283	80	***150***	80	***150***	801	801	12
July 21	6	491	107	107	428	428	485	485	252	252	32	40	32	40	32	40	32	40	129	129	6
	7	668	54	*70*	478	478	641	641	424	424	49	*68*	49	*68*	49	*68*	49	*68*	290	290	5
	8	760	60	***94***	396	396	658	658	531	531	86	102	60	***94***	60	***94***	60	***94***	450	450	4
	9	813	68	***115***	236	237	578	578	569	569	213	218	68	***115***	68	***115***	68	***115***	584	584	3
	10	843	74	***132***	86	***135***	424	424	540	540	328	328	74	***132***	74	***132***	74	***132***	688	688	2
	11	859	78	***142***	78	***142***	216	242	447	447	405	405	121	*155*	78	***142***	78	***142***	753	753	1
	12	864	79	***146***	79	***146***	79	***146***	297	302	432	432	297	302	79	***146***	79	***146***	775	775	12
Aug 21	6	295	31	31	239	239	297	297	179	179	16	*22*	16	*22*	16	*22*	16	*22*	47	47	6
	7	595	37	*51*	388	388	585	585	434	434	42	52	37	*51*	37	*51*	37	*51*	187	187	5
	8	732	51	***78***	326	326	649	649	581	581	156	156	51	***78***	51	***78***	51	***78***	354	354	4
	9	803	60	***101***	171	178	584	584	639	639	307	307	60	***101***	60	***101***	60	***101***	499	499	3
	10	841	67	***119***	67	***119***	432	432	619	619	436	436	67	***119***	67	***119***	67	***119***	608	608	2
	11	861	70	***130***	70	***130***	216	232	530	530	517	517	189	215	70	***130***	70	***130***	678	678	1
	12	867	72	***134***	72	***134***	72	***134***	378	378	545	545	378	378	72	***134***	72	***134***	701	701	12
Sep 21	7	410	18	*26*	217	217	395	395	335	335	56	56	18	*26*	18	*26*	18	*26*	61	61	5
	8	679	35	***54***	215	215	592	592	599	599	235	235	35	***54***	35	***54***	35	***54***	205	205	4
	9	795	45	***78***	78	89	565	565	703	703	416	416	45	***78***	45	***78***	45	***78***	358	358	3
	10	852	52	***97***	52	***97***	423	423	701	701	556	556	76	*104*	52	***97***	52	***97***	477	477	2
	11	879	56	***109***	56	***109***	205	209	618	618	644	644	269	269	56	***109***	56	***109***	550	550	1
	12	887	57	***113***	57	***113***	57	***113***	471	471	674	674	471	471	57	***113***	57	***113***	575	575	12
Oct 21	8	483	18	***28***	92	92	400	400	451	451	226	226	18	***28***	18	***28***	18	***28***	66	66	4
	9	718	30	***52***	32	***52***	483	483	671	671	453	453	30	***52***	30	***52***	30	***52***	191	191	3
	10	816	38	***71***	38	***71***	380	380	717	717	615	615	114	114	38	***71***	38	***71***	308	308	2
	11	860	42	***82***	42	***82***	180	180	655	655	714	714	331	331	42	***82***	42	***82***	384	384	1
	12	872	44	***86***	44	***86***	44	***86***	521	521	748	748	521	521	44	***86***	44	***86***	410	410	12
Nov 21	8	78	2	*3*	7	7	60	60	73	73	42	42	2	*3*	2	*3*	2	*3*	5	*7*	4
	9	546	18	***30***	18	***30***	343	343	517	517	379	379	21	*30*	18	***30***	18	***30***	74	74	3
	10	725	27	***48***	27	***48***	312	312	651	651	588	588	147	147	27	***48***	27	***48***	165	165	2
	11	798	32	***59***	32	***59***	150	150	629	629	705	705	346	346	32	***59***	32	***59***	234	234	1
	12	818	33	***63***	33	***63***	33	***63***	517	517	743	743	517	517	33	***63***	33	***63***	259	259	12
Dec 21	9	444	13	***22***	13	***22***	270	270	420	420	315	315	19	23	13	***22***	13	***22***	43	47	3
	10	679	22	***39***	22	***39***	281	281	609	609	559	559	149	149	22	***39***	22	***39***	120	120	2
	11	769	27	***51***	27	***51***	136	136	608	608	687	687	342	342	27	***51***	27	***51***	183	183	1
	12	794	29	***54***	29	***54***	29	***54***	506	506	727	727	506	506	29	***54***	29	***54***	206	206	12
			N		NW		W		SW		S		SE		E		NE		Hor		^ <P.M.

