

Quasi-steady state calculation method for energy contribution of sunspaces: a proposal for the European standard improvement

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Abstract

Problems concerning global warming have been faced in the building sector by diminishing energy consumption in buildings by means of three main modes of action: the use of highly efficient systems powered preferably by renewable energy sources, the improvement of the energy characteristics of the envelope and the design of passive devices both for heating and for cooling. The latter are also encouraged by the recent Directive 2009/28/EC. In particular, sunspaces have been and are still nowadays widely used because they meet two different requirements: the heating of adjacent rooms and/or of supply air with the creation of comfortable spaces to live in especially in the cold season. Although an extensive literature is present on the subject, calculation methods for appropriate dimensioning of sunspaces still suffer from a lot of uncertainties concerning both the real management of the users, the correct characteristics of the materials and the environmental boundary conditions (solar radiation and wind velocity above all) that strongly influence the performance of passive devices. Dynamic simulation tools are not largely used in this field especially because they are not yet user friendly. Moreover, problems are experienced when facing multiple reflections, precise estimation of convective coefficients, two and three-dimensional heat transmission. So, quasi-steady state calculation methods are generally preferred especially in the pre-design phase. Method 5000 and the Standard EN ISO 13790:2008 are the most common ones. Concerning the latter, research has been carried out in order to identify problems and propose solutions so to improve the results maintaining the simplified and easy approach. Calculations based on the technical standard and on the new proposal have been compared among them and with dynamic simulations concerning some particular features of sunspaces. The difference in results are pointed out and a critical analysis is presented.

1. Introduction

According to Annex I of the European Directive 2010/31/EU, even “passive solar systems” can be taken in consideration in the calculation of the energy performance of a building. The 32th preamble of the European Directive 2009/28/EC on the promotion of the use of energy from renewable sources states that “Passive energy systems use building design to harness energy”, meaning that concepts concerning energy efficiency and renewable energy exploitation are integrated in the architectural design. Sunspaces (also known as “bioclimatic greenhouses” or “conservatories”) are a particular kind of passive solar system. It is self-evident that they are not only energetic elements but they are overall architectonic spaces.

Generally speaking, the calculation methods for the energy performance of buildings and of their parts can be divided into two main categories (see the European technical standard EN ISO 13790:2008, pp. 15-16): quasi-steady state methods and dynamic methods. Obviously, the dynamic methods can model in a more realistic way the real phenomena involved in the physical behaviour of buildings and HVAC plants and they provide a greater number of output data. Nevertheless, there are reasons why quasi-steady state methods are still used. In fact the quasi-steady state methods require less input data, they are simpler to be used, less time is needed to learn how to use them properly. Because of these reasons, they are typically used by building designers not confident with energy simulations, and generally they are what local legislations require, e.g. to obtain the energy performance

certificate (technical standard UNI/TS 11300:2008 in Italy).

A reasonable approach to calculation is to use quasi-steady state methods in the early stage of the design, in order to evaluate the first design hypotheses and to reject the worst ones, and to use dynamic methods afterwards in the definition of the final details, in order to produce an efficient and accurate design.

In this paper, a summary of a more complex research study is presented where some improvements have been proposed for the quasi-steady state methods described in Standard EN ISO 13790:2008 for the calculation of the energy performance of sunspaces.

2. Energy performance of sunspaces

First of all, it must be noticed that even dynamic models usually simplify very complex real situations, whose precise mechanisms are still not well known. For example, Voeltzel, A. et al. (2001) states that in simulating highly-glazed spaces “erroneous results can be explained by the poor modelling of some physical phenomena that is usually sufficient in conventional buildings. (..) This is, namely, that there are a number of simplifying assumptions regarding shortwave (SW) and longwave (LW) radiation heat transfer that cannot be applied to highly-glazed spaces. A significant fraction of the solar radiation entering a large highly-glazed room can be lost by direct transmission to the outside, direct transmission to other zones of the building, or diffuse retransmission to the outside.” Actually, the reflection to the outside is not necessary a perfect diffuse radiation, but it is generally modelled in this way (adopting a more realistic model would be extremely complicated).

Another simplification concerns temperature distribution of space: “standard thermal building simulation codes generally assume that a room can be treated as a single zone with homogeneous air temperature. Clearly, this does not apply to large highly-glazed spaces”.

