A DYNAMIC PARAMETER FOR DEALING WITH SOLAR GAINS IN BUILDINGS

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ABSTRACT

In this paper the authors present a novel parameter for the evaluation of the building thermal loads due to the solar radiation incident on the glazed surface. The parameter is the *Solar Response Factor*, defined as the overall convective heat flux released by the building envelope to the occupied space per unit cyclic radiant heat flux acting on the outer surface of the glazing. The *Solar Response Factor* is a complex number, that depends on the frequency of the cyclic excitation and that can be expressed as a combination of the thermal and the optical properties of walls and glazing. When the solar radiation can be described as a periodic function, the definition of the *Solar Response Factor* allows an easy estimation of the building thermal loads due to solar gains.

The paper also discusses how the *Solar Response Factor* depends on the optical properties of the glazing, on the size of the windows and on the type of walls delimiting the enclosed space. Finally, the reliability of this approach is proven through comparison with a series of simulations carried out on EnergyPlus.

INTRODUCTION

Summer thermal loads of buildings are highly affected by solar heat gains. However, it is not easy to accurately handle these contributions, because of both the twofold nature of the heat they bring in (convective and radiant) and the quite complex mechanisms they activate within the storage mass. More in detail, the solar radiation penetrating through the glazing is firstly absorbed by the inner surface of the opaque envelope components. Then, the absorbed heat is partially re-emitted towards the indoor environment, due to the surface overheating: only the convective part of such thermal emission determines a thermal load for the indoor air. Furthermore, in order to assess the thermal load, one must not forget the radiant energy absorbed by the glass itself and re-emitted to the indoor environment by its inner surface.

In the majority of the simulation tools these mechanisms are treated quite rigorously, which implies a certain computational effort. However, despite the complexity of the problem, it would be interesting to define a transfer function that could estimate, with good accuracy, the thermal loads due to solar heat gains. Some attempts were done in the past in this sense. For instance, the *thermal storage factor* was defined in the context of the Carrier method (Carrier, 1962) as the ratio of the rate of instantaneous cooling load to the rate of solar heat gain. This factor has to be determined through appropriate tables depending on both the weight per unit floor area of the opaque components and the running time. Therefore, its use requires interpolation among tabular data; furthermore, it is rather rough because it does not account for the actual sequence of the wall layers, and it lacks of any theoretical basis, as it results from numerical simulations.

In this paper, a substantially different approach will be proposed. This approach is developed in the framework of the Admittance Procedure, a methodology built up in the early Seventies, where the dynamic heat transfer through the opaque walls is assessed by means of the so-called *dynamic thermal properties*, as discussed by (Loudon, 1968) (Millbank et al, 1974) and (Balcomb, 1983 a/b). Amongst these dynamic properties, the literature mentions the *Surface Factor* as a parameter to evaluate the dynamic thermal response of building components to any radiant heat flux acting on them. However, to the authors' knowledge, little reference is made to this parameter in the whole scientific literature (Beattie and Ward, 1999) (Rees et al., 2000), while its definition has been only recently recovered in the CIBSE guide (CIBSE, 2006) and in the international Standard ISO 13792:2012. In any case, the surface factor is not integrated in the most common simulation procedures. In the following, the *Surface Factor* will be used as a basis to introduce a dynamic parameter, called *Solar Response Factor*, that allows an easy but accurate calculation of the thermal loads due to solar heat gains.

THE SURFACE FACTOR

According to the definition provided by (Millbank et al., 1974), the *surface factor F* quantifies the overall rate of heat flow released by a wall to the indoor environment ($\tilde{q}_i$) per unit radiant heat gain absorbed on its inner surface ($\tilde{q}_{abs}$), when the air temperatures on both sides of the wall are held constant and equal ($\tilde{\theta}_i = \tilde{\theta}_o = 0$). The symbol "~" refers to sinusoidal functions and indicates their deviation from the mean value. So, with reference to Fig. 1, one can state Eq. (1), where ϕ is the radiant heat flux acting on the inner surface of the wall as a result of the radiant energy transmitted through the glazing and α is the mean solar absorptance of the walls:

$$F = \frac{\tilde{q}_i}{\tilde{q}_{abs}}\bigg|_{\tilde{\theta}_i = \tilde{\theta}_o = 0} = \frac{\tilde{q}_i}{\alpha \cdot \tilde{\phi}} \tag{1}$$

In order to get an operational expression for the surface factor, one can consider that the thermal energy absorbed by the wall is re-emitted towards the internal ($\tilde{q}_i$) and the external environment ($\tilde{q}_o$): under the hypotheses that $\tilde{\theta}_i = \tilde{\theta}_o = 0$, the ratio of these contributions equals the inverse ratio of the corresponding thermal impedances. This leads to the following expression:

$$\tilde{q}_i = \alpha \cdot \tilde{\phi} \cdot \left(\frac{Z - Z_{si}}{Z} \right) = \tilde{q}_{abs} \cdot \left(1 - \frac{Z_{si}}{Z} \right) \tag{2}$$

