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26-27 October 2020, Bern Switzerland
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Evaporative cooling active roof
Case study for a residential building in Cadiz

Francisco José Sánchez de la Flor¹, Álvaro Ruiz-Pardo¹, Enrique Ángel Rodríguez Jara¹ and
Servando Álvarez Domínguez²
¹Dep. of Thermal Engines and Machines, School of Engineering, University of Cádiz, Spain
²Thermal Engineering Group, Dep. of Energy Engineering, University of Seville, Spain

1. Abstract
To contribute to the reduction of greenhouse gas emissions, one of the main ways is to reduce energy consumption in buildings. This consumption is due, among other reasons, to the space cooling of buildings in summer, especially in cities of southern Europe. This article focuses on the development of one of the main natural cooling techniques for buildings in summer, which is passive cooling. With this objective, the appropriate design of a cooling system for the top floor slab for a real residential building is presented, corresponding to the European project RECO2ST.

The article presents the cooling potential of this technique calculated by means of numerical simulations and previous experimental campaigns. The use of this element is responsible for maintaining a surface temperature of approximately 2.5°C lower than that of the indoor air. This lower surface temperature has the dual benefit of eliminating the need for conditioning consumption, and of keeping the operating temperature within the limits of thermal comfort in summer.

Keywords: Reducing cooling needs, increasing comfort level, evaporative cooling, ventilated hollow core slab systems, Case study of residential building

2. Introduction
Reducing energy consumption in buildings is an essential requirement for the most ambitious goal of reducing greenhouse gas emissions. In fact, according to the latest UNEP status report on buildings and construction, this sector accounted for 36% of final energy use and 39% of carbon dioxide (CO2) emissions in 2018 [1].

In the case of warm climates, and especially for buildings for residential use, one of the main causes of energy consumption is the space cooling in summer. This is the case of the residential building studied in this article, which is located in Cádiz, Spain, and is a demonstration building for the RECO2ST project (Horizon 2020) [2].

In order to reduce energy consumption due to the thermal conditioning of buildings in summer, many and diverse techniques have been studied, with special focus on the natural cooling techniques [3] ranging from the improvement of urban climatic conditions [4], to techniques applied to the specific building, such as the use of cool roofs [5], vegetation [6], natural ventilation [7], or the use of evaporative cooling [8][9], among others.

On the other hand, and to increase their potential as much as possible, the previous cooling techniques are usually combined with the use of the building's thermal inertia. It has been found that the use of night cooling ventilation in addition of phase change materials (PCMs) is a very powerful strategy for reducing the cooling demand of buildings [10] [11]. Thermal inertia dampens and delays heating and cooling peaks, reducing energy consumption in buildings, something that exploits so-called thermally activated building systems (TABS) that consist of water pipes embedded in the building slabs [12]. When an air stream is passed through the interior of the slab, it is called ventilated hollow core slabs (VHCS) [13].
This article focuses on the study of these VHCS systems and presents an appropriate design for cooling the top floor slab of a residential building block. The design is based at the same time on computer simulations of the thermal behaviour of the building and the VHCS system, and on the other hand, on the previous experience acquired by the authors of the article in an experimental campaign of a similar system for vertical facades [14], and in the following sections is referred as evaporative cooling active roof.

2.1 Description of the evaporative cooling active roof

The objective of the evaporative cooling active roof is, firstly, to reduce the heat gains due to the high daytime temperatures of the outside air and by the solar radiation falling on the roof; secondly, to take advantage of the low humid night temperatures to evacuate heat and finally, store cold in the thermal mass of the roof. For this, the evaporative cooling active roof is composed of two sheets (slabs), an air chamber, an evaporative system and air ducts. A schematic view is shown in Figure 1.

The two sheets must be watertight to prevent air and water leaks while the outer sheet must be thermally insulated to reduce heat flow between the lower sheet and the exterior ambient. The air chamber must be connected to a mechanical ventilation system and the air must be cooled, either by means of direct humidification in the air chamber using for example nozzles, or by means of an evaporative cooling equipment before the air inlet of the chamber. The ventilation and cooling of the air must be carried out when the external conditions favour that the temperature of the circulating air in the chamber can be low enough to cool the lower sheet that is the responsible for storing the cold. Such conditions normally occur at night as the outside air temperature drops. When the air circulation does not work (Off mode), the exchange of air with the outside must be prevented in order to avoid the entry of heat, for this reason, the system must have doors in at least one of the ends, either at the outlet or at the entrance.

