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Passive solar radiant system, SIRASOL. Physical–mathematical modeling and sensitivity analysis

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Abstract

When using passive solar heating systems, it is necessary to have available an Equator-facing facade on which to install them. Rooms without such a facade are not the best option for conventional passive solar heating systems. SIRASOL is a passive solar radiant system that captures solar energy and is to be installed in the ceiling of the room. This room must not necessarily have an Equator-facing facade. Solar energy heats up a metal sheet, which is the radiant panel, which transfers heat by long-wave radiation to the room below it. This paper presents a mathematical model and a sensitivity analysis. The mathematical model was used to analyze radiant panel temperature, radiant mean temperature, operative temperature and panel surface area. Results of the sensitivity study showed that when solar radiation rises (from 200 to 800 W) panel temperature increases from 36 °C to 92 °C, whereas variations in outside and inside air temperature have a negligible impact on the panel temperature. Thus, the use of SIRASOL is possible in locations with clear skies. Moreover, from panel temperature values we calculated mean radiant temperature and thereby the room's operative temperature, which is proportional to the radiant panel area. When this area is 50% of the room's floor area, operative temperature grows 3.1 °C higher than inside air temperature when solar radiation is 500 W/m^2. The analysis shows that a thermal asymmetry appears only when SIRASOL's surface area to floor area ratio is higher than 32%.

Keywords: Passive solar system; Radiant heating; Thermal comfort; Energy savings

1. Introduction

Natural conditioning systems (NCS) are sets of components in a building which have the main function of improving its climatic behavior. They act on radiant, thermal and air movements, phenomena which are naturally produced in architecture (Serra Florensa et al., 2005). NCS like direct gain, trombe walls and sunspaces have basic common features, such as capture of incident solar radiation, storage of heat and/or use of solar energy entering the system, passive transfer of energy to space (Goulding et al., 1994), and can be integrated with the mechanical conditioning system used in the building (Athienitis and Santamouris, 2002).

NCS offer a wide range of possibilities for environmental recovery of existing buildings planned to use fossil fuel energy, or for new buildings too. When incorporating or integrating them into architecture, there is a basic requirement for their functioning: in order to capture solar energy in winter, having an available facade facing the Equator is necessary for collecting solar energy.

In urban networks, there are first floor or ground floor dwellings with no potential solar-collecting facades. However, these dwellings have an advantage, an architectural component that offers greater versatility of opportunities by being fully exposed to the sky: the roof.

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Nomenclature

Aci	inner cover area (m^2)
Ace	outer cover area (m^2)
Am	area of experimental room surfaces (walls + roof + floor) (m^2)
Ap	radiant panel area (m^2)
At	triangular section area (m^2)
Av	glazed area (m^2)
*A*1, 2, *n*	surface area 1, 2, ..., (m^2)
$ff_{\text{panel-person}}$	view factor between panel and person
$ff_{1,2,n}$	view factors between room surfaces
Gr	Grashof number
h	height of enclosure (m)
hr	radiative coefficient
hc	convective coefficient
IT	solar radiation on tilted surface
Im	mean radiation absorbed by outside walls
Id	diffuse solar radiation (W/m^2)
Ir	ground-reflected solar radiation (W/m^2)
L	geometric characteristic
Nu	Nusselt number
P	perimeter (m)
Pr	Prandlt number
Ra	Raleigh number
TRM	mean radiant temperature received by a person in a specific location in space (K)
*t*1, 2, *n*	surface temperature 1, 2,..., (K)

Greek characters

α	absorptance
ε	emittance
$\tau\alpha$	glass transmittance and solar absorptance

Subscript

ai	air of experimental room
ar	air of enclosure (W/m^2 C)
ci	surface south cover
d	diffuse solar radiation
e	thickness of south cover (m)
ext	outside environment air
em	thickness of walls (m)
k	conductivity coefficient of south cover (W/m^2 C)
km	conductivity coefficient of experimental room (W/m^2 C)
me	outside surfaces
mi	inside surfaces
p	radiant panel
v	glass

1.1. Background information on passive solar roofing systems

There are several strategic proposals, including the building's roof, that provide a passive solar system not requiring a facade towards the Equator. The literature presents different systems that could be grouped into systems of convective interchange and systems of radiant interchange.

Within the first group are solar heating systems that work using only part of the building roof, or unused roof spaces. They consist of a solar collector area where the air is heated before being distributed through pipes to the dwelling. Some of these convective systems have a two-dimensional countercurrent air-heating collector roof to heat spaces exposed to the Equator. They have been designed as systems that also respond to the need for conditioning the air of enclosures with no available vertical facade towards the Equator (Hernández et al., 2010). Systems that heat the air and then distribute it are considered to have low energy output. In addition, they require an appropriate thermally-insulated distribution system to avoid excessive losses.

The following systems use radiant interchange; in the first place, two device-like systems are cited: one is the Hybrid photovoltaic–thermal system (Vokas et al., 2006), consisting of a thermal collector in which a photovoltaic laminate is attached as a thermal absorber. This system offers a remarkable solution to the problem of domestic heating and cooling, hence contributing to the reduction of energy consumption in houses. The other one is the Roof-integrated solar heating system (Belusko et al., 2004). Research has been conducted into using a steel corrugated roof to function as an unglazed collector and a model has been developed. There are also other systems that use the whole roof structure to function, one of the pioneers is the Skytherm (Raeissi and Taheri, 2000), whose water ponds enclosed in thin plastic bags are supported by a roof (usually a metal deck) that also serves as the ceiling of the room below. In winter the ponds are exposed to sunlight during the day and covered with insulating panels at night. A similar functioning and performing system known as "Solar Roof" has been developed (Juanicó, 2008). The difference lies on a water chamber on the roof.

Systems that work by radiant heat transfer present advantages over systems that work by convective heat transfer. The most significant are:

1. Higher energy savings, because a radiant system does not have a distribution system with inherent heat losses
2. The quality of the air inside the dwelling is better because this system produces no air flows which could be sometimes uncomfortable,
3. If the radiant system is placed directly in the ceiling, it allows direct heat transfer to the person with a very simple device.