Table 4 $r_g = 0.2; L = 48°$

Date	Solar time A.M.	Direct normal irradiation W/m^2	N clear	N cloudy	NE clear	NE cloudy	E clear	E cloudy	SE clear	SE cloudy	S clear	S cloudy	SW clear	SW cloudy	W clear	W cloudy	NW clear	NW cloudy	Hor clear	Hor cloudy	Solar time P.M.
Jan 21	8	108	3	5	11	11	84	84	102	102	58	58	3	5	3	5	3	5	6	9	4
	9	582	24	34	24	34	371	371	554	554	406	406	27	35	24	34	24	34	78	78	3
	10	756	37	55	37	55	334	334	685	685	618	618	160	160	37	55	37	55	173	173	2
	11	825	45	69	45	69	167	167	660	660	737	737	367	367	45	69	45	69	243	243	1
	12	845	48	73	48	73	48	73	544	544	776	776	544	544	48	73	48	73	268	268	12
	8	557	23	33	110	110	461	461	516	516	257	257	23	33	23	33	23	33	74	74	4
	9	778	41	61	44	62	528	528	727	727	491	491	41	61	41	61	41	61	205	205	3
	10	869	53	83	53	83	415	415	767	767	658	658	132	132	53	83	53	83	326	326	2
	11	910	61	97	61	97	205	205	700	700	761	761	359	359	61	97	61	97	404	404	1
	12	921	63	102	63	102	63	102	560	560	796	796	560	560	63	102	63	102	431	431	12
Mar 21	7	471	21	29	246	246	448	448	381	381	66	66	21	29	21	29	21	29	61	61	5
	8	742	44	62	236	236	644	644	653	653	261	261	44	62	44	62	44	62	210	210	4
	9	854	60	91	95	104	611	611	758	758	454	454	60	91	60	91	60	91	368	368	3
	10	909	71	113	71	113	462	462	755	755	603	603	98	121	71	113	71	113	491	491	2
	11	935	79	127	79	127	233	236	669	669	696	696	302	302	79	127	79	127	567	567	1
	12	943	81	132	81	132	81	132	515	515	728	728	515	515	81	132	81	132	592	592	12
Apr 21	6	342	35	35	272	272	339	339	204	204	19	25	19	25	19	25	19	25	46	48	6
	7	649	45	58	420	420	632	632	472	472	50	60	45	58	45	58	45	58	190	190	5
	8	783	64	90	353	353	694	694	624	624	175	175	64	90	64	90	64	90	361	361	4
	9	851	80	117	192	199	626	626	684	684	338	338	80	117	80	117	80	117	510	510	3
	10	888	91	138	91	138	469	469	665	665	476	476	91	138	91	138	91	138	622	622	2
	11	907	97	151	97	151	247	259	574	574	562	562	219	242	97	151	97	151	693	693	1
	12	913	100	156	100	156	100	156	418	418	591	591	418	418	100	156	100	156	718	718	12
May 21	6	516	114	114	449	449	510	510	269	269	39	45	39	45	39	45	39	45	128	128	6
	7	695	66	80	503	503	673	673	451	451	61	78	61	78	61	78	61	78	291	291	5
	8	787	79	108	422	422	694	694	565	565	108	120	79	108	79	108	79	108	454	454	4
	9	839	93	133	262	262	616	616	608	608	244	246	93	133	93	133	93	133	591	591	3
	10	869	104	153	115	156	461	461	582	582	367	367	104	153	104	153	104	153	696	696	2
	11	884	110	165	110	165	251	270	490	490	448	448	156	181	110	165	110	165	763	763	1
	12	889	112	169	112	169	112	169	337	339	476	476	337	339	112	169	112	169	785	785	12
June 21	6	547	147	147	491	491	538	538	268	268	46	53	46	53	46	53	46	53	163	163	6
	7	697	83	91	525	525	672	672	430	430	68	85	68	85	68	85	68	85	326	326	5
	8	779	85	114	443	443	683	683	533	533	97	118	85	114	85	114	85	114	482	482	4
	9	826	99	138	288	288	604	604	571	571	209	222	99	138	99	138	99	138	614	614	3