2.2 Previous numerical and experimental results

To evaluate the potential of the evaporative cooling active roof, a simulation model was developed, consisting of four main modules: The first one calculates the heat transfer in the two roof sheets. The second one calculates the evolution of the air temperature. The third one calculates the temperature of the air cooled by the evaporative system; and the fourth one couples the previous modules.

The module for calculating the heat transfer through the roof sheets is based on the finite difference method, which allows the transient calculation with variable boundary conditions. The module that calculates the evolution of the air temperature assumes that the temperature is unique in each cross section of the air flow, but due to the heat exchange with the two surfaces, upper and lower, the air temperature changes in the direction of the air flow. This module also calculates the convective heat transfer coefficients. The module that calculates the air inlet temperature uses the thermodynamics of humid air; and the coupling module includes calculation of the boundary conditions at each time step, this therefore contains the calculation of the exterior and interior conditions and the transfer by long wave radiation between the two roof sheets.

The application of the previous model allows to estimate the behaviour that the evaporative cooling active roof will have. Results for a series of four days under typical summer conditions in southern Spain are shown.
in Figure 2, where three operating scenarios have been explored: without ventilation, with ventilation but without evaporative cooling, and with ventilation and evaporative cooling. It is observed how the use of ventilation produces a reduction in the interior surface temperature of the roof by approximately 1 to 2°C, with respect to the non-ventilated case. When evaporative cooling is used, the temperature drops between 2 and 4°C with respect to the case without ventilation.

The importance of the temperature drop is that in this way in the interior space will be a cooler surface than the indoor air, which means that heat will be evacuated through the roof during the 24 hours of each day. An additional benefit of having the roof surface cool is that it will cause the operating temperature to drop relative to a conventional roof, thereby producing a favourable thermal comfort condition.

An experiment that operates exactly the same as the evaporative cooling active roof, was one carried out by Ruiz-Pardo et al. [14] in which the same operation described for the roof is applied but applied to the south facade of a test hut shown in Figure 3.
Three experiments were carried out in the hut: the first, called the “reference case”, consisted of operating the facade without ventilation, that is, it worked as a conventional wall with a sealed air chamber. The second one, called “Experiment 2v”, consisted of operating the ventilation without evaporative cooling and, the third one, called “Experiment 3v”, consisted of operating the ventilation together with evaporative cooling. The results obtained are those shown in Figure 4.

In the reference configuration, it can be seen that the mean temperature of the interior surface of the approximately 1.5ºC lower than the interior. In experiments 2v and 3v, with the air chamber operating with forced ventilation at night, it can be seen that the temperature of the interior surface of the ventilated facade is lower than that of the interior. This indicates clearly that it removes heat from the interior of the house. In experiment 3v the facade is operating with evaporative system. The temperature of the interior surface decreases still further in comparison with the other experiments. As summary it can be seen that the entry into operation of the ventilation lowers the temperature of the inner surface. Without evaporative system, the temperature drops more than a 1ºC in comparison with the reference case and with the evaporative cooling the drop is near to 2.5ºC.

![Figure 4: Experimental results of a façade element working exactly equal than de evaporative cooling active roof.](image)

3. Case study

In order to show the proposed solution for a real building, in this paper a block of flats located in the city of Cádiz, Spain has been selected. It is one of the buildings demonstrating innovative technologies on which the European RECO2ST project is based. It is a building from the 60s with 5 floors with a total of 28 apartments and a constructed area of 1873 m2. At the time of writing this paper the building is uninhabited and the rehabilitation project is underway that will bring the building to nZEB consumption levels.

Technologies promoted by the RECO2ST project will be included, as well as other more conventional ones, such as: replacement of current windows to new more energy efficient windows, increase in the level of insulation in external walls and roofs, installation of a centralized ACS system whose principal source is a solar thermal installation.

In particular, it is interesting to reduce the energy needs of the building to evacuate the heat from the top floor, a reason that justifies the installation described here.
3.1 Location and building characteristics

The study building is located on Calle Doctor Marañón, in Cádiz, Spain (36.5°N, 6.26°W) with an orientation on its main facade of 22° east with respect to the south.