In this context, there exists the possibility of having a passive solar system whose characteristics are:

- It is a functional, practical, environmentally conscious and architecturally integrated solution for spaces with no exposure to the Equator.
- It is a natural energy device of easy incorporation that produces low energy consumption of auxiliary heating systems.

The aforementioned systems of heat transfer by radiation require a solar system integrated with roof systems in new buildings, or need to disable the building for their implementation. This is the reason why it is difficult to use them for energy rehabilitation in old buildings.

Systems using ceiling radiant panels are cooled or heated through hydronic systems or through air. However, no systems with radiant panels directly using solar energy to raise their temperature, like the one proposed in this work, could be found in the literature.

In the literature there are two types of radiant panels in ceiling: for refrigerating and for heating, the latter being the least developed and studied.

Chrenko, developed an exhaustive study of the behavior of radiant panels for heating placed on the roof under controlled experimental conditions in periods of calm in air movements (Mercado et al., 2009). The results referred to the panel performance, its geometrical ratio and its incidence on the space comfort are listed below:

- It is possible to use panels on low roofs (up to 2.2 m) without fear of excessive radiation on the head, by taking certain precautions like the panel area, its dimensions, and the view factor between panel and occupants. This situation has potential for dwellings with roofs with a minimum height of 2.40 m.
- According to the radiant panel's geometry, the dimensional ratio showing less percentage of discomfort is the one in which the width-length ratio 1in 2 prevails, considering a subject sitting below the center of the panel. The radiant panel limit temperatures are associated to the solid angle formed by the panel and the occupant, the lowest value of the angle, the highest temperature of the panel.
- An increase of 3 °C in the surrounding radiant mean temperature has been recorded as pleasant.

A recent work states that using radiant panels on the roof is a practical solution to obtain a more comfortable thermal environment than using a conventional convective heating system (Imanari et al., 1999).

As a consequence of what has been reviewed thus far, in this paper we present a mathematical model and a design sensitivity analysis for a passive solar system that, placed on a roof, captures solar energy and transfers heat in radiant manner to the space to be heated (SIRASOL). It can be incorporated in standing buildings or in new projects and can also be used in buildings with no Equator-facing facades.

The objectives are:

- to develop a mathematical model for SIRASOL,
- to analyze the functioning and output of the system from the physical–mathematical modeling,
- to perform a sensitivity analysis of SIRASOL's main variables.

2. System description

This device is called *passive solar radiant heating system* (*SIRASOL* according to its Spanish name, which is *Sistema de calefacción radiante solar pasivo).*It works as an independent device and can be incorporated to buildings (old and new) without potential solar-capturing facades.

The design of SIRASOL's geometry is simple; it is based on the position of the sun in Mendoza city in winter and in some months of intermediate seasons. At the solar midday, the sun reaches an altitude of 33°.41′ in winter and of 50° in the months of May and September. From this, a calculation was made of the best capture angle that maximizes solar gain throughout the entire period of system use. From these data it was concluded that a 45° angle of tilt for the capturing surface (north glass cover) would fulfill the premise. The system is configured from this glass surface, the south cover, aimed to minimize heat losses, rests directly on the solar capturing surface; the lateral tympana (made of glass) seal the system and, by being transparent, allow for a higher solar gain. Finally, the radiant panel is the horizontal surface where solar radiation is absorbed; it links the system enclosure to the room, directly providing the latter with heat through thermal radiation.

Fig. 1 shows SIRASOL location inside a room. Fig. 2 shows a scheme of SIRASOL. It is a passive solar system that has the shape of an extended pyramid with east–west orientation, which is placed on the roof of the room. Its tilted glass, facing the Equator, works as solar collector. The solar radiation transmitted by glass is absorbed by the plate that works simultaneously as a radiant panel. This radiant panel is placed in the ceiling of the inside space. Due to the geometry used, an air chamber is formed between the glass collector and the radiant panel. Three of the four surfaces of this enclosed chamber that are in contact with the outside are closed with single glass: the side facing the Equator has an optimized tilt angle and the east and west sides are vertical glass and act as auxiliary capturers during the morning and afternoon hours.

The south side, opposite to the largest capturing surface, is a tilted opaque cover to minimize heat losses; it is thermally insulated, with its inner surface covered with a high-reflectance material (aluminum foil). The heating system communicates with the space to be heated through a

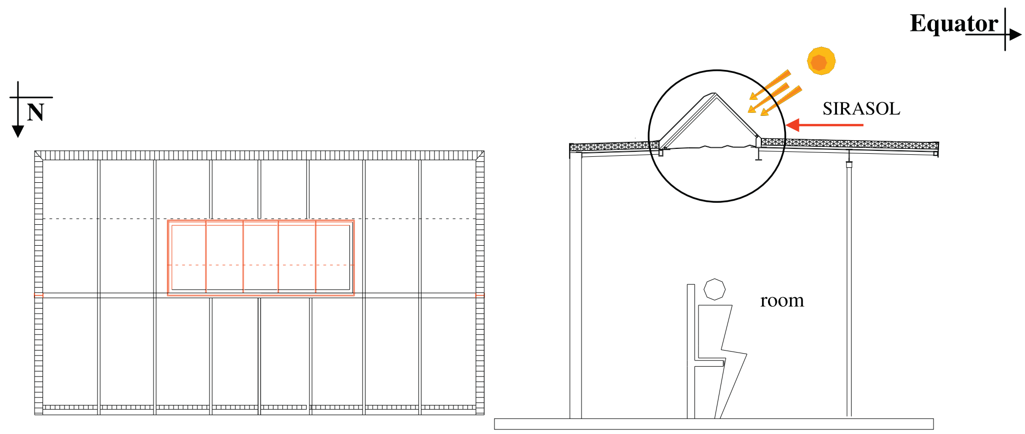


Fig. 1. SIRASOL location in the room.

