Diurnal Radiative Cooling of Spaces in Mediterranean Climate

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ABSTRACT

The absence of solar radiation at night gives good opportunities for passive cooling of buildings in hot climates with frequently clear sky. However the possibility of also taking advantage of a clear sky cooling potential during the day is seldom considered.

Thermal radiation to sky can be used to cool. A body surface emits thermal radiation (far IR) and if direct solar radiation (visible and near IR) and thermal radiation coming from other surfaces do not reach it, there would be a net heat flux out.

A previous prototype was done with a simple element. That experiment confirmed that was possible to reduce around two degrees the interior temperature of the test unit exposed to sun light in July.

In this work a new design based on the first one is developed to adapt it to architectonical needs in order to reduce interior spaces temperature in hot climates.

The aim of this design is focused to so an architectonical adaptation is needed. Modular and replicable units could be a solution that permits to fulfill large flat surfaces as roofs or other architectonic elements. In this occasion, measurements were taken from a modular model with a geometrical design that avoided de direct solar incidence. These measurements were taken by a pyrgeometer during two weeks of August and results were similar to the previous experiment.

INTRODUCTION

A body surface emits thermal radiation (far InfraRed, IR), and if it can be made that direct solar radiation (visible and near IR), and thermal radiation from other bodies (far IR) do not reach the body surface, there would be a net heat flux out of the body, cooling it (Head 1962). The cooling can be obtained by selective surfaces, that reflect visible and near infrared solar radiation (near IR), avoiding direct solar gains, while they are emitters for far infrared radiation, if they are appropriately exposed, and allowing radiation going to sky. Cooling can also be achieved with the help of reflective surfaces and geometry (Trombe 1967 and Hull 1986). A polished surface with high reflectance to infrared radiation is able to reflect the image of the sky and maintain the radiation characteristics (Granqvist 1982). An emitting surface "seeing" the reflected image of sky, will loss energy to the reflected part of cold sky (Craig et al. 2008).

The previous prototype tested in Barcelone was done with a single element (Serra et al. 2010). In that occasion, the analysis let us know that it is possible to reduce the inside temperature of a chamber, in about two degrees, during the sunny hours if an emitting surface can see nothing but the cold sky zone and its emitted radiation is thrown far away without reflection that take it back. That prototype checked the effect with a single element covering the entire top side of the box. The vertical development was very high and this dificults the practical applications in architecture.

In this work we consider the possibilities of irradiative cooling in Mediterranean climate for cooling interior spaces of buildings. We want to test a variant of the first model that incorporates the principle refrigerator to a replicable element that fill a flat roof being easy to construct and modular. The second main goal is about the system should use cheap, easily available materials in the existing industry such us aluminum foil and cardboard.

To face this challenge we have deepened the geometric study of the protection element of the emitting sheet, so that the surface occupied by the protection system was reasonable and the effective emitting area was the largest as possible. Geometry must help us to make that the emmiting surface only would see the cold zone of the sky even by reflection.

The emitting surfaces were white painted metal sheet as in the first model. In order to reduce thermal exchange with exterior air (Johnson 1975, and Golaka et al. 2007), we installed a thin 50 µm transparent polyethylene film 3 mm before the emitting surface. In this way the polyethylene film does not receive direct solar radiation and its life is expected to be longer because no significant UltraViolet (UV) radiation reaches the film. The test model was made with common materials and located in a village near the Mediterranean coast, and measurements were taken, by a pyrgeometer, during two weeks of August.

GEOMETRICAL APPROACH

Those two features, an easy construction and avoid IR radiation, can be both obtained if a suitable geometry for a lateral screen system is designed. We did a very detailed study of the geometry of the unit module. Such geometry should comply with the protection requirements of solar incidence both direct and reflected. The geometric study started from the solar path during the worst day -summer solstice- on a stereografic diagram, to narrow the sky zone without the sun passing throw, see Figure 1. Zones 1 and 2 on the diagram represent the coolest zone of celest voult, away both from the sun path and from the horizon, to avoid radiation emitted from extern objects that could reduce the net heat flux out from our emitting surface.