Figure 5 shows a bird's-eye view of the building from the main street, and from the inner courtyard on the north side of the building. In this figure it is seen that in the current situation of the building there is a flat roof.

![Figure 5: 3D-view of the building: (a) Pointed-south façade; (b) Pointed-north façade.](image)

3.2 Initial cooling needs

To assess the cooling needs of the building in the initial situation, an energy simulation of the building has been carried out with the official tool in Spain for energy certification of buildings. It is the LIDER-CALENER Unified Tool (HULC) that performs a detailed calculation in transitory regime of the building’s thermal behaviour on an hourly basis [15].

For the use of this software tool, the building to be calculated must be entered with the geometric detail that can be seen in figure 6, and the walls, floors and windows must be described by introducing the layers of materials that form them (see Tables 2 and 4).

![Figure 6: 3D-view of the building model using HULC software tool.](image)
The main building characteristics are summarized in the following tables.

<table>
<thead>
<tr>
<th>Total façade area</th>
<th>1.479</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>449</td>
</tr>
<tr>
<td>East</td>
<td>324</td>
</tr>
<tr>
<td>South</td>
<td>436</td>
</tr>
<tr>
<td>West</td>
<td>270</td>
</tr>
<tr>
<td><strong>Total roof area</strong></td>
<td><strong>328</strong></td>
</tr>
<tr>
<td><strong>Total ground floor area</strong></td>
<td><strong>215</strong></td>
</tr>
</tbody>
</table>

*Table 1: Building exterior areas (m2).*

<table>
<thead>
<tr>
<th>Windows to wall ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
</tr>
<tr>
<td>East</td>
</tr>
<tr>
<td>South</td>
</tr>
<tr>
<td>West</td>
</tr>
</tbody>
</table>

*Table 2: Building window to wall ratio.*

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (m)</th>
<th>Conductivity (W/m·K)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Façade walls</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial stone</td>
<td>0.020</td>
<td>1.300</td>
<td>1.700</td>
</tr>
<tr>
<td>EPS expanded polystyrene</td>
<td>0.020</td>
<td>0.038</td>
<td>30</td>
</tr>
<tr>
<td>1/2 feet metric LM or catalan 40 mm &lt; G &lt; 50</td>
<td>0.115</td>
<td>0.991</td>
<td>2.170</td>
</tr>
<tr>
<td>Gypsum plaster 1000 &lt; d &lt; 1300</td>
<td>0.020</td>
<td>0.570</td>
<td>1.150</td>
</tr>
<tr>
<td><strong>Party walls</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster 1000 &lt; d &lt; 1300</td>
<td>0.020</td>
<td>0.570</td>
<td>1.150</td>
</tr>
<tr>
<td>Simple LH partition [40 mm &lt; thickness &lt; 60 mm]</td>
<td>0.040</td>
<td>0.445</td>
<td>1.000</td>
</tr>
<tr>
<td>EPS expanded polystyrene</td>
<td>0.020</td>
<td>0.029</td>
<td>30</td>
</tr>
<tr>
<td>Simple LH partition [40 mm &lt; thickness &lt; 60 mm]</td>
<td>0.040</td>
<td>0.445</td>
<td>1.000</td>
</tr>
<tr>
<td>Gypsum plaster 1000 &lt; d &lt; 1300</td>
<td>0.020</td>
<td>0.570</td>
<td>1.150</td>
</tr>
<tr>
<td><strong>Ground floors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marble [2600 &lt; d &lt; 2800]</td>
<td>0.020</td>
<td>3.500</td>
<td>2.700</td>
</tr>
<tr>
<td>EPS expanded polystyrene</td>
<td>0.020</td>
<td>0.038</td>
<td>30</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.350</td>
<td>0.707</td>
<td>1.420</td>
</tr>
<tr>
<td><strong>Interior floors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marble [2600 &lt; d &lt; 2800]</td>
<td>0.020</td>
<td>3.500</td>
<td>2.700</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.250</td>
<td>1.190</td>
<td>1.280</td>
</tr>
<tr>
<td>EPS expanded polystyrene</td>
<td>0.020</td>
<td>0.038</td>
<td>30</td>
</tr>
<tr>
<td>Plate of laminated marble [PYL] 750 &lt; d &lt; 900</td>
<td>0.020</td>
<td>0.250</td>
<td>825</td>
</tr>
<tr>
<td><strong>Roofs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand and loose stone [1.700 &lt; d &lt; 2.200]</td>
<td>0.020</td>
<td>2.000</td>
<td>1.450</td>
</tr>
<tr>
<td>EPS expanded polystyrene</td>
<td>0.020</td>
<td>0.038</td>
<td>30</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.300</td>
<td>0.667</td>
<td>1470</td>
</tr>
<tr>
<td>Plate of laminated marble 750 &lt; d &lt; 900</td>
<td>0.020</td>
<td>0.250</td>
<td>825</td>
</tr>
</tbody>
</table>
The results of the building's energy simulation for the summer period show that the top-floor spaces are, in general, those with the highest cooling demand with values above 12 kWh/m² as can be seen in Figure 7.