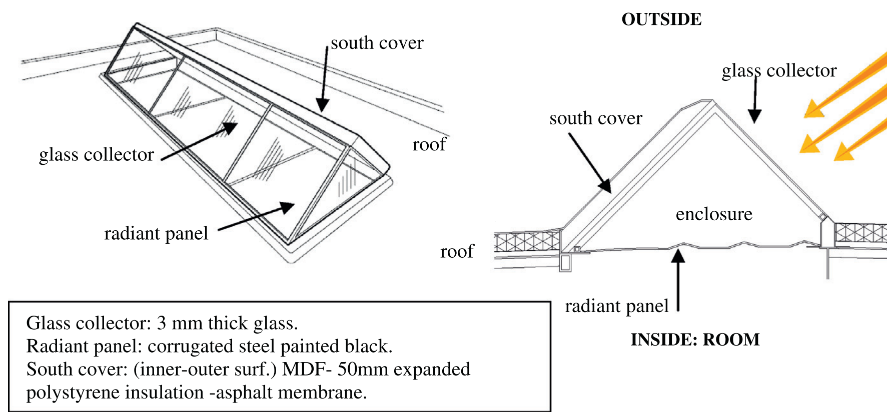


Fig. 2. SIRASOL system descriptive scheme.

radiant panel; this is the element that transfers thermal energy to the building by long-wave radiation.

We performed a physical–mathematical analysis from using a thermal network. The first step is developing the thermal network system and analyzing its mathematical expression in order to calculate radiant panel temperature. This process requires adjusting the iteration equation from the results of the analysis and the results of panel temperature (*Tp*), and radiant and convective heat transfer coefficients.

Then, from this adjustment we analyzed the optimal radiant panel area. For this study we used three scenarios with different proportions of surface area covered with a hypothetical space and of SIRASOL's radiant panel area. Next, we performed the sensitivity analysis of *Tp* based on solar radiation on a horizontal surface and on outside and inside air temperature.

The importance of operative temperature is that it was used as comfort evaluation parameter because it is close to the temperature the person will feel (Goulding et al., 1994).

In order to estimate operative temperature and determine optimum panel dimensions, we carried out the thermal network analysis of SIRASOL; this enabled calculating radiant panel temperature (*Tp*). From *Tp* we estimated mean radiant temperature (*TRM*) and *Tai* (Dry bulb temperature of inside air) for a person standing immediately below the radiant panel. Finally, from *TRM* we calculated the operative temperature (*TO*) and with it we assessed the system's functioning.

3. Thermal network and mathematical model of SIRASOL

Sunlight hits directly on the radiant panel, heating it during diurnal hours. Because of this, there is heat transfer from the radiant panel to the room and the enclosure, and then from these to the outside. These heat transfers depend on the following parameters:

- Surface temperatures, of both the system's inner surfaces and the room.
- Inside air temperature of the room.
- Inside air temperature of the system's own enclosure.
- Climatic conditions: solar radiation, outside air temperature and inside air temperature.
- Thermal resistance of walls and roof of the room and enclosure.

The following working hypotheses were assumed with the purpose of developing a simplified thermal model of the system:

- The surface of the radiant panel is assumed to be isothermal, that is to say, there are no edge effects (one-dimensional model).
- The inner and outer surfaces of the metal panel are assumed to be at the same temperature.
- The inner and outer surfaces of the glass are assumed to be at the same temperature.
- There are no elements that accumulate energy.
- The surfaces of the room to be heated are assumed to be at a homogenous temperature, equal inside air temperature.
- All outside walls have the same solar absorption coefficient.
- The envelope of the room is light-weight.

Fig. 3 presents the thermal network corresponding to SIRASOL system, enclosure, room and outside environment.

Solar radiation absorbed by radiant panel expressed as S1 and S2, and envelope of room as mean radiation absorbed by the outside walls (Im) are estimated by the following equations:

$$S1 = IT \cdot (\tau\alpha)\ [\mathrm{W/m^2}] \quad (1)$$

$$S2 = ((Id + Ir) \cdot (\tau\alpha)_d \cdot (1 - \alpha_{ci})) \cdot \alpha_p\ [\mathrm{W/m^2}] \quad (2)$$

$$I_m = \frac{1}{N}\sum_{i=1}^{N}(IT\alpha_{me})i \quad (3)$$

Fig. 3 presents all thermal resistances involved in the SIRASOL process. The energy balance performed is expressed by the following equation:

$$(S_1 + S_2) \cdot Ap = hc_{p-ai} \cdot Ap(Tp - Tai) + hr_{p-mi} \cdot Ap(Tp - Tmi) + hc_{p-ar} \cdot Ap(Tp - Tar) + hr_{p-v}Ap(Tp - Tv) + hr_{ci-p} \cdot Ap(Tp - Tci) \quad (4)$$

From Eq. (4) it is possible to know panel radiant temperature (Tp) as function of absorbed solar radiation, room air temperature (Tai), enclosure air temperature (Tar) and outside air temperature (Text). This is shown in the following equation:

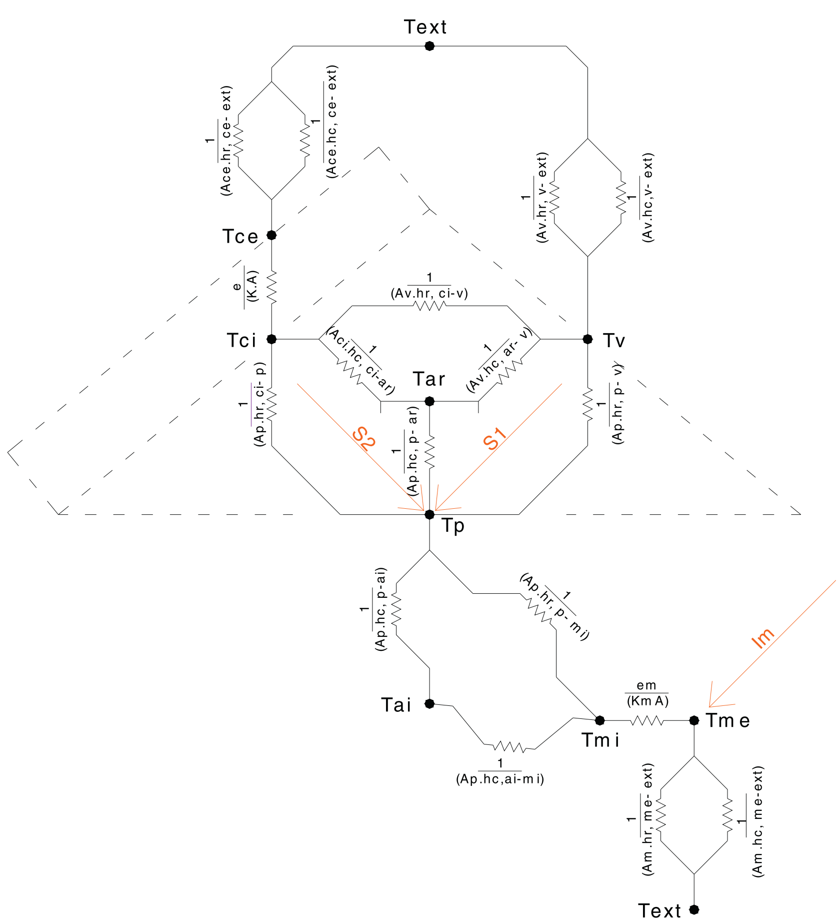


Fig. 3. Mathematical–thermal network of SIRASOL incorporated into the room. Dashed line indicates the cross section of SIRASOL. See nomenclature.

$$
\begin{aligned}
Tp = {} & \frac{(S_1 + S_2)Ap}{A3} \\
& + \frac{Tai}{A3}\left(hc_{p-ai}Ap - \frac{hr_{p-mi} \cdot Ap \cdot hc_{ai-mi} \cdot Am}{A1}\right) \\
& + \frac{Tar}{A3}\left(hc_{p-ar} \cdot Ap - \frac{h4 \cdot Av \cdot hr_{p-v} \cdot Ap}{A2}\right) \\
& - \frac{Text}{A3}\left(\frac{hev \cdot Av \cdot hr_{p-v} \cdot Ap}{A2} - \frac{hr_{p-mi} \cdot he \frac{km}{e} \frac{Ap \cdot Am}{A0}}{A1}\right) \\
& + \frac{hr_{ci-p}}{A3} Ap \cdot Tci + \frac{\frac{km}{e} \alpha_{me} Am I_{me}}{A1 A3}
\end{aligned} \tag{5}
$$

where:

$$he = hc_{me\text{-}ext} + hr_{me\text{-}ext}$$

$$hev = hc_{v\text{-}ext} + hr_{v\text{-}ext}$$

$$h4 = hc_{ar\text{-}v} + hr_{ci\text{-}v}$$

$$A0 = \frac{km}{em} + he \tag{6}$$

$$A1 = -hr_{p-mi}Ap - hc_{ai-mi}Am - \frac{km}{em}Am + \left(\frac{km}{em}\right)^2 \frac{Am}{A0} \tag{7}$$

$$A2 = -hr_{p-v}Ap - h4Av - hevAv \tag{8}$$

$$
\begin{aligned}
A3 = {} & hc_{p-ai} \cdot Ap + hr_{p-mi} \cdot Ap + \frac{hr_{p-mi}^2 \cdot Ap^2}{A1} + hr_{p-v} \\
& \cdot Ap + \frac{hr_{p-v}^2 \cdot Ap^2}{A2} + hc_{p-ar} \cdot Ap + hr_{ci-p} \cdot Ap
\end{aligned} \tag{9}
$$

In Eq. (5), to calculate S1 we used measurements of solar radiation on horizontal surface. Then we estimated solar radiation on tilted glass cover by the isotropic model (Duffie and Beckman, 1991) and ($\tau\alpha$ product of glass transmissivity and radiant panel solar absorptance respectively. Determination of a convective heat transfer coefficient (h_c) and radiative heat transfer coefficient (h_r) is necessary to estimate Tp.

Radiant heat transfer is of the greatest importance due to the characteristics of the system. Its impact is analyzed for the room, the enclosure and to the outside environment. The h_r calculus can be linearized and the expression of radiant heat transfer can be calculated from expression the following equation (Duffie and Beckman, 1991):

$$Q = A_1 h_r (T_2 - T_1) \tag{10}$$

Consequently, coefficient h_r is defined as the following equation:

$$h_{r1-2} = \frac{\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{1-2}} + \frac{(1-\varepsilon_2)A_1}{\varepsilon_2 A_2}} \tag{11}$$

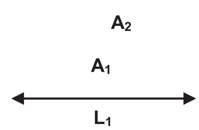
It is possible to estimate h_r from Eq. (11) by taking the emissivity of each material as follows:

ε panel = 0.88 (steel sheet painted black).
ε inner surface of south cover = 0.05 (aluminum foil).
ε glass = 0.93.
ε room walls = 0.85 (MDF painted in light color).

Assumed initial surface temperatures are the following:

$T1$: $Tp = 54\,°C$ from similar heating radiant panel (Chrenko, 1953).
$Tai = Tmi = 20\,°C$ (as dry bulb temperature of inside air).
Tar = intermediate value between Tp and Text, in this case arithmetic average was considered.
$Tar = Tci$ because thermal resistance of the south cover is very high.

In order to estimate the view factor (F_{1-2}) involved in radiant heat transfer within the system, we used the equation established by Bejan (1993) for a triangular enclosure as presented in the following equation:



$$F_{1-2} = \frac{L_1 + L_2 - L_3}{2 \times L_1} \tag{12}$$

Then we calculated solar radiation on tilted glass cover by the isotropic model. Table 1 shows h_r values calculated between radiant panel and room surfaces (hr_{p-mi}), between radiant panel and glass (hr_{p-v}), between radiant panel and inner surface of south cover (hr_{p-ci}), between surface of south cover and glass (hr_{ci-v}), between glass and atmospheric radiation (hr_{v-ext}) and between outer room surface and atmospheric radiation (hr_{me-ext}), for the thermal model presented.