	10	854	109	157	130	164	453	453	544	544	322	322	109	157	109	157	109	157	716	716	2
	11	869	115	169	115	169	250	272	452	452	399	399	143	178	115	169	115	169	780	780	1
	12	873	117	173	117	173	117	173	305	314	426	426	305	314	117	173	117	173	801	801	12
July 21	6	491	115	115	436	436	493	493	260	260	40	46	40	46	40	46	40	46	129	129	6
	7	668	69	80	494	494	656	656	440	440	64	78	64	78	64	78	64	78	290	290	5
	8	760	82	108	418	418	680	680	553	553	108	119	82	108	82	108	82	108	450	450	4
	9	813	96	133	264	264	606	606	596	596	241	242	96	133	96	133	96	133	584	584	3
	10	843	107	152	118	156	456	456	572	572	360	360	107	152	107	152	107	152	688	688	2
	11	859	113	164	113	164	251	269	482	482	440	440	156	180	113	164	113	164	753	753	1
	12	864	115	168	115	168	115	168	333	335	468	468	333	335	115	168	115	168	775	775	12
Aug 21	6	295	34	34	243	243	301	301	182	182	20	24	20	24	20	24	20	24	47	47	6
	7	595	48	58	399	399	596	596	445	445	53	60	48	58	48	58	48	58	187	187	5
	8	732	69	90	344	344	667	667	599	599	173	173	69	90	69	90	69	90	354	354	4
	9	803	84	117	195	199	608	608	663	663	331	331	84	117	84	117	84	117	499	499	3
	10	841	95	137	95	137	461	461	647	647	465	465	95	137	95	137	95	137	608	608	2
	11	861	102	150	102	150	248	258	561	561	549	549	220	239	102	150	102	150	678	678	1
	12	867	104	154	104	154	104	154	411	411	578	578	411	411	104	154	104	154	701	701	12
Sep 21	7	410	23	29	222	222	400	400	340	340	61	61	23	29	23	29	23	29	61	61	5
	8	679	46	62	227	227	604	604	611	611	247	247	46	62	46	62	46	62	205	205	4
	9	795	63	90	97	103	583	583	721	721	434	434	63	90	63	90	63	90	358	358	3
	10	852	75	111	75	111	447	447	724	724	579	579	99	120	75	111	75	111	477	477	2
	11	879	82	125	82	125	231	233	644	644	670	670	295	295	82	125	82	125	550	550	1
	12	887	85	129	85	129	85	129	498	498	701	701	498	498	85	129	85	129	575	575	12
Oct 21	8	483	23	31	97	97	405	405	456	456	231	231	23	31	23	31	23	31	66	66	4
	9	718	42	59	43	59	494	494	682	682	464	464	42	59	42	59	42	59	191	191	3
	10	816	54	81	54	81	396	396	733	733	631	631	131	131	54	81	54	81	308	308	2
	11	860	62	94	62	94	200	200	675	675	734	734	350	350	62	94	62	94	384	384	1
	12	872	64	99	64	99	64	99	542	542	769	769	542	542	64	99	64	99	410	410	12
Nov 21	8	78	3	4	8	8	61	61	74	74	42	42	3	4	3	4	3	4	5	7	4
	9	546	24	33	24	33	349	349	523	523	384	384	27	34	24	33	24	33	74	74	3
	10	725	37	54	37	54	322	322	662	662	599	599	157	157	37	54	37	54	165	165	2
	11	798	45	67	45	67	163	163	642	642	719	719	359	359	45	67	45	67	234	234	1
	12	818	48	72	48	72	48	72	531	531	757	757	531	531	48	72	48	72	259	259	12
Dec 21	9	444	16	25	16	25	274	274	423	423	319	319	22	26	16	25	16	25	43	47	3
	10	679	30	44	30	44	289	289	617	617	567	567	157	157	30	44	30	44	120	120	2
	11	769	38	57	38	57	147	147	619	619	698	698	353	353	38	57	38	57	183	183	1
	12	794	41	62	41	62	41	62	518	518	740	740	518	518	41	62	41	62	206	206	12
			N		NW		W		SW		S		SE		E		NE		Hor		<P.M.