At this stage, one can remark that the thermal impedance Z_{si} between the surface of the wall and the indoor air is purely resistive: thus, $Z_{si} = R_{si}$, being R_{si} the inner surface thermal resistance. Moreover, the reciprocal of the wall thermal impedance Z is by definition the thermal admittance Y. Such positions yield the following expression for the surface factor:

$$F = \frac{\tilde{q}_i}{\tilde{q}_{abs}} = 1 - Y \cdot R_{si} \tag{3}$$

$$\varphi_F = \frac{P}{2\pi} \cdot arctan\left(\frac{Im(F)}{Re(F)} \right) \tag{4}$$

The definition given in Eq. (3) corresponds to the one provided in the CIBSE guide and in the international Standard ISO 13792:2012. The thermal admittance can be calculated according to the ISO Standard 13786:2007. The result of Eq. (3) is a complex number, that can be quantified in terms of amplitude and argument. The latter can be assessed through Eq. (4), and will always result negative, which indicates a delay of the wall response to the radiant heat flux acting on it.

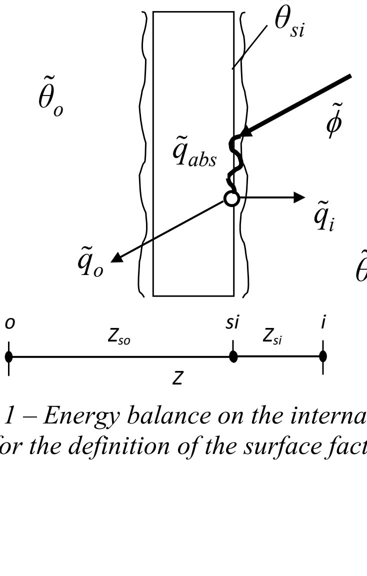

Figure 1 – Energy balance on the internal surface for the definition of the surface factor

The period of the cyclic excitation is usually $P = 24$ h in building simulation. With reference to the mean value of the cyclic excitation, a *stationary surface factor* can be defined as well, by using the wall thermal transmittance U in place of the thermal admittance Y:

$$\bar{F} = 1 - U \cdot R_{si} \tag{5}$$

THE SOLAR RESPONSE FACTOR

According to its definition, the surface factor F is useful to measure the dynamic response of a wall to a radiant heat flux acting on it. Now, it is our intention to extend the analysis to the whole envelope of a room, so as to define a relationship between the thermal loads and the solar radiation impinging on the glazed surface.

In order to get an operational definition for the *Solar Response Factor*, let us first consider that the rate of thermal energy admitted into the enclosure due to the solar radiation available on the glazing is composed of three contributions:

- *thermal energy transmitted directly through the glazing* (short-wave radiation, $\lambda < 3$ μm): it is proportional to the solar transmittance τ_g of the glazing, and can be calculated by Eq. (6), where χ is a coefficient that accounts for any shading or obstruction intercepting the solar radiation ($\chi \leq 1$):

$$\tilde{\psi}_t = \sum_g \left(\tau_g \cdot \tilde{I}_g \cdot A_g \cdot \chi_g \right) \tag{6}$$

- *thermal energy absorbed by the glazing and released by irradiation by its inner surface* (long-wave radiation, $\lambda > 3$ μm): the solar radiation absorbed by the glazing is partially re-emitted towards the indoor environment, proportionally to the difference between the g-value and the solar transmittance τ_g. In order to isolate the radiant component of this contribution, one can adopt Eq. (7) and Eq. (8):

$$r_{g,r} = \left(g_s - \tau_g \right) \cdot x_r \tag{7}$$

$$\tilde{\psi}_r = \sum_g \left(r_{g,r} \cdot \tilde{I}_g \cdot A_g \cdot \chi_g \right) \tag{8}$$

- *thermal energy absorbed by the glazing and released by convection on its inner surface*: here, in order to isolate the rate of convective heat flux re-emitted by the glazing towards the indoor environment, Eq. (9) and Eq. (10) can be used:

$$r_{g,c} = \left(g_s - \tau_g \right) \cdot x_c \tag{9}$$

$$\tilde{\psi}_c = \sum_g \left(r_{g,c} \cdot \tilde{I}_g \cdot A_g \cdot \chi_g \right) \tag{10}$$

In Eq. (7) and Eq. (9), x_c and x_r measure the rate of the heat flux exchanged respectively by convection and by irradiation on the inner surface of the glazing ($x_c + x_r = 1$).