To obtain h_c Nusselt non-dimensional number, we used geometric factor L and thermal conductivity of the fluid (k air) as indicated in the following equation:

$$h_c = \frac{k}{L} \times Nu \tag{13}$$

To calculate Nusselt number (Nu), the literature presents numerous correlations with Rayleigh number (Ra). Those quoted by Incropera and Dewitt (1996) were used, by establishing a differentiation for hot and cold plates according to their location inside the enclosure (above or below). For computing convection heat transfer between radiant panel and air temperature in the room we used Eq. (14) that considers the warm surface on the upper part of the room.

$$Nu = 0.27 Ra^{\frac{1}{4}} \quad (10^5 \leqslant Ra_L \leqslant 10^{10}) \tag{14}$$

In the case of the heat interchange produced between panel and enclosure, we considered the ratio of Eqs. (15) and (16) according to Raleigh's value. In this case, Eqs. (15) and (16) assume the warm surface on the lower part of the room.

Table 1
Values of radiant heat transfer coefficient h_r (W/m^2 °C) calculated for thermal network.

hr_{p-mi}	hr_{p-v}	hr_{p-ci}	hr_{ci-v}	hr_{v-ext}	hr_{me-ext}
5.91	3.32	0.26	0.31	0.31	0.28

$$Nu = 0.54Ra^{\frac{1}{4}}\ (10^4 \leqslant Ra_L \leqslant 10^7) \tag{15}$$

$$Nu = 0.15Ra^{\frac{1}{3}}\ (10^7 \leqslant Ra_L \leqslant 10^{11}) \tag{16}$$

Number *Ra* is commonly obtained by a combination of Prandlt (*Pr*) and Grashof (*Gr*) numbers, as shown in Eq. (17).

$$Ra = \Pr \times Gr \tag{17}$$

Depending on the different forms of space where convection is produced, whether triangular or prismatic (enclosure or room respectively), the geometric parameters vary and must be taken into account to obtain factor *L*.

In the case of considering the room-radiant panel relationship (prismatic space) (Incropera and Dewitt, 1996) Eq. (18) is used:

$$L = \frac{Ap}{P} \tag{18}$$

In the case of the enclosure-radiant panel relationship, to obtain factor *L* one must consider a triangular section (Asan and Namali, 2001), so that *L* is the result of

$$L = \frac{At}{h} \tag{19}$$

From this value of *L* it is possible to estimate *Ra* as is shown in Table 2.

Once the Ra number is obtained, it is possible to use the adequate correlation for each case: panel- room air (Eq. (14)) and panel-enclosure air (Eq. (15), (16) correspondingly), to estimate Nusselt number and subsequently h_c. These are listed in Table 3.

Assuming the temperature values of *Tp*, *Tar* and *Tv*, and values of h_r and h_c, we tested the mathematical model of the system by calculating *Tp* according to Eq. (3). Subsequently, knowing *Tp*, we recalculated *Tv* and *Tar* in order to validate the model. Once these temperatures were obtained, they were calculated again performing 10 iterations until observing that variability in the results was negligible. The resulting convective h_c, and radiant h_r heat transfer coefficients are shown in Table 4.

3.1. Radiant panel temperature

In order to calculate *Tp*, we used real measured data on solar radiation on horizontal surface, outside air temperature and inside air temperature of a room located in INCIHUSA laboratory, with the aim to obtain an estimate closer to the actual temperature that the radiant panel can achieve.

Therefore *Tp* can be calculated from Eq. (5) based on data on hr and hc, absorbed solar radiation (S1 and S2,

Table 2
Raleigh number values.

Ra air experimental room-interior wall	1.41E + 08
Ra air experimental room-pan el	1.84E + 09
Ra enclosure-panel	3.95E + 07
Ra enclosure-glass	3.28E + 07

Table 3
Values of convective heat transfer coefficient h_c (W/m^2 °C) to be applied to the thermal network.

hc_{mi-ai}	hc_{p-ai}	hc_{p-ar}	hc_{v-ar}	hc_{v-ext}	hc_{me-ext}
4.09	10.33	3.37	0.72	8.98	4.09

calculated from Eqs. (1) and (2)), inside air temperature measured in the room (*Tai*), and outside air temperature (Text). Results are shown in Fig. 4.

From the resulting *Tp* data one notices the directly proportional ratio that exists between incident solar radiation on the radiant panel and its temperature. *Tp* achieves 65 °C with solar radiation levels of 500–550 W/m^2. This indicates that the system would respond satisfactorily, because *Tp* rises, This temperature will have direct influence on mean radiant temperature (*TRM*) and consequently on operative temperature (*TO*), the latter being the one that the user will perceive.

3.2. Mean radiant temperature

To obtain mean radiant temperature (*TRM*), we considered a prism-shaped room, with four equal walls, 3 m wide and 2.4 m high, to be heated. This hypothetical reference room was assumed to be built with traditional masonry, single glass windows and energy efficient roof.

Once the geometry of the system is defined, SIRASOL is considered to be placed in the center of the room and the person below it (for improving the performance as was shown by Fanger in Banhidi (1991)).

Three case studies were proposed that consider the same room, and different surface areas of radiant panel of SIRASOL (Fig. 4).

- Case 1 = panel area = 1/8 of space area to be heated (12.5%).
- Case 2 = panel area = 1/4 of space area to be heated (25%).
- Case 3 = panel area = 1/2 of space area to be heated (50%).

Chrenko's diagram (Chrenko, in Banhidi, 1991) is used for view factor estimation, as it deals with a methodology proposed for situations with similar characteristics to the evaluated system (a system of radiant heating placed in the ceiling and a person in the center below it). Results for view factor for indicated case studies (Fig. 5) are:

- $ff_{\text{panel-person}}$ Case 1 (12.5%) = 0.25.
- $ff_{\text{panel-person}}$ Case 2 (25%) = 0.45.
- $ff_{\text{panel-person}}$ Case 3 (50%) = 0.62.

TRM is calculated from *Tp*, view factors and data from first four days of measurements. *TRM* values obtained with Eq. (20) are indicated in Fig. 6.