In fig. 9 is plotted the evolution of $SGH^{\text{max.}}_{\text{cloudy}} - SGH^{\text{max.}}_{\text{clear}}$ varying the wall exposure from north to west, for different values of latitudes. The curves show a similar behavior in which there is a peak value that, increasing deviation from north exposure, decreases until to zero. This trend is more pronounced for high latitudes. In the latitudes between 15° and 35° the peak is in correspondence of an exposure deviation of about 4° from north. For major latitudes the peak disappears but, in a significant range of angles of exposure, the difference $SGH^{\text{max.}}_{\text{cloudy}} - SGH^{\text{max.}}_{\text{clear}}$ seems to stabilize on a constant positive value before to decrease to zero. So, also for wall exposure not strictly facing north, care must be taken for evaluating *SHG* in clear day condition because, as described, could not be the most conservative condition for a correct calculation.

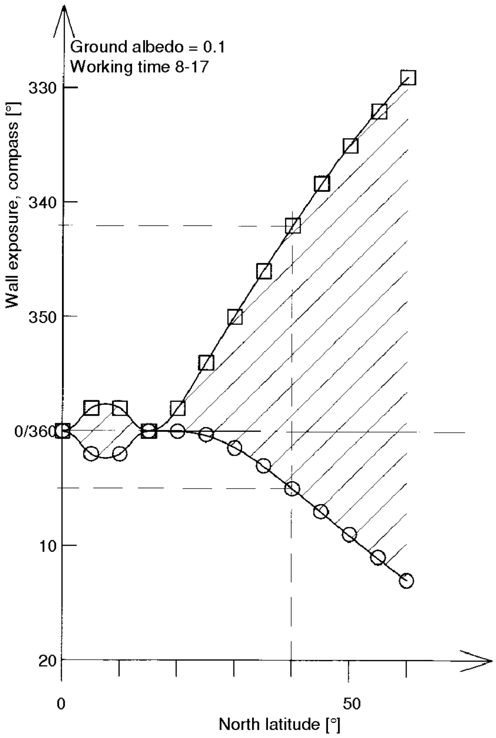

Figure 8. Wall exposures for which $SGH^{\text{max.}}_{\text{cloudy}} - SGH^{\text{max.}}_{\text{clear}} > 0$ *e. g.* for Latitude of 40° north, it is $SGH^{\text{max.}}_{\text{cloudy}} - SGH^{\text{max.}}_{\text{clear}} > 0$ if the wall exposure differs from north by less then 5 degrees toward east or less then 18 degrees toward west

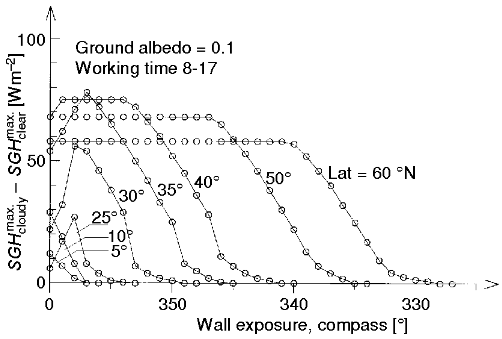

Figure 9. Evolution of $SGH^{\text{max.}}_{\text{cloudy}} - SGH^{\text{max.}}_{\text{clear}}$ varying the wall exposure

Note that the procedure search for the maximum value of SHG_{CLOODY} in the range $0 \le k_{\text{T}} \le 1$. For the extreme case $k_{\text{T}} = 1$, it is $SHG_{\text{CLOUDY}} = SHG_{\text{CLEAR}}$ (see fig. 4). This is why in tabs. 3 and 4 SHG_{CLOODY} appears never smaller then SHG_{CLEAR}.

Nomenclature

A_{SI}	– apparent normal solar irradiation at air mass = 0, [Wm^{-2}]
A_{ST}	– apparent solar time [hours]
$a(\Theta)$	– absorption coefficient for beam component
a	– absorption coefficient for diffuse component
B	– atmospheric extinction coefficient, [air mass-1]
C	– diffuse radiance factor (clear day), [–]
F_{SG}	– angle factor between ground and surface, [–]
F_{SS}	– angle factor between sky and surface, [–]
H	– daily radiation on a horizontal surface [Wm^{-2}]
H_{A}	– hour angle, [dec. degrees]
H_{D}	– diffuse daily radiation on a horizontal surface, [Wm^{-2}]

H_0 – daily extraterrestrial radiation on a horizontal surface, [Wm^{-2}]
I – hourly radiation on a horizontal surface, [Wm^{-2}]
I_B – beam radiation, [Wm^{-2}]
I_{BH} – beam irradiance on the horizontal plane, [Wm^{-2}]
I_D – diffuse hourly radiation on a horizontal surface, [Wm^{-2}]
I_{DGV} – ground diffuse irradiance on the vertical surface, [Wm^{-2}]
I_{DH} – diffuse irradiance on the horizontal plane, [Wm^{-2}]
I_{DN} – direct normal irradiance, [Wm^{-2}]
I_{DSV} – sky diffuse irradiance on the vertical surface, [Wm^{-2}]
I_{DV} – total diffuse irradiance on the vertical surface, [Wm^{-2}]
I_S – total radiation, [Wm^{-2}]
I_{TH} – total irradiance on the horizontal plane, [Wm^{-2}]
I_0 – hourly extraterrestrial radiation on a horizontal surface, [Wm^{-2}]
K_T – daily clearness index, [–]
k_T – hourly clearness index, [–]
L – latitude, north positive, [dec. degree]
N – Inward flowing fraction of the absorbed radiation, [–]
n_D – day of the year, [–]
SHG_A – Solar heat gain absorbed component, [Wm^{-2}]
SHG_T – solar heat gain transmitted component, [Wm^{-2}]
SHG_{CLEAR} – solar heat gain in clear day, [Wm^{-2}]
SHG_{CLOUDY} – solar heat gain in cloudy day, [Wm^{-2}]
Y – ratio of sky diffuse irradiance on vertical surface to sky diffuse irradiance on horizontal surface