In order to face this problem, authors have monitored and analysed the thermal behaviour of sunspaces through real scale prototypes (placed in Trento – Italy) for a period of one year. Surface temperatures, air temperatures and air velocities

(internal and external) were measured in different positions (Figure 1).



Fig. 1 – Sensors in the sunspace prototype during a monitoring campaign

Figure 2 shows some monitored data. It is possible to observe that, except for the floor, during the day/night cycle the temperature oscillations are very high. The floor temperatures are the lowest ones during the day and the highest ones during the night because of the thermal inertia of the ground.

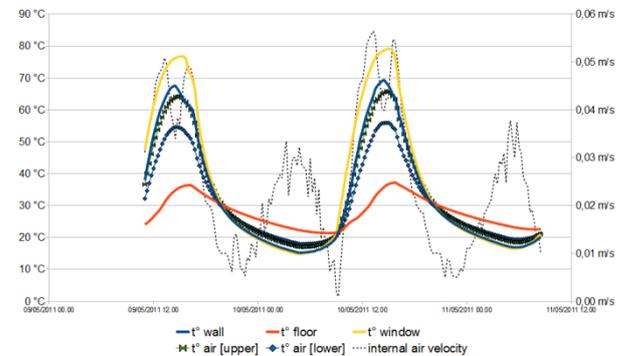


Fig. 2 – Surface temperatures and air velocities within a sunspace

Air temperatures were measured at two different heights. The temperatures of the lower sensor are obviously closer to the floor temperature. In some moments of the day, temperatures in different positions inside the sunspace are very similar: in those conditions, since the windows are closed, air velocity has its minimum values, while the maximum velocities are experienced in correspondence of the greatest differences in temperature among the internal surfaces between each other.

A model of the sunspace was created with the software IDA-ICE. Because of the big differences among the temperatures of the inner surfaces, the monitored air temperatures change a lot depending on the sensor position. However, the IDA-ICE model considers only uniform air temperature within a zone so in order to validate the model, a comparison between the surface temperatures trend of the model and the one of the real sunspace was performed (see Figure 3).

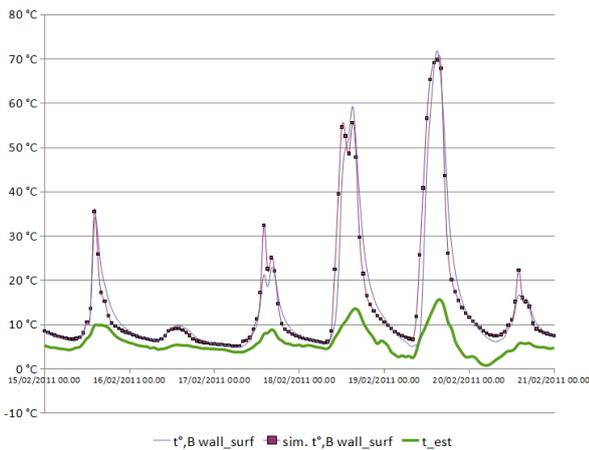


Fig. 3 – Wall temperatures: comparison between results of the model and monitored data

Average difference is very low, less than 3%, and temperature trends over the day fit very well. So the dynamic model was a good representation of the real situation, even if its proper definition and calibration was time consuming and required a lot of successive iteration. It is for this reason that usually designers prefer quasi-steady state methods even in the calculation of passive systems, requiring even greater approximations.

3. EN ISO 13790:2008

The Standard EN ISO 13790:2008 deals with passive solar systems in ANNEX E “Heat transfer and solar heat gains of special elements”. It proposes the calculation of energy performance of buildings through a quasi-steady state method, simpler than dynamic models. The calculation procedure of sunspaces proposed by the technical standard is illustrated in Figure 4.

In particular, thermal losses through a sunspace are calculated considering it as common unheated space, i.e. like an adjacent space that is unheated but whose temperature is higher than the external one because of buffer effect.

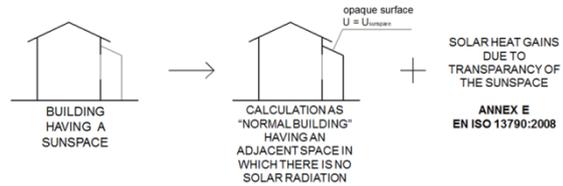


Fig. 4 – The calculation procedure of ANNEX E of EN ISO 13790:2008

On the other hand, the solar heat gains due to the presence of a sunspace have to be calculated in a different way than for common unheated spaces. In fact some phenomena that in “normal” unheated spaces are neglected have an important role in the energy behaviour of sunspaces. Such phenomena are presented in Figure 5.