Table 4
Values of h_r and h_c estimated from panel temperature.

hr_{p-mi}	hr_{p-v}	hr_{p-ci}	hr_{ci-v}	$hr_{v\text{-}ext}$	hr_{me-ext}	hc_{mi-ai}	$hc_{\mathrm{p}-ai}$	hc_{p-ar}	hc_{v-ar}	hc_{v-ext}	hc_{me-est}
6.03	3.20	0.25	0.27	0.29	0.28	4.09	10.64	5.13	0.61	6.82	2.71

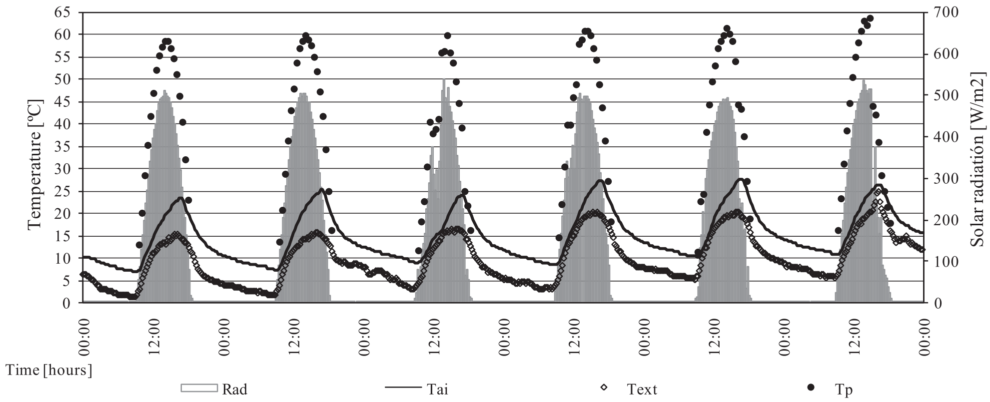


Fig. 4. *Tp* values calculated for 6 solar days in winter 2007.

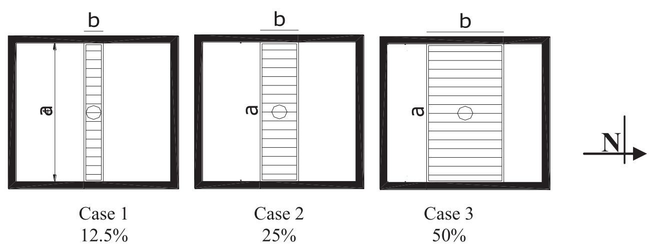


Fig. 5. Case studies for pre-sizing radiant panel.

$$TRM = \frac{Tp\ ff_0\ Ap + t_1 ff_1 A_1 + t_2 ff_2 A_2 + \ldots + t_n ff_n A_n}{ff_0\ Ap + ff_1 A_1 + ff_2 A_2 + \ldots + ff_n A_n} \tag{20}$$

In Fig. 6 it can be observed that as panel size increases, so does *TRM*. In identical room thermal conditions of the space, the thermal difference is marked by radiant panel temperature and panel area. At a same *Tp*, the panel surface area will proportionately impact the influence of radiant interchange and, accordingly, on *TRM*.

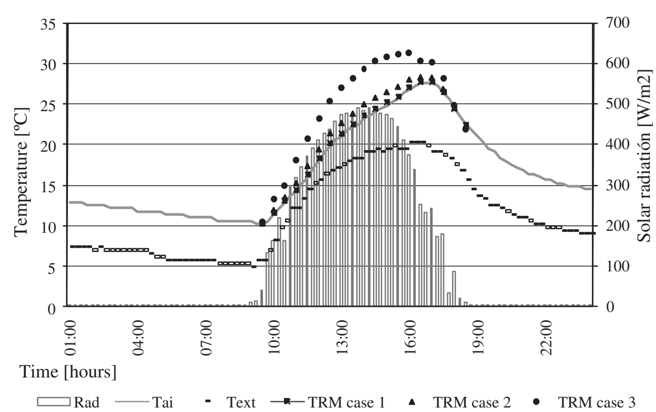


Fig. 6. *TRM* values calculated for a typical solar winter day of July 18, 2007.

3.3. Operative temperature

Tp has an incidence on *TRM*, consequently it will have direct influence on operative temperature (*TO*) and on the person's thermal comfort.

In order to calculate *TO*, Eq. (21) is applied, taking into account the results obtained from *TRM* and the measured inside air temperature in the room. ISO International Standard (ISO 77300, 1994) establishes that, for an air speed of less than 0.2 m/s, operative temperature (*TO*) can be calculated as the average of air temperature and *TRM* temperature, as expressed in the following equation:

$$TO = \frac{Tai + TRM}{2} \tag{21}$$

The values obtained are shown in Fig. 7, for a person standing in the center of the space, for each case study.

The difference between *TO* and *Tai* is higher as the surface area of SIRASOL related to the room area is larger.

It can be observed in Fig. 7 that the behavior of operative temperature in diurnal hours differs depending on each case, which is evidence of the influence of *TRM* on this parameter. Fig. 6a shows that differences between *TO* (for case 3) and *Tai* range from 3.1 °C (max) to 1.4 °C (min) with an average of 2.6 °C. For case 2, the difference is lower than for case 3, with values between 0.9 °C (max), 0.4 (min) and an average of 0.7 °C. For case 1, the difference is negligible. It is important to note that solar radiation of up to 500 W/m^2 (max) is typical of winter days.

Fig. 8 shows *TO* for different cases vs. *Tai* for diurnal hours (9:30 am to 6:00 pm). It can be seen that all *TO* values are higher than *Tai*, thus increasing the thermal comfort of the user.

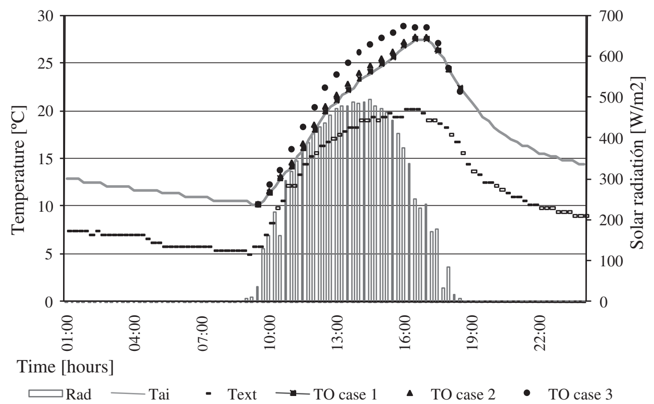


Fig. 7. *TO* values calculated for a typical solar winter day of July 18, 2007.