Now, let us introduce the *Solar Response Factor* Ω. It can be defined as the overall convective heat flux released to the internal air by all inner surfaces of the envelope per unit cyclic solar irradiance acting on the outer glazed surface:

$$\Omega = \frac{\sum_{w}\left(\tilde{q}_{w,c} \cdot A_w\right) + \sum_{g}\left(\tilde{q}_{g,c} \cdot A_g\right)}{\sum_{g}\left(\tilde{I}_g \cdot A_g\right)} \qquad (11)$$

In Eq. (11), I_g is the solar irradiance incident on the glazed surface, i.e. the sum of the diffuse and the direct component. Let us observe that the walls react to the direct solar radiation admitted through the windows (ψ_t) as well as to the radiant component emitted by the glazing (ψ_r), thus generating a thermal flux respectively indicated as $q_{w,c}|_t$ and $q_{w,c}|_r$. Hence, it is useful to define the following parameters:

$$\Omega_t = \frac{\sum_{w}\tilde{q}_{w,c}\big|_t \cdot A_w}{\tilde{\psi}_t} \qquad (12)$$

$$\Omega_r = \frac{\sum_{w}\tilde{q}_{w,c}\big|_r \cdot A_w}{\tilde{\psi}_r} \qquad (13)$$

Now, by using Eq. (12) and Eq. (13) in Eq. (11), the latter can be expressed as in Eq. (14), by accounting for the definitions provided in Eq. (15):

$$\Omega = \Omega_t \cdot \tau_g^* + \Omega_r \cdot r_{g,r}^* + r_{g,c}^* \qquad (14)$$

$$\tau_g^* = \frac{\sum_{g}\tau_g \cdot A_g \cdot \tilde{I}_g \cdot \chi_g}{\sum_{g} A_g \cdot \tilde{I}_g} \qquad r_g^* = \frac{\sum_{g} r_g \cdot A_g \cdot \tilde{I}_g \cdot \chi_g}{\sum_{g} A_g \cdot \tilde{I}_g} \qquad (15)$$

In the previous equations, τ_g and g_s are time-varying, as they depend on the angle of incidence of the solar radiation on the glazing. However, in this context they will be assigned a constant value, namely the one holding for the diffuse radiation.

The calculation of Ω_t and Ω_r

In order to evaluate the parameters defined in Eq. (12) and Eq. (13), one needs to model the space distribution of the radiant heat flows into the enclosure. In this paper, the Ulbricht hypothesis is adopted, according to which the thermal power ψ emitted by a radiant heat source in an enclosed space is evenly distributed over the whole inner surface of the enclosure[1]. This leads to the following equation for the flux circulating within the enclosure:

$$\tilde{\phi} = \frac{\tilde{\psi}}{\left(1-\bar{\rho}\right) \cdot A_{tot}} \qquad (16)$$

Here, $\bar{\rho}$ is the weighted average reflectivity of the envelope. When Eq. (16) is applied to long-wave radiation, one can adopt $1-\bar{\rho}_{lw} = \bar{\alpha}_{lw}$, since both walls and glazing are opaque to infrared waves with $\lambda > 3$ μm. On the contrary, with reference to short-wave radiation ($\lambda < 3$ μm), i.e. when assessing the distribution of the solar energy admitted through the glazing and reflected by the walls, one must account for the rate of radiation escaping from the enclosure, due to the transparency of the glazing. In this case, Eq. (17) applies; here, $f = A_g / A_{tot}$ measures the fraction of glazed surface to the overall surface of the enclosed space. The higher is the fenestration surface, the more important is this effect.

$$\left(1-\bar{\rho}_{sw}\right) = \left(1-\rho_{g,sw}\right) \cdot f + \left(1-f\right) \cdot \bar{\alpha}_{w,sw} \qquad (17)$$

As to Ω_r (see Eq. 13), it is possible to state the rate of heat flow released by the inner surface of a wall in response to the long-wave radiant heat flux emitted by the glazing as:

$$\tilde{q}_w\big|_r = \alpha_{w,lw} \cdot \frac{\tilde{\psi}_r}{\left(1-\bar{\rho}_{lw}\right) \cdot A_{tot}} \cdot F_w = \frac{\tilde{\psi}_r}{A_{tot}} \cdot F_w \qquad (18)$$

However, this is the overall response of the wall, where the convective and radiant terms are still combined together. In order to assess the only convective component $q_{w,c}|_r$ of such heat flux, as required by the definition of Ω, one can observe that the convective and the overall flux are inversely proportional to the respective surface thermal resistances. Hence, Eq. (19) can be stated: here, h_c and h_r are the surface heat transfer coefficients by convection and radiation, respectively. Their sum is the *combined heat transfer coefficient* h_o, whose reciprocal is the surface thermal resistance R_{si}. The use of Eq. (18) and Eq. (19) in Eq. (13) leads to the operational formulation of Ω_r provided in Eq. (20).

