A daytime passive cooling radiation system

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ABSTRACT

There is a broad consensus that the lack of solar radiation at night provides a good opportunity for the passive cooling of buildings in climates with frequently clear skies. The idea is to design surfaces angled towards the sky that cool during the night due to infrared radiation and are sufficiently robust against solar radiation during the day. However, the possibility of also taking advantage of a clear sky's cooling potential during the day is rarely considered. Perhaps due to the brightness of a clear blue sky, it is not easy to comprehend that its radiant temperature is very low, sometimes even lower than that of a clear night sky in the same place. Evidently, this low temperature occurs in the part of the sky – the largest part – where the sun is not present at that time. The movement of the sun leads us to think that it covers the whole sky, whereas in reality it only covers a tiny portion at any moment. The rest of the sky has a very low radiant temperature. Taking a preliminary geometric study as the starting point, designs have been developed that will take advantage of the cooling potential of the sky. The inherent advantage of such a technique is that the movements of the sun are precise and well known, thereby increasing the possibilities of success. In this paper, we present the results of a small sky-powered cooling device. Specifically, it consists of a box in a high place – in this case the roof of an eight-storey building – that contains a predetermined quantity of water. The exterior weather conditions – our study took place in Barcelona in July – and the conditions inside the box were measured and compared. We aimed to assess whether it was possible to maintain a temperature inside the box that was lower than the external temperature. Here, we present the experimental results and the conclusions, as well as several potential applications in architecture.

1. INTRODUCTION

In Mediterranean countries, it is common to feel discomfort inside buildings on hot days. The excess heat indoors is usually attributed to the air conditions (temperature and humidity). Experience shows that if we go outside a building and stand in a position sheltered from direct radiation (in the shade), the feeling of discomfort diminishes and is rapidly replaced by a sensation of thermal comfort. The usual explanation for this improvement is that the air temperature is lower, the humidity has dropped or there is a breeze outside. However, we can prove that when the conditions outside a building are the same as those inside it in terms of temperature, humidity and a lack of air movement, the feeling of greater comfort outside is still notable. This effect can only be attributed to the mean radiant temperature. According to the Stefan-Boltzmann law and common considerations, very little cooling of buildings can be attained in the infrared spectrum. However, with an appropriate design of systems to take advantage of radiation, significant and useful results can be achieved in the field of architecture. The cooling effect of radiation towards a clear blue sky may have a considerable impact on thermal comfort (Isalgué, 1997). The capacity of nocturnal radiative cooling has been studied in Parker (2005), and the cooling capacity of special surfaces has been examined in Tazawa (1996 and 1997), Tanemura (1999) and Jaffer (2007). This is of interest to us, due to the daytime cooling capacity under clear skies (and sun), using low cost materials.

2. PRINCIPLES

The first principle to consider is that the "blue sky is cold". Although there is notable short-wave radiation in the visible spectrum, the intensity of radiation is low from a clear sky, when taken as a whole, and equivalent to that of a surface at a temperature at 240 - 280 K (approximately between – 33 and 7 ºC).

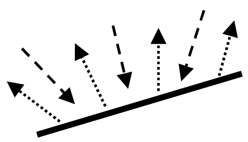
If the sky is cloudy, the temperatures are higher and close to that of the air at the altitude of the clouds. Logically, the clearer the atmosphere, the lower the equivalent radiation temperature of the sky will be.

The second principle to take into account is the vision of the sky for a specific surface. In the case of a horizontal surface with no obstructions above the horizon, there will be full correspondence between the surface and the sky. Thus, the radiation exchange will therefore be independent from the rest. However, the presence of the sun in the sky has a considerable impact on this exchange, as it sheds a high intensity of radiation on the surface, to the order of 1000 W / m².