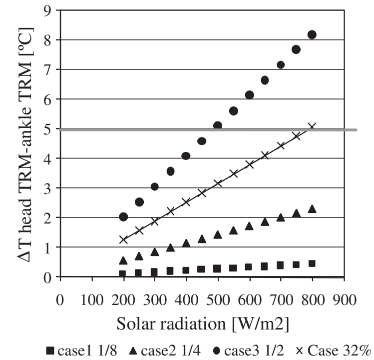


Fig. 9. Radiant temperature asymmetry for the three cases considered.

As seen, SIRASOL gives enough warmth to increase *TO*. However *TRM* could turn out uncomfortable if the difference in temperature between head and ankle is higher than 5 °C according to ISO 7730. In order to study the possible vertical radiant asymmetry caused by SIRASOL, head-ankle differences are analyzed for all three cases. Fig. 9 shows the temperature difference at head and ankle level. This difference must be lower than 5 °C so as not to have a thermal asymmetry in a room with SIRASOL system installed.

Fig. 8 shows the ratio of SIRASOL's surface area to the room's floor area (12.5%, 25%, 50%) for three different cases. In cases 1 and 2 there is no radiant asymmetry. In case 3, and when solar radiation exceeds 500 W/m^2, there will be thermal asymmetry. A SIRASOL area to room area ratio of 32% is the largest area of SIRASOL that produces no radiant asymmetry.

3.4. Sensitivity analysis

The sensitivity analysis examines *Tp* variation in terms of characteristic parameters: solar radiation, outside air temperature and inside air temperature.

In Fig. 10 it can be noticed that, for a solar radiation increase from 200 to 800 W, *Tp* increases from 36 °C to 92 °C, namely ΔT of 52 °C, when *Tai* is fixed at 20 °C; Text is fixed at 18 °C. *Tp* varies very little when *Tai* and Text change.

To know *Tp* variations in function of Text, we considered typical winter day values (10–22 °C) and, in function of *Tai*, the typical inside temperature values (18–24 °C).

Fig. 11 shows *Tp* when Text changes from 10 °C to 22 °C and Tai is fixed at 18 °C, and solar radiation on horizontal surface is equal to 500 W/m^2. In this case *Tp* is high for different values of outside temperatures. This demonstrates the potentiality of SIRASOL in cold and sunny places.

Fig. 12 indicates *Tp* variation when Tai changes from 18 °C to 24 °C. It is possible to see that *Tp* varies very little, from 58 °C to 61.6 °C.

The effect of inside air temperature on *Tp* performance is lower in relation to solar radiation. Yet, the importance of inside air temperature lies in its influence on the comfort conditions for the person in the room. However, a *Tp* over 50 °C influences *TRM* and *TO*.

3.5. Situation of SIRASOL under particular climate conditions

As inferred from the sensibility analysis, panel temperature is directly proportional to the level of solar radiation. For this reason, it is noted that at times or localities of low outside temperatures, heat losses that must be attended to are those to be produced by the room envelope. With

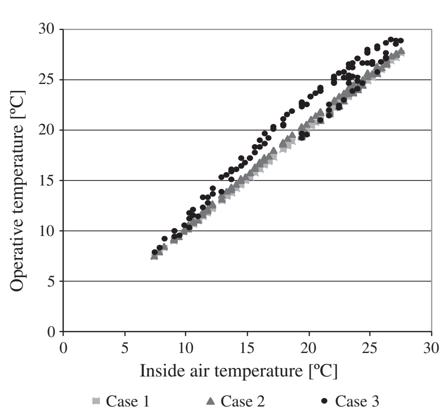


Fig. 8. *To* vs. *Tai* values calculated for 6 solar days in winter 2007.

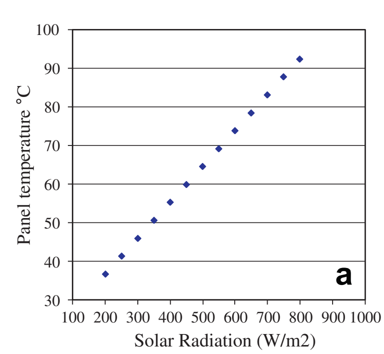


Fig. 10. *Tp* Sensitivity analysis for *Tp* variation in function of solar radiation.

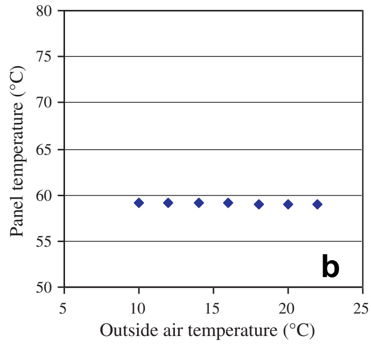


Fig. 11. *Tp* Sensitivity analysis for *Tp* variation in function of outside temperature.

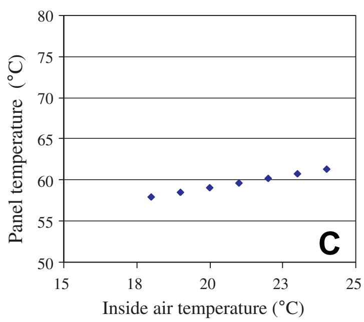


Fig. 12. *Tp* Sensitivity analysis for *Tp* variation in function of inside temperature.

closures allowing conservation of the heat gained through SIRASOL, the comfort temperature reached during hours of sunlight would be maintained for a longer period of time.

The climate conditions in Mendoza city show a high percentage of days with clear skies (sunshine hours = 65%, (Grossi Gallegos and Righini, 2007)). However, in order to consider a cloudy sky situation, we present two days representative of these conditions (Fig. 13). The records of maximum solar radiation levels measured on the horizontal surface fluctuate between 150 and 300 W/m^2.

Next to be calculated are panel temperature, mean radiant temperature and operative temperature for solar radiation values lower than 300 W/m^2.