$$\tilde{q}_{w,c}\big|_r = \tilde{q}_w\big|_r \cdot \frac{h_{c,w}}{h_{c,w} + h_{r,w}} = \tilde{q}_w\big|_r \cdot h_{c,w} \cdot R_{si,w} \qquad (19)$$

$$\Omega_r = \frac{\sum_{w}\left(F_w \cdot A_w \cdot h_{c,w} \cdot R_{si,w}\right)}{A_{tot}} \qquad (20)$$

As concerns the calculation of Ω_t (see Eq. 12), one can follow the same path as for the evaluation of Ω_r. The only difference is that, in this case, one must apply Eq. (17) to calculate the term $1-\bar{\rho}_{sw}$, since we are dealing with short-wave radiation; this leads to the following equation:

$$\Omega_t = \frac{\sum_{w}\left(\alpha_{w,sw} \cdot F_w \cdot A_w \cdot h_{c,w} \cdot R_{si,w}\right)}{\left[\left(1-\rho_{g,sw}\right) \cdot f + \left(1-f\right) \cdot \bar{\alpha}_{w,sw}\right] \cdot A_{tot}} \qquad (21)$$

In conclusion, the replacement of Eq. (20) and Eq. (21) into Eq. (14) provides an operational tool for the calculation of the *Solar Response Factor* Ω of the enclosure. According to its definition, Ω depends on:

- the geometry of the enclosure (A_{tot}, f, A_w);
- the optical properties of the envelope (α_w, ρ_g, τ_g);
- the presence of shadings and obstructions (χ);
- the thermophysical properties of the walls, that affect the calculation of the surface factors F_w;
- the convective and radiant surface heat transfer coefficients (h_c and h_w) of both the walls and the glazing.

[1] According to the ISO Standard 13791:2012, the Ulbricht hypothesis is reasonable as long as the average reflectivity of the enclosure is not lower than 0.7.

Since the *Solar Response Factor* Ω depends on the Surface Factor, it is a complex number expressed in terms of amplitude |Ω| and argument φ_Ω.

In addition, it is possible to define the *stationary solar response factor* $\bar{\Omega}$: it is a real number obtainable through the same relations as those used for Ω, but just replacing the surface factor *F* with the *stationary surface factor* $\bar{F}$ (see Eq. 5).

Using the Solar Response Factor

The usefulness of the Solar Response Factor is twofold:

1. it allows to classify buildings in relation to their response to the solar radiation, by means of a couple of parameters (amplitude and phase);
2. it allows to predict the thermal loads due to solar radiation in the time domain through a few simple operations.

As concerns this second point, one firstly needs to calculate Ω (and $\bar{\Omega}$) according to the geometry and the thermophysical properties of the enclosure. Then, one must apply the Fourier analysis to the periodic excitation (i.e. the solar irradiance I_g incident on the glazing surface) to get the harmonic components. Finally, the time profile of the thermal loads can be assessed through Eq. (22), where the harmonic components of the response are summed up to the order $n = N_h$.

$$Q_{sol}(t) = A_g\left[\bar{\Omega}\cdot\bar{I}_g + \sum_{n=1}^{N_h}|\Omega_n|\cdot\left|\tilde{I}_{g,n}\right|cos\left(\frac{2\pi n}{P}\cdot t + \varphi_{\Omega n}\right)\right] \quad (22)$$

The only limitation might lie in the need of using constant parameters, whereas the optical properties of the glazing as well as the surface heat transfer coefficients usually vary with time.

In order to verify the reliability of this approach, a validation has been performed, and is presented in the following. It is based on the comparison between the thermal loads due to solar radiation calculated with EnergyPlus and those calculated with Eq. (22) for a simple test room, whose size is 5 × 5 × 3 m^3. As concerns the envelope of the test room, three different building typologies were considered:

- *Type A*: heavy masonry walls (stone walls);
- *Type B*: hollow clay bricks construction;
- *Type C*: highly-insulated lightweight envelope.

Actually, three variants were conceived for type B, depending on the number of brick leaves and on the position of the insulating material. However, the three proposed solutions have the same *U*-value:

- *Type B.1*: double-leaf cavity walls with the insulation placed in the air gap;
- *Type B.2*: double-leaf cavity walls with the insulation placed on the inner side of the wall;
- *Type B.3*: single leaf walls with distributed insulation (light-weight insulating bricks).

The details concerning the composition of walls, floors and ceilings are reported in the Appendix, where the values of the corresponding surface factors *F* are also provided. In the calculation, two walls are structured as *external walls*, whereas the others look like *internal walls*. In any case, all opaque surfaces have the same short-wave absorptance (α_{sw} = 0.3).