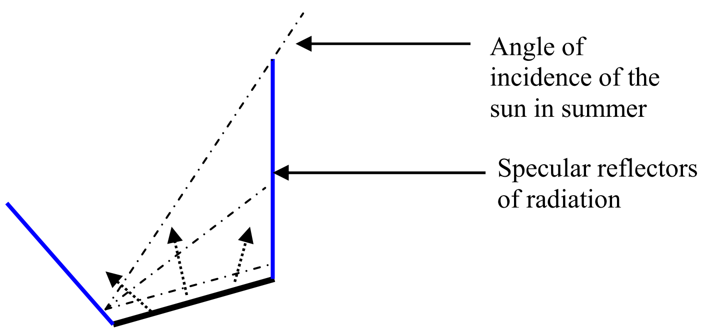
In addition, it can be shown that a specular reflective surface, with high reflectance of infrared radiation, captures the image of the sky and maintains its radiation characteristics almost completely. Thus, a geometric device that screens the vision seen from the receiving surface of everything except the clear sky, and even screens the sun, is practically equivalent to a surface that is totally exposed to this sky (solid angle of 2π steradians).

3. DESCRIPTION OF THE SYSTEM

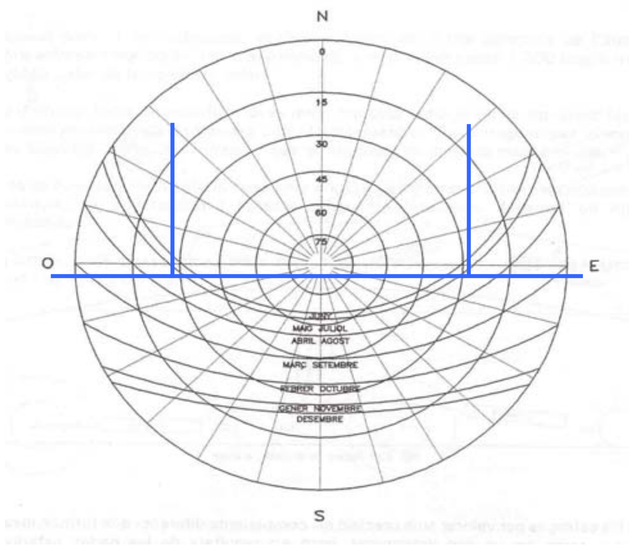
a. *Surface collection via a metal plate* that emits infrared radiation. This may be a cold selective surface (white paint, etc.).

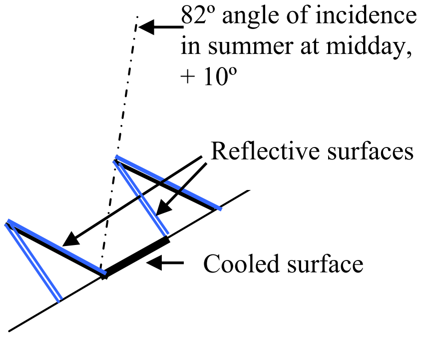


b. A *system of screens that reflect infrared* and hide both the passage of the sun (in summer) and the land surfaces (buildings, trees, mountains, etc.) that are visible from the plate. These screens, which are covered on the inside with a specular reflective surface, reflect the image of the sky onto the absorbent surface, so that this surface sees (directly or by reflection) a total solid angle of 2π.

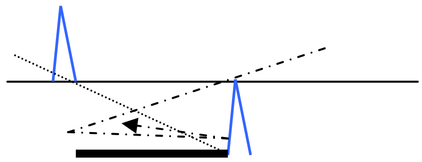


On the basis of these concepts, specific designs can be proposed:
For the latitude of 42º (as in Barcelona, Rome, New York, etc.):





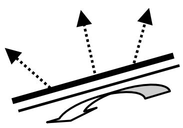
With the addition of lateral screens to reduce the incidence of sun at dawn and dusk (25º)



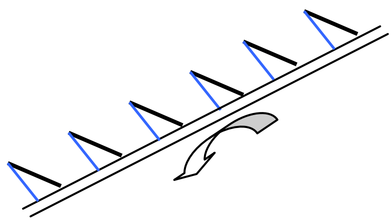
The cooled surface represents approximately 40% of the total cover.

Depending on the latitude, the geometry of the screen and reflection system should have different characteristics.