From the results shown in Fig. 14, it can be noticed that panel temperature, in the case of very low levels of solar radiation, is insufficient to significantly affect mean radiant temperature and hence operative temperature.

Besides, and continuing to pay attention to particular situations, the summer season is analyzed. A slat-like parasol has been designed that blocks the access of direct solar radiation in the summer season and allows, moreover, its access in the winter season (Fig. 15). Due to the studied protection and capture angles, the slats will not reduce efficiency and will allow the sun to fully influence the capturing area.

As seen for the cloudy sky situation, a major reduction of the possibility of overheating will be achieved only by

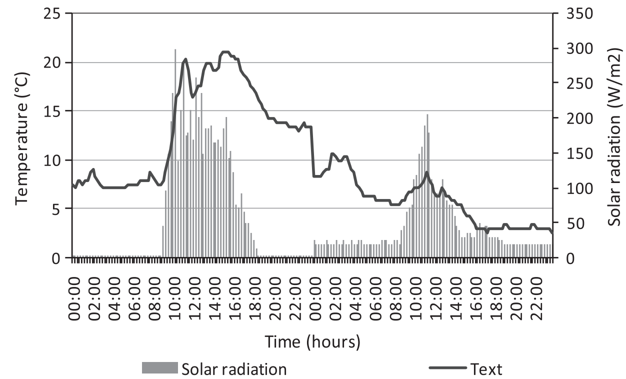


Fig. 13. Solar radiation and outside temperature for a cloudy day (07/05/2007 and 08/24/2007).

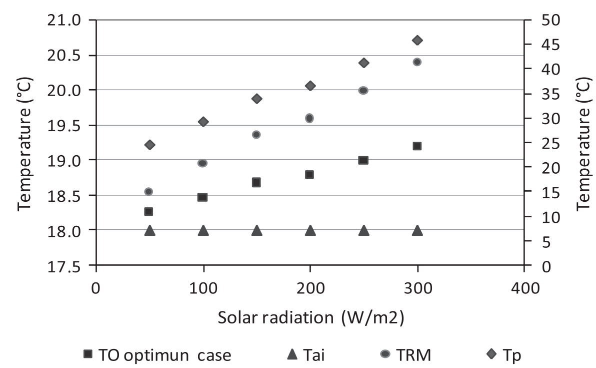


Fig. 14. Estimation of *TO* for solar radiation values corresponding to cloudy days.

greatly reducing direct solar radiation. Aiming to continue the mathematical estimation, the situation of the operative temperature is considered for a solar radiation of 200 W/m^2 (which is the amount of diffuse radiation that can reach the radiant panel, estimated from data from the National Weather Service, Argentina). Also assumed are a Tai of 24 °C and a variable Text from 25 to 45 °C, mean and absolute maximum values recorded for Mendoza city. From the results obtained it can be observed that the panel temperature, though high for the season, does not alter the operative temperature (Fig. 16). The importance of this

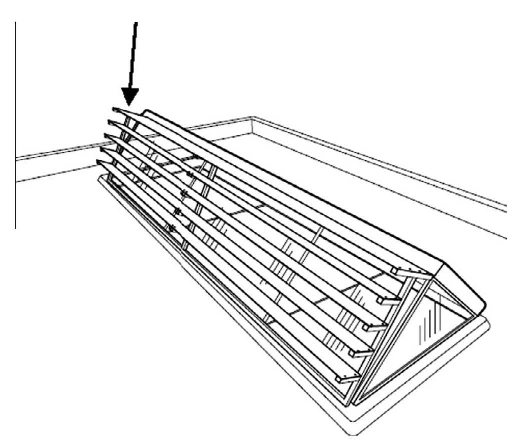


Fig. 15. Slat-like parasol descriptive scheme in SIRASOL.

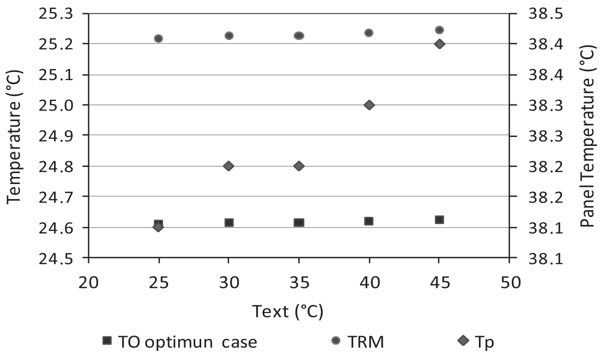


Fig. 16. Estimation of *TO* for diffuse solar radiation values corresponding to the radiation that could impact the panel in the summer.

analysis lies in that it demonstrates that SIRASOL will not negatively influence the temperature perceived by the person. That is to say, it will not alter the conditions of the inside space.

4. Conclusion

A passive solar system, SIRASOL, which works on the roof of rooms, is presented. It passively generates heat that is transferred to the room mainly by radiation.

The importance of SIRASOL is emphasized because it allows the use of a passive heating solar system without a north facade. The procedure has shown that thermal performance is very sensitive to the power of solar radiation.

We were able to calculate the temperature of the radiant panel from environmental conditions: solar radiation, outside and inside air temperature. *Tp* achieves 65 °C with solar radiation levels of 500–550 W/m^2. From the sensitivity analysis it is concluded that there is a direct relationship between solar radiation and *Tp*. As the radiation level rises, *Tp* rises proportionally (from 200 to 800 W *Tp* increases from 36 °C to 92 °C, when Tai is fixed at 20 °C; Text is fixed at 18 °C). For outside and inside temperature, *Tp* variation is negligible; therefore it can be said that SIRASOL will perform well in cold and sunny weather.

The thermal asymmetry between head and ankle levels was studied for obtaining an optimal radiant panel surface area. When solar radiation is lower than 500 W/m^2, thermal asymmetry is negligible for all cases studied. If solar radiation rises up to 800 W/m^2, a thermal asymmetry appears only when SIRASOL's surface area is 32% larger than the floor area.

The conclusions demonstrate that the thermal comfort of a room can be enhanced by using a passive solar radiant system (SIRASOL) that instantly transfers solar energy in the form of radiant heat into the space.

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