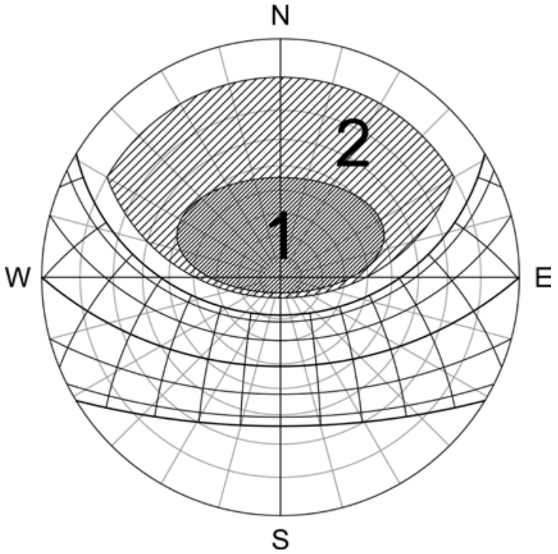

Figure 1 A stereographic diagram for Barcelona, near 41° north latitude. Zones 1 and 2 are preferred for thermal radiation exchanged. Zone 1 has lower equivalent radiant temperatures.

The vertex of a 134° opening cone, looking to the correct direction to the north for this latitude about 41° north, will never see the sun it sees the cold sky zone (see figure 2). We must place the emitting surface behind the initial vertex to obtain a large enough area for the irradiative surface, although this brings up a narrower conical element. So we extended the generatrices of the cone beyond the vertex looking for an ortogonal angle with the opposite sheed to avoid reflected rays coming back. Then we transformed the cone to a pyramidal piece because planar forms are more usefull to replicate and add elements. This choice should provide an eligible prototype for construction useful to add units in order to fulfill a roof.

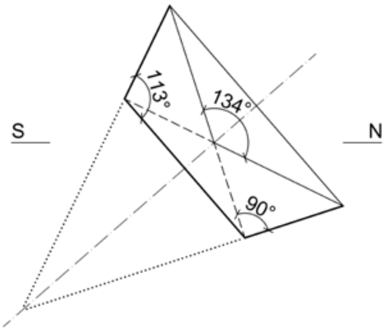

Figure 2 The diagram shows the overture of the first conical unit element with an overture of 134º toward the cold zone of the sky, and the geometrical definition of the replicable pyramidal unit.

Finally the side flaps were extended to protect the interior of possible radiation reflected in them and even folds were we calculated graphically the correct angle to improve the efficiency of the global suitable surface. Lateral slopes in contact to the emitting surface respond to the pyramid design explained above, bottom slope was further worked in order to maximize the efficiency. Its tilt was modified in the far part because the high of incident solar rays in that point was minor and if we fold it back we can reduce the occupied roof area by each basical unit (see figure 3).

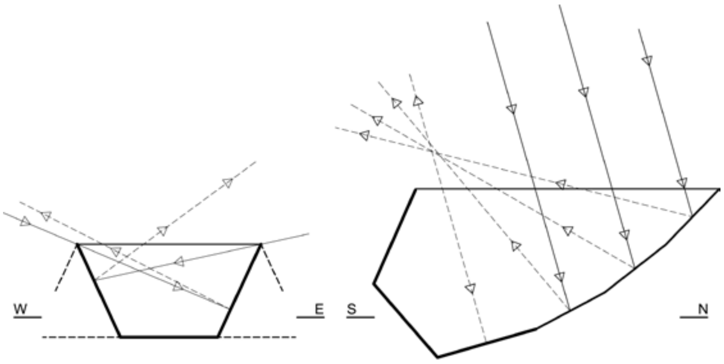

Figure 3 Shows the two sections of the basical unit and the reflected sun rays of sun on the side screens. Folding the northen screen reduces the ratio between emiting surface and global roof surface.

Different units can be easily aggregated. Some faces are extended in order to cover the horizontal roof with high performance. Lateral extreme screens are also extended to avoid sunlight entering during the first and last hours of the summer days. As a result of this process, we obtain a geometric model with an effective surface area of 1/6 of total roof area.

PROTOTIPE AND MESUREMENTS

The roof model was installed on a 50cmx50cmx30cm box, with 7 cm of expanded polystyrene thermal insulation, see figure 4.