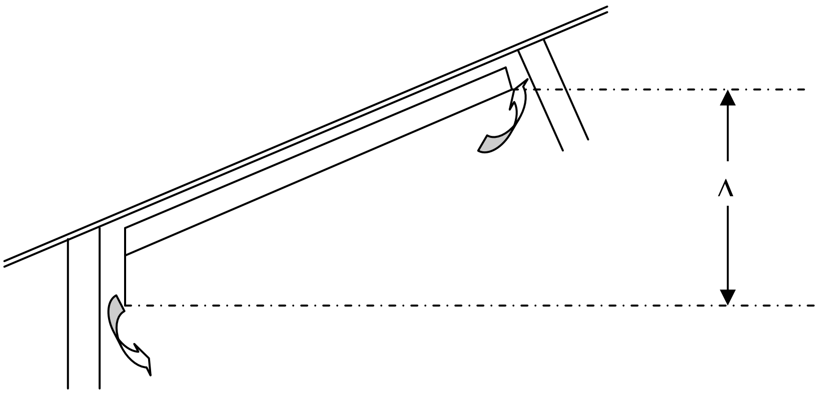
c. *Exchange of the plate with the air that flows below* it by conduction through the thin metal and surface convection. The surface-air contact area can be increased by corrugating the plate.



Together this would result in:



d. <u>*Circuit of air to the premises*</u> by creating a difference in height that facilitates the flow of air by thermal convection from the hotter air in the premises, which comes from its highest point (thermal stratification).



4. EVALUATION OF COOLING POWER

4.1 Flow of heat from the plate to the sky

If we assume that the temperature at the surface of the plate is 18ºC, i.e. (T_p= 291 K) (which is essential to maintain sufficient flow of cooling to the interior), the emission of radiation from the plate can be evaluated as:

Stefan Boltzmann for the black body: $M(n) = 5.67 \cdot 10^{-8} \cdot T^4$ (W/m²) (1)

If we take a reduction factor of ~ 0.9 for the emission of the plate and the sky:

In the plate (cold selective body): $M \sim 5 \cdot 10^{-8} \cdot T_p^4$ (W/m²) (2)

In the sky (equivalent temperature T_c): $M \sim 5 \cdot 10^{-8} \cdot T_c^4$ (W/m²) (3)

Thus, in our case: $\Delta M \sim 5 \cdot 10^{-8} \cdot (T_p^4 - T_c^4)$ (W/m²)

For a sky temperature of – 20ºC (T_c = 253ºC): $\Delta M \sim 160$ (W/m²)

4.2 Flow of heat form the plate to the air circulating below

If we assume that the temperature of the air circulating below the plate is 23ºC, the surface energy exchange for a flat plate could be:

$q = h \cdot \Delta T = 6.2 \cdot (23 - 18) = 31$ (W/m²) (4)

If we assume that the plate is corrugated in 1.45 to 1: $q = 31 \cdot 1.45 \sim 45$ (W/m²)

If the useful cooled surface is 40% of the cover, for a section 1 m wide and 4 m long, the results are:

$q = 45 \cdot 0.40 \cdot 4 \sim 72$ W (for 1 m width of the system)

It is assumed that the remaining flow of energy, with respect to that collected by the plate, will be transferred to the outside air with a higher coefficient of surface transfer (due to the possible presence of the wind), in the order of 15 – 20 (W/m²/ºC). If there is no wind, the temperature of the plate will be lower and the system will perform better.

4.3 Capacity of the air flow to cool the premises

If we assume that the air temperature in the premises is 26ºC and the circulation of air below the plate that returns to the premises is at 20ºC (corresponding to the mean temperature of 23ºC that was considered previously), a heat transfer of 67 (W/m²) requires a flow of air (C) per unit of the surface of the cooled plate of:

$$C \cdot svh \cdot \Delta T = 72 \qquad (5)$$

$$C = 72 / 6 / 0.33 \sim 36\ m^3 / h / m^2$$

(where svh = specific volumetric heat of the air in Wh per m³)

This assumes a flow of air through a 0.1 m-wide chamber at a velocity of:

$V = 36 / 0.1 / 3600 \sim 0.1$ m/s (which is low enough, as shown below)

4.4 Thermal circulation in the air circuit

We assume that the air circuit functions by natural convection for a metre of width of the premises. The induced pressure will be:

$$\Delta P = \Delta\delta \cdot g \cdot \Delta h \qquad (6)$$

where: ΔP: pressure difference
$\Delta\delta$: difference in density of air between 23 and 26ºC, ~ 0.012 kg/m³
g: acceleration of gravity: 9.81 (m/s²)
Δh = difference in height in the air circuit ~ 1.07 m

then: $\Delta P = 0.12 \cdot 1.07 = 0.128$ Pa

If we apply a hydrodynamic calculation to the circuit, with a velocity V and an approximate resistance factor of f = 0.075, the result is a loss of pressure due to friction in the conduit:

$$\Delta P = f \cdot (L / D) \cdot \delta \cdot V^2 / 2 \qquad (7)$$

Where: L = length of the path ~ 4.4 m,
D = height of the conduit ~ 0.1 m and
δ = air density ~ 1.27 kg/m³)

then: $\Delta P = 0.075 \cdot (4.14/0.1) \cdot 1.27 \cdot (0.1)^2 / 2 \sim 0.019$ Pa

The effect of resistance at certain points to flow (narrowed sections, bends, etc.) is not considered in the previous calculation. To take this into account, an approximation is used in which the point losses in this type of circuit are much higher than the linear losses, which results in total in:

$\Delta P = 0.019 \cdot 4 = 0.076$ Pa (lower than the available pressure)

If we assume the above, the flow of transported heat, Q, is:

$$Q = v \cdot A \cdot D \cdot \Delta T \cdot sh \qquad (8)$$

When: A = 1 m width of the conduit,
ΔT = 6 ºC
sh = specific heat ~ 1000 J

then: $Q = 0.11 \cdot 1 \cdot 0.1 \cdot 6 \cdot 1000 \sim 66$ W (for 1 m width of the system)

The approximate value of energy that is transferred to the interior environment for premises that are 3 m wide, with 4 m of depth considered and a surface of 12 m² is:

$P_{total} = 66 \cdot 4 = 264$ w

Sufficient cooling power to compensate for heat gains in a well isolated room protected from solar radiation.