Furthermore, the room is equipped with a window, whose size is A_g = 5.5 m^2, which corresponds to the 5% of the whole envelope surface (*f* = 0.05). The window has a double glazing filled with air, with a thermal transmittance U_g = 2.9 $W\cdot m^{-2}\cdot K^{-1}$; the optical properties, calculated according to UNI EN 410:2011 with reference to diffuse radiation, are as follows:

$$\boldsymbol{\tau}_g = 0.59 \qquad \boldsymbol{\rho}_g = 0.22 \qquad \mathbf{g}_s = 0.664$$

In the calculation of the solar response factor Ω, no obstruction or shadings were considered (χ = 1). As concerns the parameters describing the proportion of convective and radiant energy re-emitted on the inner surface of the glazing, x_c = 0.47 and x_r = 0.53 were adopted: these values derive from UNI 673:2011, where h_c = 3.6 $W\cdot m^{-2}\cdot K^{-1}$ and h_r = 4.1 $W\cdot m^{-2}\cdot K^{-1}$ are suggested when dealing with a glazing having standard emissivity (ε = 0.837).

Validation of the proposed model

For each type of envelope, four different simulations were carried out, so as to investigate all the possible exposures of the glazing. The weather data are those available on EnergyPlus for Catania (Southern Italy). It is to be reminded that no forcing condition other than the solar radiation incident on the glazing must be taken into account in this context, according to the definition framework of both the *surface factor F* and the *solar response factor* Ω. The response of the enclosure to other forcing conditions, such as the outdoor temperature fluctuations, can be dealt with through other dynamic parameters (e.g. the *thermal admittance* and the *decrement factor*), that are not addressed in this paper. For this reason, in the simulations with EnergyPlus a constant air temperature was imposed in the test room (θ_i = 26°C), and all the envelope elements were considered adjacent to other rooms with the same temperature.

Now, in order to calculate the solar response factor Ω for the test room, let us clarify that, as concerns the definition of a reliable constant value for the heat transfer coefficient h_c and the inner surface thermal resistance R_{si} of the opaque envelope components, one might apparently refer to the values suggested by either the standards ISO 6946:2008 (R_{si} = 0.13 $m^2\cdot K\cdot W^{-1}$) or ISO 13792:2012 (R_{si} = 0.22 $m^2\cdot K\cdot W^{-1}$), the latter being more suitable for summer conditions.

However, in the authors' opinion, the definition framework of the surface factor implies different boundary conditions than those adopted in the above mentioned standards. In fact, the absence of forcing conditions other than the solar radiation admitted through the glazing should determine an homogenization of the inner surface temperatures, thus decreasing the rate of radiant heat transfer if compared to an "ordinary" situation; consequently, higher values of R_{si} should be considered. The values retained in this paper are those listed in Table 1. Now, we are able to assess the solar response factor Ω of the test room for each building typology. The results for the first harmonic (P = 24 h), in terms of amplitude and argument, are reported in Table 2: the argument φ_Ω is negative, which means a delay in the response of the enclosure to the periodic excitation.

Finally, a further cause for reflection concerns the choice of the optical properties of the glazing: provided that they must be assigned constant values, the sensitivity of the results to such values was investigated. To this aim, the calculation of the thermal loads was carried out not only by referring to diffuse radiation, but also by adopting "*detailed*" values of τ_g, ρ_g and g_s, provided by a preliminary investigation on Energy Plus, and depending on the glazing exposure. As shown in Table 3, the difference between "*detailed values*" and "*diffuse values*" is important only for a window due south, where the average glass solar reflectance is generally higher, due to the pronounced angle of incidence.

A first outcome of the validation is shown in Fig. 2 and Fig. 3. Here, the curve of the daily thermal loads obtained through EnergyPlus is compared with the results of Eq. (22), whose calculation was carried out by using N_h = 6 harmonics, since a preliminary analysis showed that no improvement would arise by adding higher harmonics. For the sake of brevity, the comparison is limited to case A and case B.1, with the window due south or west; however, the other cases present the same behaviour. For each diagram two curves are reported, that refer to the use of the *diffuse* or the *detailed* optical properties. The proposed model shows very good agreement with EnergyPlus when detailed optical properties are used, whereas some discrepancy arises in the case of diffuse optical properties.