Solar gains due to the presence of the sunspace must be multiplied by the utilization factor, as is usually done.

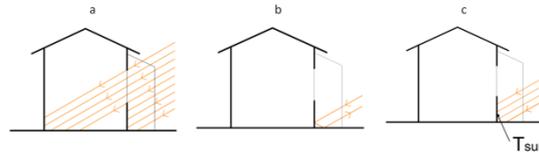


Fig. 5 – a. Part of the solar radiation enters directly the heated space; b. Part of the radiation is reflected to the external environment; c. Part of the radiation is absorbed by the opaque surfaces of the sunspace but it does not contribute to the increase of the sunspace temperature because it is conducted towards other environments.

The solar gain Q_{ss} , that the presence of the sunspace provides to the heated space, is considered as the sum of the direct gain Q_{sd} through the partitions that divide the heated space from the sunspace (both through transparent and through opaque parts) and the indirect gain Q_{si} relative to the increase of the sunspace temperature (i.e. Q_{si} is the increase of the buffer effect because of solar radiation):

$$Q_{ss} = Q_{sd} + Q_{si} \tag{1}$$

Figure 6 is a schematic representation of the physical quantities that ANNEX E considers in the calculation of the gain due to solar radiation in a sunspace adjacent to a heated space.

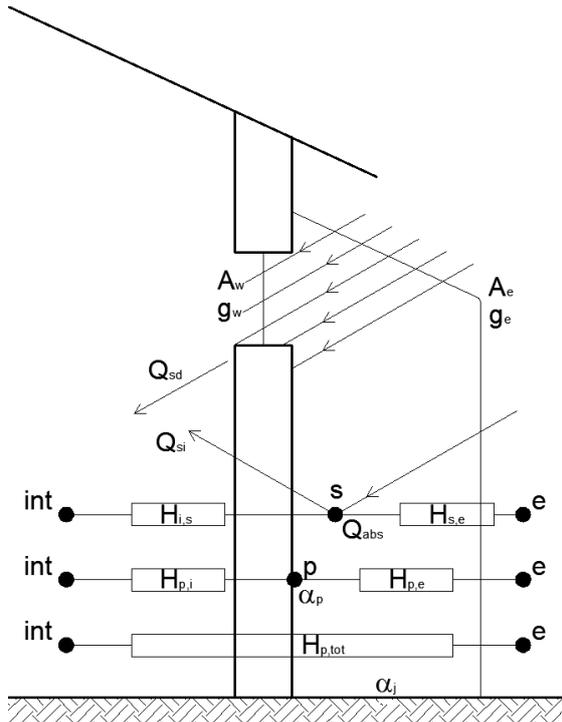


Fig. 6 –Calculation scheme proposed by ANNEX E of EN ISO 13790:2008 (image reviewed and modified by the authors)

The standard assumes that “the absorbing surfaces are all shaded in the same proportion by external obstacles and by the outer envelope of the sunspace”.

The direct solar heat gains, Q_{sd} , expressed in megajoules, are the sum of heat gains through the transparent and opaque parts of the partition wall. Equation (E.2) in EN ISO 13790:2008 is:

$$Q_{sd} = F_{sh}(1 - F_{F,e})g_e \left[(1 - F_{F,w})g_w A_w + \alpha_p A_p \frac{H_{p,tot}}{H_{p,e}} \right] I_p t \quad (2)$$

where

subscript “w” is relative to the transparent part between sunspace and heated space

subscript “e” is relative to the transparent part between sunspace and external environment

subscript “p” is relative to the opaque part between sunspace and heated space

F_{sh} is the shading correction factor

$F_{F,e}$ is the frame area fraction, i.e. the frame area to total surface ratio

g is the effective total solar energy transmittance of the glazing

A is relative to surfaces

α_j is the average solar absorption factor of absorbing surface j

$H_{p,tot}$ is the heat transfer coefficient by transmission from the internal environment, through the opaque part of the partition wall and through the sunspace, to the external environment (see paragraphs 8 and 9 of EN ISO 13790:2008 and Figure 6)

$H_{p,e}$ is the heat transfer coefficient by transmission from the absorbing surface of the partition wall, via the sunspace, to the external environment (see paragraphs 8 and 9 of EN ISO 13790:2008 and Figure 6)

I_i is the solar irradiance on surface i during the calculation step

ANNEX E states: “The indirect heat gains are calculated by summing the solar heat gains of each absorbing area, j , in the sunspace, but deducting the direct heat gains through the opaque part of the partition wall”, while for “normal” unheated spaces solar gain is calculated from solar energy that enters through their external envelopes.