5. GENERAL DIAGRAMS OF THE PROPOSED SYSTEM

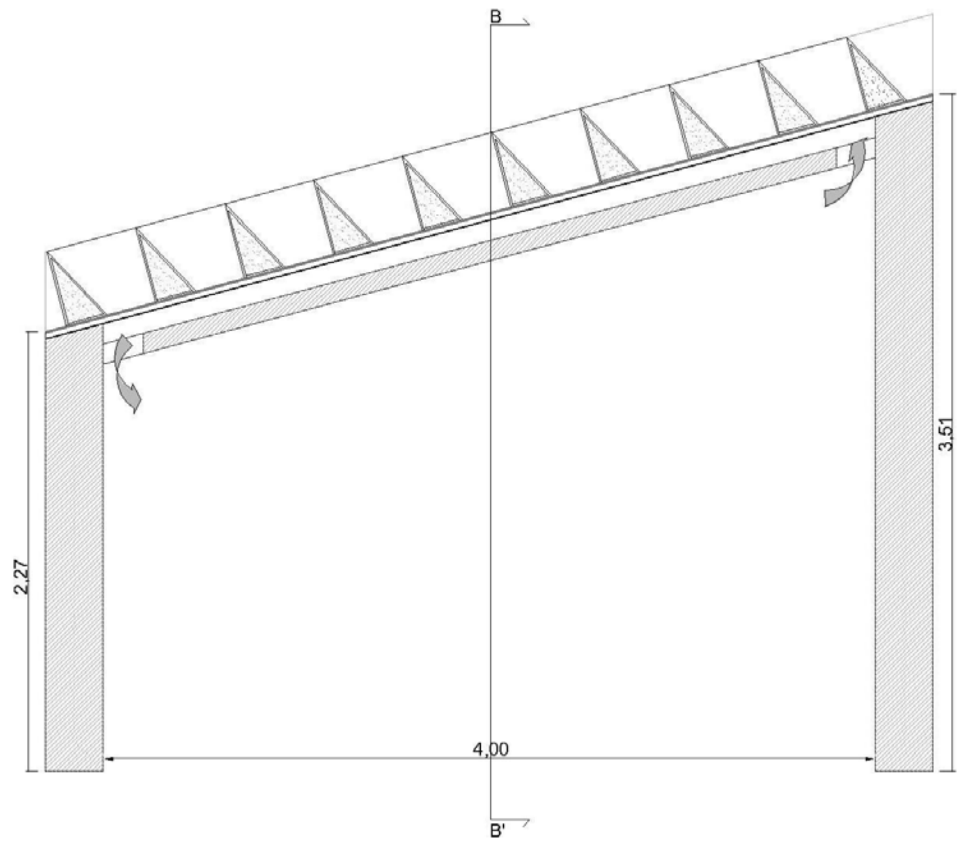


Figure 1. Longitudinal section of the proposed system.

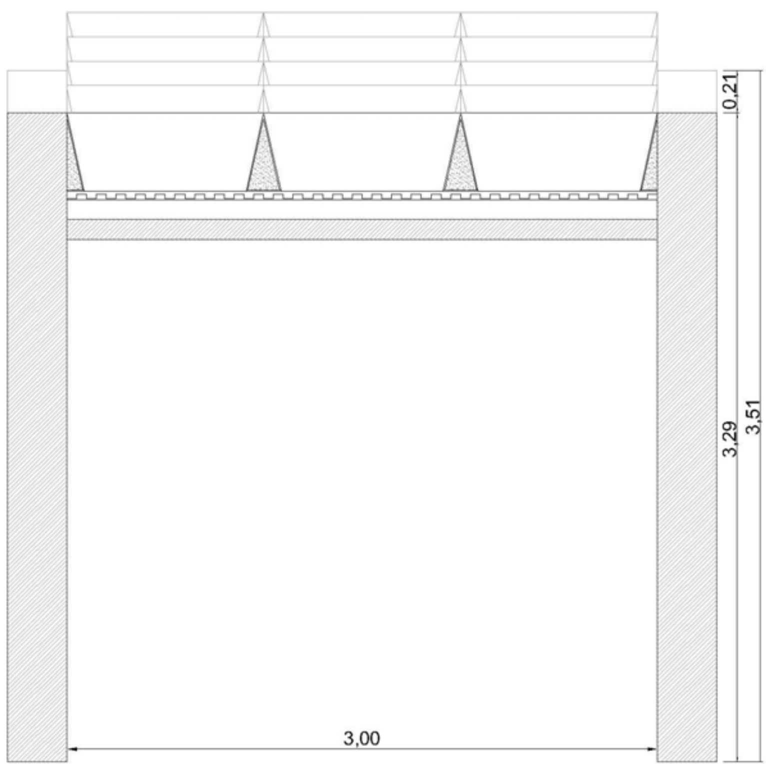


Figure 2. Cross-section of the proposed system.