Greek letters

β – solar altitude, [dec. degrees]
γ – sun-wall azimuth, [dec. degrees]
δ – solar declination, [dec. degrees]
Θ_H – angle of incidence relative to the – normal to the ground, [dec. degrees]
Θ_S – angle of incidence respect the normal to the surface, [dec. degrees]
ρ_G – ground reflecting coefficient, dim.less
Σ – tilt angle from the horizontal [dec. degrees]
τ – transmission coefficient for diffuse component, [–]
$\tau(\Theta)$ – transmission coefficient for beam – component, [–]
Φ_D – diffuse ratio, [–]
φ – solar azimuth [dec.degrees, from south, east positive]
Ψ – wall azimuth, [dec.degrees, from south, east positive]

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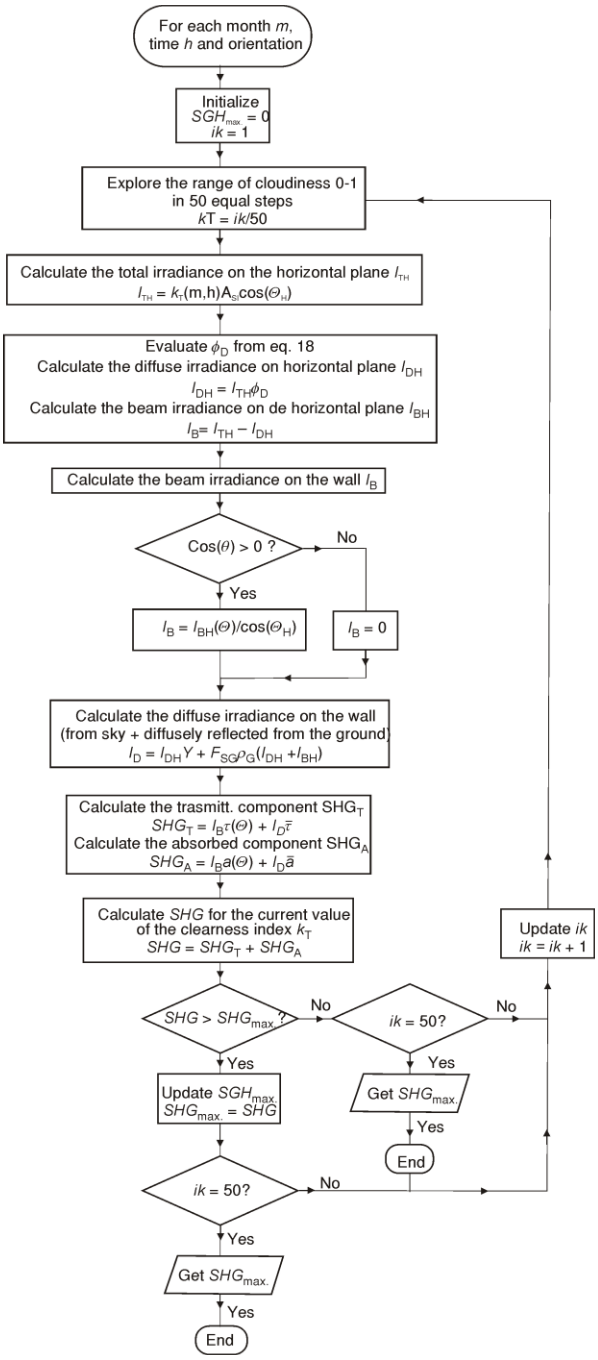
APPENDIX

Calculation procedure for $SHG_{max.}$

- I_{TH} = total irradiance on the horizontal plane;
- I_{BH} = beam irradiance on the horizontal plane;
- I_{DH} = diffuse irradiance on the horizontal plane.
- It is assumed F_{SG} = 0.5 (ground horizontal, reflected radiation isotropic).



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