Equation (E.3) in EN ISO 13790:2008 is:

$$Q_{si} = (1 - b_{tr}) \cdot F_{sh,e}(1 - F_{F,e})g_e \sum_j (I_j \alpha_j A_j) - F_{sh,e}(1 - F_{F,e})g_e \alpha_p A_p \frac{H_{p,tot}}{H_{p,e}} I_p t \quad (3)$$

where b_{tr} is the adjustment factor (“The reduced temperature difference compared to heat transmission to the external environment is taken into account in ISO 13789 by an adjustment factor, $b_{tr,x}$, that reduces the heat transfer coefficient instead of the temperature difference”).

For the other symbols that are presented in equation (3) the explanation of equation (2) can be considered. The heat gain due to solar radiation on the partitions between heated space and sunspace is subtracted because it was already calculated by equation (2) as direct heat gain.

But it is possible to observe that the equation (3) is not dimensionally consistent, because the time t multiplies only the subtrahend. So, a different calculation of Q_{si} is proposed in section “Analysis and proposals”, subsection “Indirect heat gain”.

4. Analysis and proposals

In this section specific aspects of the calculation of energy contribution of sunspaces are considered.

The method proposed by technical standard EN ISO 13790:2008 is critically analysed and some proposals for its modification are presented.

4.1 Solar heat entering through windows

Solar heat entering through windows regards both direct heat gains and indirect ones.

According to equation (47) of EN ISO 13790:2008, the total solar energy transmittance of the transparent part of a window can be expressed as

$$g_{gl} = F_w \cdot g_{gl,n} \tag{4}$$

where

$g_{gl,n}$ is the value of the total solar energy transmittance if the radiation has a direction normal to the window surface

F_w is a correction factor that was introduced in order to consider that “the time-averaged total solar energy transmittance is somewhat lower than g_n ”. In fact thermal energy transmittance is lower if solar radiation is not normal to the glazed surface.

In the absence of national values, the value of the correction factor F_w is fixed and it is recommended to be 0.9. Neither the European technical standard, nor the Italian (UNI/TS 11300-1:2008) nor the German one (DIN 18599-2:2007) take into consideration different values for different months.

Oliveti, G. (2009) proposed a linear regression that allows to estimate the correlation factor F_w as a linear function of the latitude:

$$F_w = a_1 L + a_2 \tag{5}$$

where

L is the latitude of the considered locality

a_1 and a_2 are parameters that depend on the month and on the orientation of the surface.

Since Oliveti shows that the linear regression improves in a significant way the calculation of the solar gains, next versions of the technical standards could provide parameters for it.

If data for the specific locality where the building is situated are available, the F_w value can be simply calculated even in a spreadsheet. According to Oliveti, the coefficient F_w relative to the time period Δt can be expressed as

$$F_w = \frac{\sum \left[\frac{g_b}{g_{gl,n}} I_b + \frac{g_d}{g_{gl,n}} I_d + \frac{g_r}{g_{gl,n}} I_r \right] \Delta t}{\sum [I_b + I_d + I_r] \Delta t} \tag{6}$$

where

I_b is the direct radiation on the external side of the window

I_d is the diffuse radiation from the sky on the external side of the window

I_r is the diffuse radiation coming from the ground on the external side of the window

g_b the total solar energy transmittance considering only the direct radiation

g_d the total solar energy transmittance considering only the diffuse radiation from the sky

g_r the total solar energy transmittance considering only the diffuse radiation coming from the ground

subscript “n” indicates radiation normal to the windowpane.

If $g_{b,n}$ is the total solar energy transmittance for normal radiation, the total solar energy transmittance for any other inclination of the radiation can be considered as

$$g_b = F_{w,dir}(\theta) \cdot g_{b,n} \tag{7}$$

where θ is the angle between the normal direction of the window and the solar radiation.

As example, in Figure 7, the model of $F_{w,dir}(\theta)$ that is present in the software for dynamic simulations IDA – ICE and the models presented in Karlsson, J. et al. (2000) for a window having a Ag+ coating layer and for a window having a SnO₂ coating layer are printed.