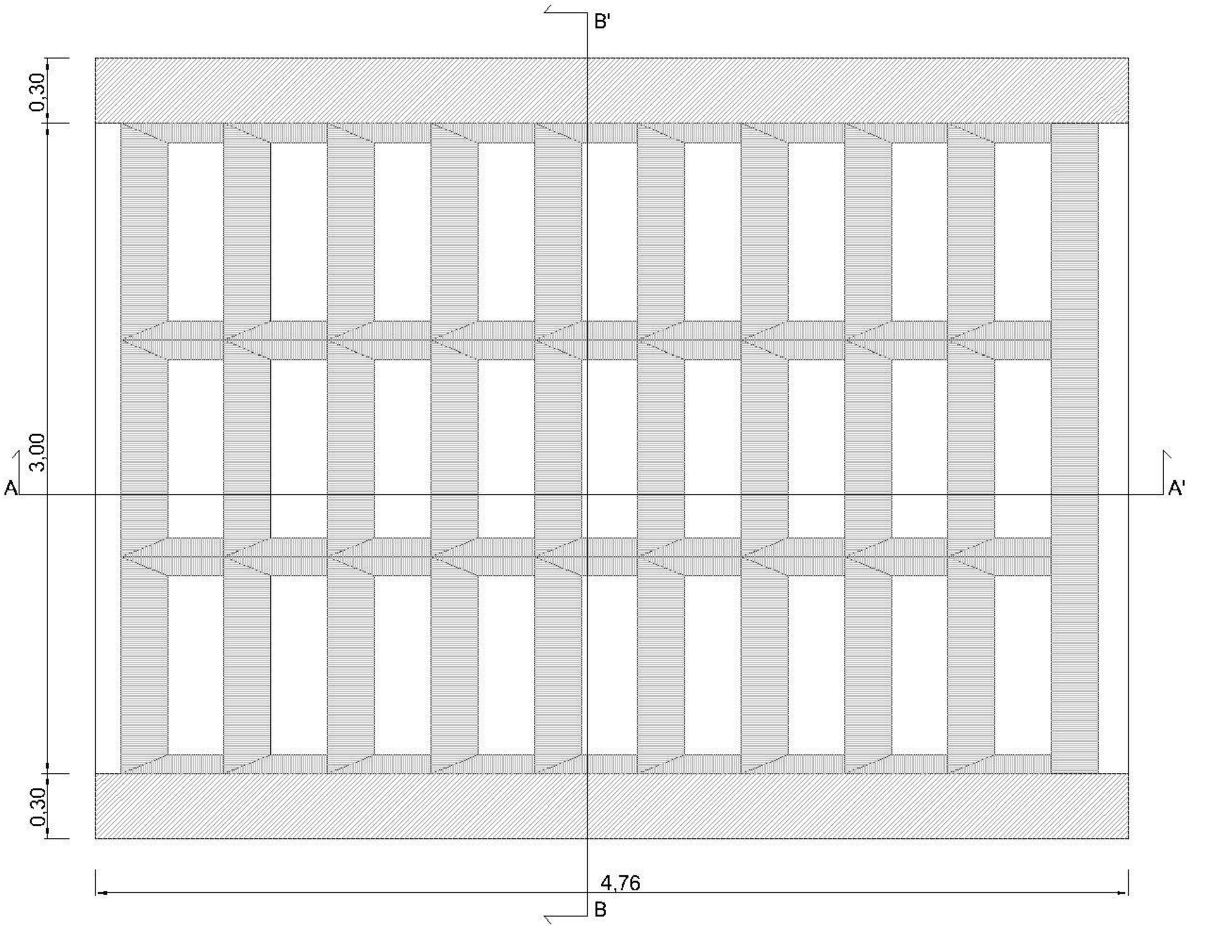
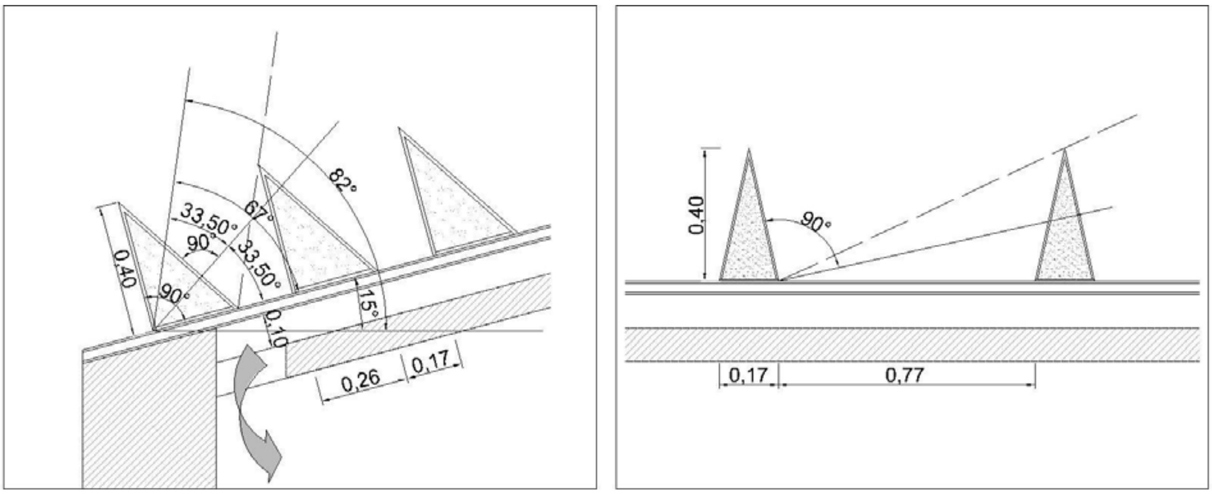