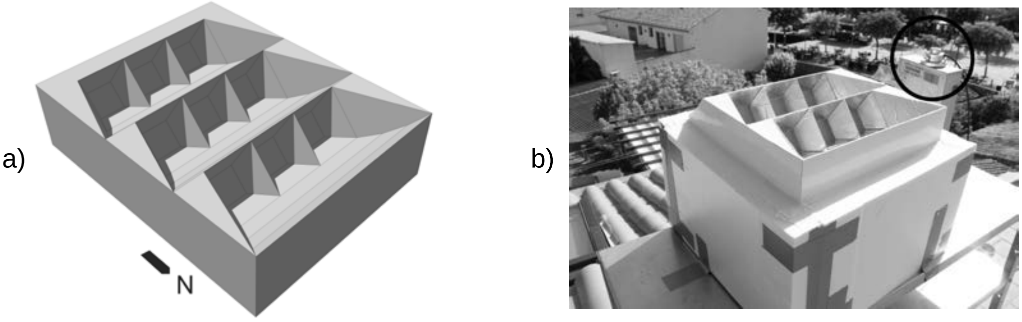

Figure 4. a) Digital 3D model. b) Photograph of the built prototype. The circle shows the pyrgeometer.

The emitting surfaces were white painted metal sheet. In order to reduce thermal exchange with exterior air (Tazawa 1996, and Tazawa 1997), we installed a thin 50 µm transparent polyethylene film 3 mm before the emitting surface. In this way the polyethylene film does not receive direct solar radiation and its life is expected to be longer because no significant UV radiation reaches the film.

The model has been checked during a period of sunny days of August, in a roof of a house in Sant Llorenç del Penedés (near Barcelona).

Measures of thermal emission have been done with a Pyrgeometer 1239 from Hukseflux thermal sensors with a Cambell Scientific datalogger 21538, and compared with solar radiation from a Pyranometer at the automatic meteorological station (XEMA 2013) placed in El Vendrell (5 km from the scale model). Both devices measure total (direct and diffused) radiation in different wavelengths.

The obtained results for the modular case show that during some sunlight hours the interior temperature is higher than exterior temperature.

The figure 5 shows the measured solar radiation and the thermal radiation emitted to the sky. The average of received solar radiation is higher than emitted thermal radiation. The emitted is relatively low due to the Mediterranean Sea influence, because of meteorological reasons (dominant South component winds from the sea, in summer, and large evaporation of water). Relatively high humidity (near 67% with mean temperature near 26ºC) lowers the cooling radiation effect, because the opacity of water vapors to IR radiation. However, according to the measurements from the Pyrgeometer, it should be pointed out that even in this case, it is possible to emit near 100 W/m^2 to the sky.

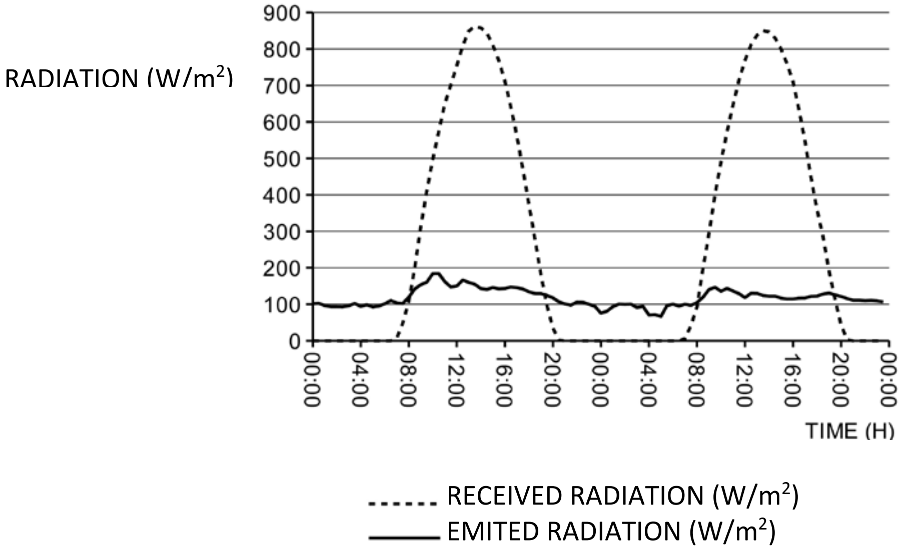

Figure 5 Dotted line shows global solar radiation on horizontal surface from meteorological station. Continuous line shows net IR radiation emitted to the sky from the Pyrgeometer

With the above data and the exterior temperature we computed a thermal balance equation for the interior of the model. We take into account the exterior air temperature, the thickness of the thermal insulation, the thermal radiation from the emitting surfaces, a heat transfer from the sun exposed sides of the model (surface temperature measured with a 66 IR Thermometer from FLUKE) and an approach to the diffuse radiation on the roof.