Table 1. Values retained for h_c and R_{si}

		Ceiling	Floor	Walls
h_c	[W·m^{-2}·K^{-1}]	1.0	1.5	1.5
R_{si}	[m^2·K·W^{-1}]	0.8	0.6	0.6

Table 2. Test room: amplitude and argument of Ω

CASES		A	B.1	B.2	B.3	C
|Ω|	[-]	0.107	0.164	0.203	0.172	0.314
φ_Ω	[h]	-1.9	-2.0	-1.6	-1.8	-0.6

Table 3. Average optical properties of the glazing

	Diffuse	North	East	South	West
τ_g	0.589	0.558	0.589	0.472	0.588
ρ_g	0.220	0.250	0.220	0.333	0.219
g_s	0.664	0.633	0.662	0.547	0.663

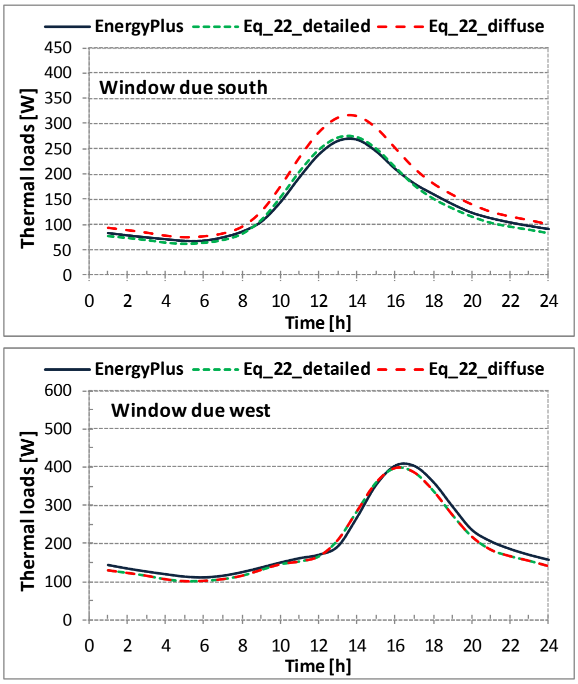

Figure 2 – Comparison between reference and calculated thermal loads (case A)

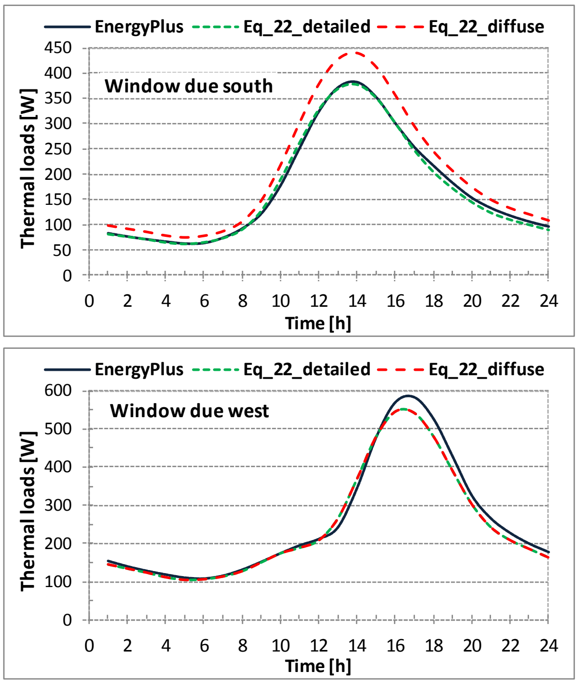

Figure 3 – Comparison between reference and calculated thermal loads (case B.1)

A further comparison is based on the calculation of the daily energy need L due to solar radiation, see Eq. (23). Table 4 reports the error made on this parameter for all the proposed building typologies and all the window exposures when using the *detailed* optical properties, if compared to EnergyPlus. Finally, Table 5 shows the error on the peak thermal load.

$$L = \int_0^{24} Q_{sol}(t)\,dt \qquad (23)$$

Table 4. Error on the daily thermal load, L

CASES	*A*	*B.1*	*B.2*	*B.3*	*C*
NORTH	-2.5%	-3.4%	-3.9%	-3.5%	-7.0%
EAST	-5.0%	-4.5%	-4.6%	-2.4%	-7.4%
SOUTH	-1.5%	-1.3%	-1.5%	-1.7%	-5.4%
WEST	-5.1%	-4.6%	-4.7%	-2.4%	-5.8%

Table 5. Error on the peak thermal load, $Q_{sol,max}$

CASES	*A*	*B.1*	*B.2*	*B.3*	*C*
NORTH	-1.3%	-4.5%	-1.3%	-2.2%	-5.3%
EAST	-4.7%	-6.2%	-0.7%	-2.7%	-5.9%
SOUTH	+1.9%	-1.2%	+4.5%	+1.8%	-0.5%
WEST	-1.3%	-6.4%	-0.4%	-2.1%	-3.8%

As shown by this validation, the use of Eq. (22) tends to underestimate the thermal loads of the test room. However, the highest discrepancy in the calculation of the daily energy need is 7.4% (see Table 4): it occurs in case C, where the very lightweight envelope emphasizes the role of the solar gains. On the whole, the outcome of the validation is very satisfactory, given that a quite large window area was considered (A_g = 5.5 m^2): better results were obtained in case of an enclosure with smaller windows.