Figure 3. Diagram of a perpendicular view of the cover of the proposed system.
Note: if it rains, a slight separation between the screens and the surface of the plate allows the water to flow off the plate.



Figures 4-5. Diagram of the longitudinal and transverse screens.

6. EXPERIMENT

6.1 Description of the experiment

To verify the effectiveness of the general system described above, we built a prototype with a chamber that is approximately 0.5 m * 0.5m * 0.5 m, and a cover designed for the latitude of Barcelona.

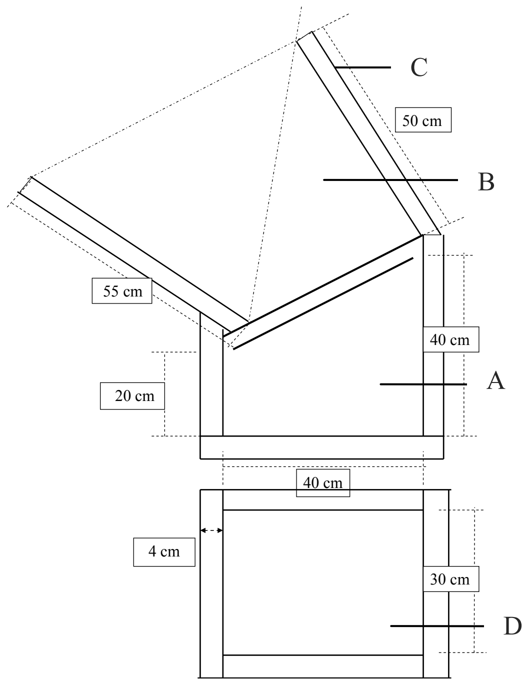
The walls and base of the chamber are made from 5 cm-thick expanded polystyrene, and are stuck to the chamber with glue and tape. Inside the chamber, we placed 3 bottles of mineral water, with a total volume of 1.5 l, to include a certain thermal mass and prevent rapid fluctuations in temperature. The cover, which is angled to the North, is made up of a 0.3 mm-thick copper sheet, painted on the outside with a water-based paint. In this prototype, the screens are made from cardboard and stuck with tape to the chamber. They are covered on the inside with commercial aluminium foil, such as that used in kitchens, with the shiny side out.

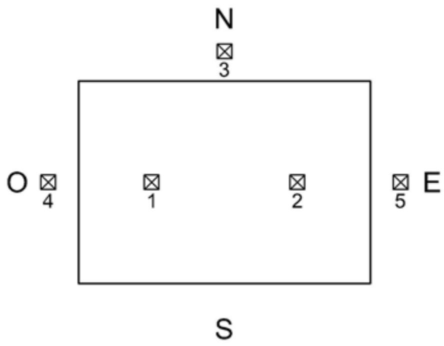
Figure 6. View to the SW from the site of the experiment.

Figure 7: View to the SE from the site of the experiment.

Figures 8-9. Model of the proposed system.

Data acquisition was carried out with 5 Testo (model) temperature and humidity sensors. These were positioned and programmed to take the temperature every ten minutes for several hours, as a control. Then, two sensors (no. 1 and 2) were placed inside the chamber and the other three were placed outside on the West (no. 4), North (no. 3) and East (no. 5) of the chamber, which was placed on the roof of a building in Barcelona, as shown in the above figures. The results of the recordings on 23 to 25 July 2007 are shown in Figure 12.