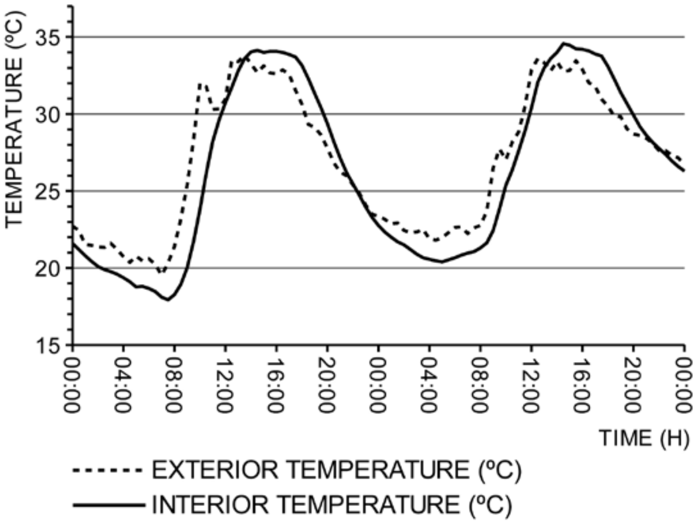

Figure 5 Dotted line shows the exterior temperature and continuos line the interior one.

The measured interior temperatures at 14h are no more than 0.3ºC different from those calculated by this approach. An excessive entrance of heat due to direct solar radiation incidence on the model area increases exterior surface temperatures. A high value of diffuse radiation conditions of Mediterranean summer sky also contributes to reduce the efficiency of this prototype as cooling device.

If solar protection had been applied to the lateral walls of the modular system, as it was done in the first model, the computation result would be 1.3 ºC lower. In this case, the interior temperature would be lower than external temperature during almost all day. Further on, an increase of roof thermal insulation in the parts which receive direct sunlight could have improved the results.

CONCLUSION

We consider two prototypes of radiative cooling roof. First one is a simple unit where the whole roof acts as IR emitting surface and lateral protections to direct sunlight are added. Second one is a modular design where the emitting surface is 1/6 of the roof area because of the integrated sunlight protections.

In both cases the space to be cooled was near 40x40x30 cm and was thermally insulated with at least 5 cm of expanded polystyrene except for the emitting surfaces.

First prototype was tested in Barcelona and the measured interior temperature was near 2ºC lower than exterior. This result is in agreement with a basic calculation taking into account heat transfer trough the walls and thermal emission from the roof. Exterior surfaces of the model were at exterior air temperature because they were protected from direct solar radiation.

In the second case the interior temperature was 2.5ºC lower than exterior only during night hours, while it was near 2.5ºC higher than temperature during some sunlight hours. This result can be understood because of solar gains through the sunlit walls and indirect solar radiation gains through the roof. The measured interior temperatures at 14h are no more than 0.3ºC different from those calculated by the thermal balance equation. If solar protection had been applied to the lateral walls of the modular system, as it was done in the first model, the result would have been better.

Summarizing, the possibilities of diurnal radiative cooling during summer in Mediterranean climate are mainly bounded by three factors. First of them is the relatively high humidity and low transparence of atmosphere to IR radiation. However, according to the measurements from the Pyrgeometer, it should be pointed out that it is possible to emit near 100 W/m^2 to the sky in our summer climate. Second one is the need to restrict, with an appropriate geometry, the aperture of the radiating system to the cold zone of the sky vault. And third factor is the absolute need to reduce the entrance of direct or diffuse solar radiation. Even with these bounds, we show that it is possible to obtain diurnal radiative cooling in sunny places by appropriate selection of geometry and easy to obtain materials.

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