FURTHER RESULTS

In this section the paper discusses more in detail the Solar Response Factor Ω as a function of the type of walls delimiting the enclosed space and the size of glazed surface, described through the non-dimensional parameter *f*. To this aim, Fig. 4 shows the amplitude and the argument of Ω versus *f*, for each building typology mentioned above. Here, the short-wave absorptance of the opaque surfaces is always α_{sw} = 0.3; the optical properties of the glazing refer to diffuse radiation. From Fig. 4 one can notice that, for any building typology, the higher is *f*, the lower is the amplitude |Ω| of the solar response factor. Actually, a larger glazing surface determines a higher rate of short-wave radiant losses per unit solar radiation available on the outer surface, due to the glazing transparency.

One can also observe that the three building typologies show a quite different behaviour: the curve associated with a heavyweight envelope (Type A) is the one with the lowest values of |Ω|, which proves how the high inertia of massive materials (such as lava stones) can emphasize the attenuation of the solar gains. In this example, only the 8-12% of the incident solar radiation is converted into heat loads for the enclosure. The highest values of |Ω| occur for the lightweight envelope (Type C): in this case, due to the lack of massive materials capable of damping down the thermal wave, |Ω| keeps between 0.2 - 0.35. This means that the thermal loads would be three times as high as for Type A, under the same forcing condition. As concerns Type B (hollow clay blocks), this shows an intermediate behaviour; the highest values of |Ω| are those occurring for Type B.2, as expected: indeed, in this case the layer of insulating material is placed on the inner surface of the wall, thus "hiding" the thermal mass and preventing it from working effectively. Furthermore, Fig. 4 also describes the dependence of the argument φ_Ω on the fenestration surface: the argument measures the time delay of the response (thermal loads) to the excitation (solar radiation).

It is possible to observe that the variation of φ_Ω with *f* is less pronounced than for the amplitude |Ω|, especially when dealing with the building typologies implying an insulating material closer to the indoor space (Type A and Type B.2). The time shift is almost constant and extremely low for Type A (φ_Ω = 0.6 – 0.7 h), whereas it keeps around 1.5 – 2 hours for all the other building solutions.

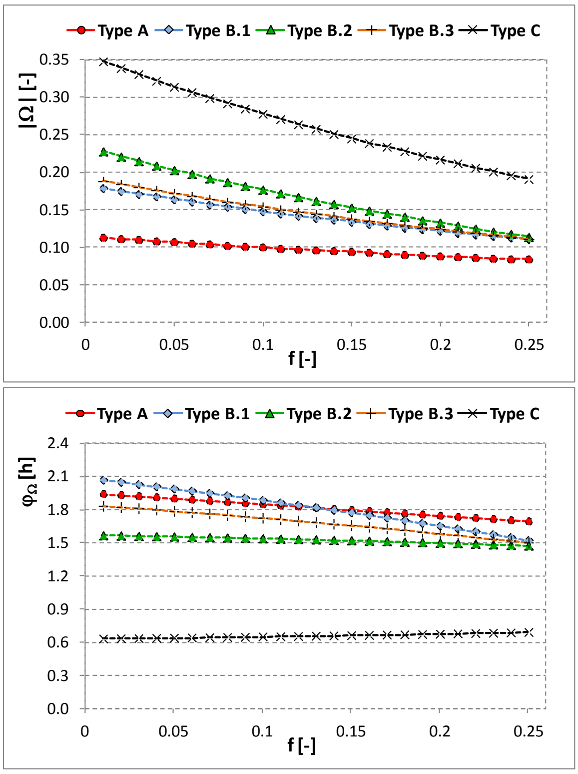

Figure 4 – Amplitude (up) and argument (bottom) of Ω as a function of the glazing surface

CONCLUSION

The *Solar Response Factor*, introduced in this paper, is appropriate and very useful to characterize the energy performance of buildings. Indeed, it makes it possible to quantify the heat flow transferred by convection from the inner surface of the envelope to the indoor air in response to the solar radiation acting on the glazing, thus allowing the determination of the thermal loads. The formulation of this parameter is derived analytically, and involves all of the thermophysical properties of the envelope.