Figures 10-11. Diagram of the model of the proposed system and a diagram of the position of the thermal sensors.

A, cooled surface; B, lateral screens covered in aluminium; C, surface covered with aluminium, which stops solar radiation from reaching the cooled surface, and, together with the lateral screens and the protection to the North, ensures that higher heat exchange occurs by radiation between the cooled plate and the high atmosphere. D, isolated space to cool.

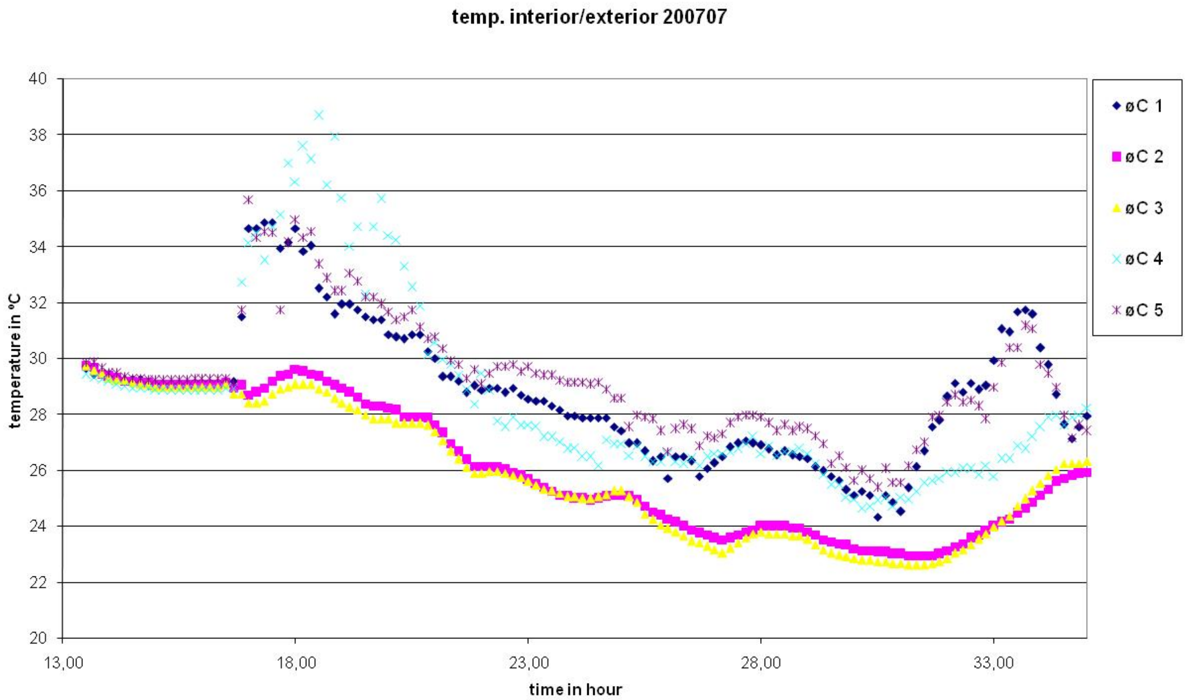


Figure 12. Graph of the interior/exterior temperature in July 2007.

The results of the test show a clear drop in the interior temperature of the model compared to the exterior temperature.

Due to the small size of the model, there is a high ratio between the covering surface/volume, which means that the cooling performance will be much less than that of premises with architectural dimensions and a similar shape.

7. CONCLUSIONS

In hot climates and periods, the proposed system takes advantage of the cooling radiation of the sky in daytime hours, with notable efficiency and no consumption of artificial energy.

Logically, the system continues to work during the night, which generates more efficient cooling that can be regulated by controlling the air circulation system.

The system can be adapted to different latitudes by changing the geometry of the reflective screens. Thus, it could be used on much of the planet.

The cost of incorporating the system into buildings could be relatively low if it is included in the architectural plans. Obviously, it costs nothing to run.

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