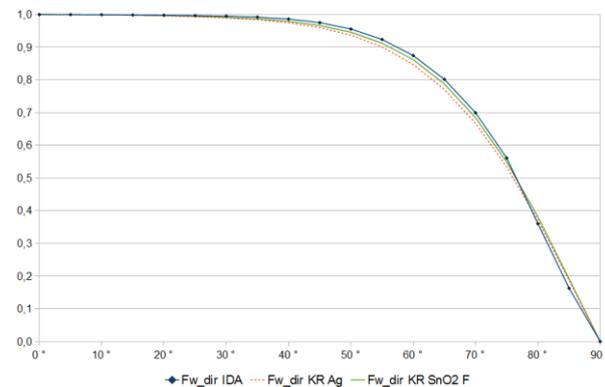


Fig. 7 – Three functions of the correction factor F_w . On the horizontal axis: angle between the radiation and the windowpane. On the vertical axis: the correction factor

The model proposed by IDA-ICE handles the angle dependence of $F_{w,dir}$ by using different trigonometric functions for three different angle intervals. For the diffuse radiation the reduction factor of the entering short-wave radiation is considered equal to 0,85 which derives from the average of $F_{w,dir}$ over the hemisphere.

For Bolzano the F_w values have been calculated both using the linear regression proposed by Oliveti and using the model of IDA-ICE (with climatic data from Comitato Termotecnico Italiano). The trend of the values is similar, as Figure 8 shows.

If F_w were calculated in this way for each Italian locality and printed in an atlas depending on the widely used commercial glasses, results of the Standard method could be much more accurate.

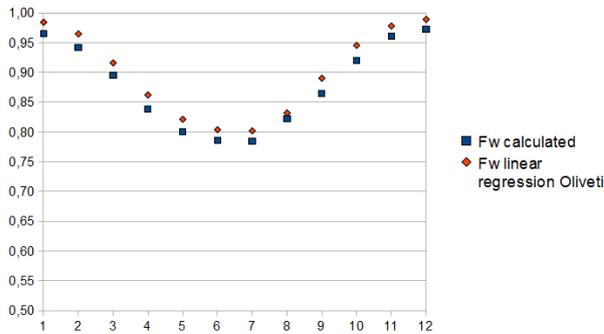


Fig. 8 – F_w trend throughout the year (monthly values)

4.2 Direct heat gain

Considering the solar radiation and the shading correction factor F_{sh} , which does not depend only on the external envelope, separately for every surface the equation (2) for the direct gain can be written in a new form:

$$Q_{sd} = (1 - F_{F,e})g_e \cdot \left[\sum_j (F_{sh,w} \cdot (1 - F_{F,w})g_w A_w I_w)_j + \sum_k \left(F_{sh,p} \cdot \alpha_p A_p I_p \frac{H_{p,tot}}{H_{p,e}} \right)_k \right] t \quad (8)$$

For the calculation of shading factors the Italian technical legislation refers to the paragraph 14.4 of UNI/TS 11300-1:2008, while the German legislation to ANNEX A of DIN V 18599-2:2007. Actually, if the geometry of the shading elements is complicated a precise calculation is possible only through a three-dimensional model.

For a more precise calculation, we could consider that for direct radiation in the heated space, the global solar transmittance of the sunspace external envelope g_e is not involved. In fact, g_e considers also the convective exchange. The solar direct transmittance τ_e , which considers only the solar heat that enters as radiation, could be taken in consideration. A heat proportional to $(g_e - \tau_e)$ could be considered released by the external window of the sunspace to sunspace air as convective exchange. It would increase the indirect heat gain.

4.3 Indirect heat gain

In this subsection a situation of absence of ventilation from and to the sunspace is considered, while some considerations concerning ventilation are presented in subsection “Ventilation”.

Here the floor slab is considered as adiabatic, because implicitly the technical standard considers it as such when it calculates the solar gain (but obviously it considers the heat losses through the floor when it calculates $H_{s,e}$, the heat transfer coefficients between the sunspace and the external environment). The issue of the heat losses through the ground is dealt with by subsection “Solar heat dispersion through opaque surfaces”.