The main quality of the *Solar Response Factor* is that it represents a transfer function of the whole enclosure, and allows to qualify the response of the building to solar excitations through a single complex number, i.e. through a couple of real numbers (amplitude and time shift). In this sense, it can be used to make comparisons between different building solutions in the design stage, or to classify existing buildings in relation to their capacity to attenuate the effects of solar radiation, without the need of complex dynamic simulations. If compared to the *thermal storage factor* defined in the Carrier method (Carrier, 1962), or to the *effective absorption coefficient* proposed by (Oliveti et al., 2011), the *Solar Response Factor* shows solid theoretical bases and is more general and rigorous.

Furthermore, the *Solar Response Factor* can be integrated, in the framework of the Admittance Method, with other dynamic transfer properties such as the *thermal admittance* and the *decrement factor*, thus allowing a *complete analytical solution* of the thermal balance on the indoor air. This approach can be implemented in whatever user-defined software, and requires a very limited computational effort.

NOMENCLATURE

Symbols

A	area (m^2)
f	fraction of glazed surface (-)
F	surface factor (-)
g_s	glass g-value (-)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
I	solar irradiance ($W\ m^{-2}$)
L	daily energy need ($Wh\ day^{-1}$)
n	order of the harmonic (-)
N	total number of harmonics (-)
P	time period (h)
q	density of heat flux ($W\ m^{-2}$)
Q	thermal load (W)
r	fraction of heat flux re-emitted (-)
R	thermal resistance ($m^2\ K\ W^{-1}$)
U	thermal transmittance ($W\ m^{-2}\ K^{-1}$)
Y	thermal admittance ($W\ m^{-2}\ K^{-1}$)
Z	thermal impedance ($m^2\ K\ W^{-1}$)

Greek letters

α	absorptance (-)
λ	wavelength (μm)
ρ	reflectance (-)
τ	transmittance (-)
φ	time shift (h)
ψ	thermal power of a radiant source (W)
χ	reduction coefficient for shadings (-)
ϕ	radiant heat flux ($W\ m^{-2}$)
Ω	solar response factor (-)

Subscripts

abs	absorbed
c	convective
g	glazing
h	harmonic
i	indoor
lw	long-wave
o	outdoor
r	radiant
si	inner surface
so	outer surface
sw	short-wave
t	transmitted
w	wall

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APPENDIX : INVENTORY

EXTERNAL WALL: Type A

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.096	-2.3
Lava stones	0.60		
Outer plaster	0.01		

EXTERNAL WALL: Type B.1

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.352	-3.3
Hollow clay bricks	0.08		
Air cavity	0.03		
Polystyrene	0.05		
Hollow clay bricks	0.25		
Outer plaster	0.01		

EXTERNAL WALL: Type B.2

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.678	-1.5
Polystyrene	0.05		
Hollow clay bricks	0.08		
Air cavity	0.03		
Hollow clay bricks	0.25		
Outer plaster	0.01		

EXTERNAL WALL: Type B.3

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.398	-2.4
Lightweight clay bricks	0.38		
Outer plaster	0.01		

EXTERNAL WALL: Type C

Material	s [m]	F [-]	φ_F [h]
Steel	$0.5\ 10^{-3}$	0.812	-0.4
Polyurethane	0.08		
Steel	$0.5\ 10^{-3}$		

INTERNAL WALL: Type A

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.095	-2.2
Lava stones	0.40		
Outer plaster	0.01		

INTERNAL WALL: Type B (all)

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.335	-2.3
Hollow clay bricks	0.08		
Outer plaster	0.01		

INTERNAL WALL: Type C

Material	s [m]	F [-]	φ_F [h]
Gypsum board	0.012	0.812	-0.4
Air cavity	0.06		
Gypsum board	0.012		

FLOOR: Type A

Material	s [m]	F [-]	φ_F [h]
Concrete tiles	0.01	0.192	-3.6
Lean concrete	0.06		
Pumice-gypsum flooring	0.12		
Inner plaster	0.01		

FLOOR: Type B (all)

Material	s [m]	F [-]	φ_F [h]
Concrete tiles	0.01	0.319	-2.0
Lightweight screed	0.05		
Concrete-slabs flooring	0.2		
Inner plaster	0.01		

FLOOR: Type C

Material	s [m]	F [-]	φ_F [h]
Linoleum	0.004	0.43	-1.2
Lightweight screed	0.05		

CEILING: Type A

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.295	-2.7
Pumice-gypsum flooring	0.12		
Lean concrete	0.06		
Concrete tiles	0.01		

CEILING: Type B (all)

Material	s [m]	F [-]	φ_F [h]
Inner plaster	0.01	0.124	-2.5
Concrete-slabs flooring	0.20		
Polystyrene	0.05		
Lightweight screed	0.05		
Concrete tiles	0.01		

CEILING: Type C

It has the same structure as the external wall. However, due to the different surface thermal resistance (see Table 1), the following values hold:

$$|F| = 0.75 \qquad \varphi_F = -0.5\ [h]$$