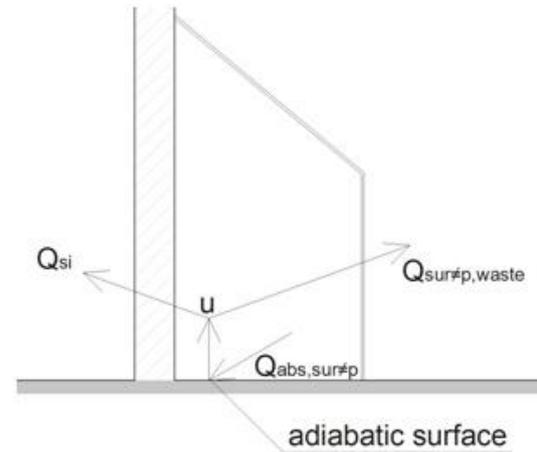


Fig. 9 – Indirect heat gain

The increase of the sunspace temperature due to solar radiation absorbed by the internal surfaces, except the partition, can be considered as:

$$(\Delta T_u)_{sol} = \frac{Q_{abs,sur\neq p}/t}{H_{i,s} + H_{s,e}} \quad (9)$$

where

$H_{i,s}$ is the heat transfer coefficient by transmission from the internal space to the sunspace (see Figure 6)

$H_{s,e}$ is the heat transfer coefficient by transmission from the sunspace to the external environment (see Figure 6)

$Q_{abs,sur\neq p}$ is the solar radiation that is absorbed by the surfaces inside the sunspace, except the partition walls, i.e.

$$Q_{abs,sur\neq p} = (1 - F_{F,e}) \cdot g_e \cdot \sum_{j \neq p} (F_{sh,j} I_j \alpha_j A_j) t \quad (10)$$

Solar radiation that is absorbed by partition walls is not considered because its contribution to the reduction of energy demand of the heated space is already considered in equation (7).

The indirect heat gain Q_{si} is the effect on the heat transmission through the wall (see Figure 6):

$$Q_{si} = H_{p,i} \cdot (\Delta T_p)_{sol} t = \frac{H_{p,i}}{H_{p,e} + H_{p,i}} \cdot Q_{abs,sur\neq p} \quad (11)$$

Considering equation (9), equation (10) can be written as

$$Q_{si} = \frac{H_{p,i}}{H_{p,e} + H_{p,i}} \cdot (1 - F_{F,e}) \cdot g_e \cdot \sum_{j \neq p} (F_{sh,j} I_j \alpha_j A_j) t \quad (12)$$

A different approach is presented by Wall, M. (1996): it presents values of the “solar collector property”, defined as the ratio between the solar heat that is absorbed by the sunspace and the solar radiation that enters through the external windows. Such values are results of dynamic simulations and are relative to different conditions (different properties of the windows, different shapes of the sunspace, different properties of the surfaces, and so on). Wall, M. (1996) regards the Swedish climate. A new similar study could be developed for other climatic conditions.

4.4 Ventilation

ANNEX E states that “if there is a permanent opening between the conditioned space and the

sunspace, it shall be considered as part of the conditioned space”. For a precise calculation of the ventilation losses in such a situation, the amount of heat absorbed by the air flow from the sunspace should be taken into consideration. The calculation, in order to be really accurate, needs to consider the convective exchange coefficients, the air stratification, the position of the openings through which there are air flows. The only way to achieve this accuracy is probably the use of Computational Fluid Dynamic simulations. Therefore the technical standard is not the proper tool to evaluate a situation with permanent ventilation through the sunspace. In a next study the supply air temperature in the heated space could be calculated through Computational Fluid Dynamic simulations for a great variety of situations, in order to give indications to the designers. For example, with the output of CFD analyses the study could present graphs or tables that provide the supply air temperature in the heated space as function of some variables and of some parameters (mean sunspace temperature, geometry, position of the openings, air flow and so on).

4.5 Solar heat dispersion through opaque surfaces

A part of the solar heat absorbed by the sunspace inner surfaces does not heat the air because it is lost directly to the external environment. For example, a part of the solar heat absorbed by the floor is lost directly through the ground. The technical standard does not consider this dispersion. In some cases, this approximation can be unacceptable, e.g. for sunspaces whose floor slab does not have insulating layers for some reason. A model having an uninsulated floor slab ($U_g = 1,34 \text{ Wm}^{-2}\text{K}^{-1}$) and another model with a well insulated one ($U_g = 0,32 \text{ Wm}^{-2}\text{K}^{-1}$) were simulated dynamically. The thermal transmittances were calculated through COMSOL Multiphysics, a FEM software. The sections of the models are presented in Figure 10 and in Figure 11. The test reference year of Bolzano provided by the Comitato Termotecnico Italiano was used.

In Figure 12 the calculated increases in air temperatures due to solar radiation are presented. The calculation was made through the software IDA-

ICE. It is evident that if there is no heat insulation, the temperatures are much lower.

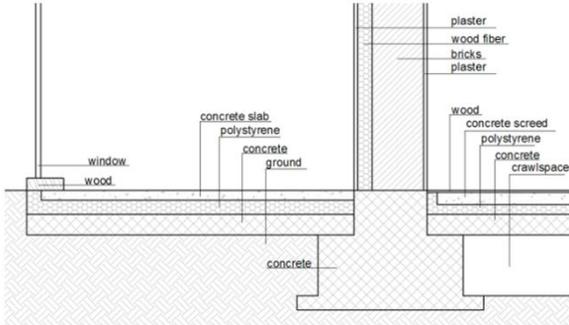


Fig. 10 – Sunspace with insulated floor slab

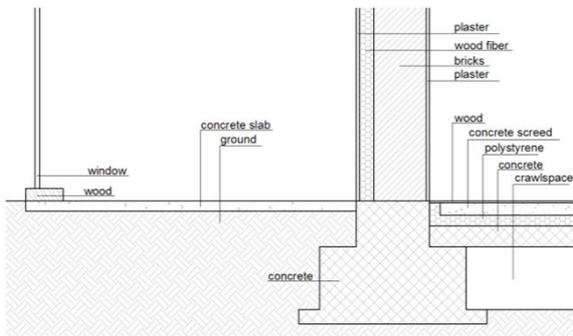


Fig. 11 – Sunspace with uninsulated floor slab

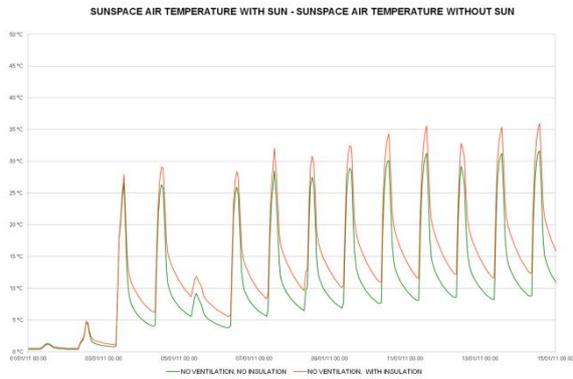


Fig. 12 – Temperature increase due to solar radiation in the case of insulated floor slab and in the case of uninsulated floor slab

Figure 13 represents schematically the heat exchanges from the point of view of the sunspace floor (as a simplification, there is no specific calculation for the IR exchange).

The temperature of the sunspace floor can be calculated as follow:

$$T_j = \frac{\frac{Q_{abs,j}}{t} + h_{ho}A_g \cdot (T_j - T_s) + U_{jo}A_g \cdot (T_j - T_o)}{h_{ho}A_g + U_{jo}A_g} \quad (13)$$

where

$Q_{abs,j}$ is the solar radiation that is absorbed by the sunspace floor

h_{ho} is the surface coefficient of heat transfer for internal horizontal surfaces

U_{jo} is the thermal transmittance between the sunspace floor and the external environment through the ground and it could be calculated through a FEM software or with technical standard EN ISO 13370:2008

A_g is the floor area

T_j is the floor temperature

T_s is the sunspace air temperature

T_o is the external air temperature.

Therefore the temperature increase due to solar radiation is:

$$(\Delta T_j)_{sol} = \frac{Q_{abs,j}/t}{h_{ho}A_g + U_{jo}A_g} \quad (14)$$

The part of heat due to solar radiation that is lost directly through the ground and that should be subtracted from $Q_{abs,sur\#p}$ can be calculated as:

$$\begin{aligned} (Q_l)_{sol} &= U_{jo}A_g \cdot (\Delta T_j)_{sol} = U_{jo}A_g \cdot \frac{Q_{abs,j}/t}{h_{ho}A_g + U_{jo}A_g} \\ &= U_{jo} \cdot \frac{Q_{abs,j}/t}{h_{ho} + U_{jo}} \end{aligned} \quad (15)$$

It can be easily demonstrated that

$$\frac{U_{jo}}{h_{ho} + U_{jo}} = \frac{U_g}{h_{ho}} \quad (16)$$

where U_g is the thermal transmittance between the sunspace air and the external air.

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