In view of these results, the decision was made to design a system based on evaporative cooling for the slab of the top floor of the building described below.

4. Design of the evaporative cooling active roof for the case study

The specific design of the evaporative cooling active roof has been carried out taking into account the particularities of the building, the climate and the availability of materials. The following describes the design carried out for the rehabilitation of the residential building in Cádiz discussed in this article.

4.1 Components of a evaporative cooling active roof

The building to be rehabilitated is made up of two symmetrical blocks. Consequently, all the elements of the evaporative cooling active roof of one block are repeated in the other as shown in Figure 8. Therefore and in order to simplify explanations, in this section reference will be made to the components of only one of the two blocks.
4.1.1 Indirect evaporative air cooler

As stated in the general description of the evaporative cooling active roof, the air entering the air chamber must be driven by a mechanical medium and cooled, either by means of direct humidification in the air chamber using for example nozzles, or by means of an evaporative cooling equipment before the air inlet of the chamber. In this case, the second option has been chosen since it was considered easier to install and maintain. On the other hand, the external cooling equipment can be direct or indirect cooling, having opted in this case for indirect cooling and in particular, based on the Maisotsenko cycle [16] because it can achieve air temperatures lower than the wet bulb. The principle of operation of this indirect cooler consists of separating the cooled air stream into two parts, one of which is recirculated and humidified to act as a heat sink for the incoming hot stream as shown in Figure 9.

![Figure 9: Indirect evaporative cooler based on Maisotsenko cycle.](image)

The selected equipment includes a supply air fan that is responsible for driving both Cool supply air and Exhaust air.

4.1.2 Air ducts

The cooled air in the Indirect evaporative cooler is brought into the roof air chamber through the air ducts. Because in each of the two blocks of the building, the roof has been divided into three sections, the cooled air ducts are divided into three as shown in Figure 8. The design of these ducts has been made in such a way that pressure losses are minimized, so that the nominal air flow established by the Indirect evaporative cooler fan can be achieved by regulating a damper included in the ducts.
4.1.3 Slabs and air chamber

The basic core of the evaporative cooling active roof is made up of the two sheets (slabs) and the ventilated air chamber. As stated in section 2.1, the objectives of this element are to avoid chlorine gains from outside, store cold in the lower sheet and remove heat from inside. That is why the outer sheet is isolated and the lower one is not. A section of the layers that make up this roof can be seen in Figure 10.

![Figure 10: Evaporative cooling active roof cross section.](image)

A2. Cellular concrete for 2.5% slope formation (e = 2-10cm).
A3. Double asphalt waterproofing sheet
A4. Bastard regularization mortar, e.min = 1.5cm.
A5. Liquid bituminous waterproofing sheet with external reinforcement sheet.
A6. Protection mortar.
A9. 4 cm thick ceramic rasillones.
A10. Gripping mortar.
A11. 14x28cm ceramic tile flooring, Bonares type for exteriors.
A12. Ventilated chamber.

On the other hand, the air flow that circulates through the chamber must be as uniform as possible in order to achieve a temperature as uniform as possible over its entire surface. For this reason, it is necessary to establish a series of channels that force the air to be distributed throughout the roof surface. One option to achieve this flow distribution is that shown in Figure 11, where the orange lines correspond to rows of bricks that make up the channel walls.

![Figure 11: Air channels for flow distribution inside the chamber.](image)
5. Expected results

Simulations were carried out using the model mentioned in section 2.2 that allows to establish the expected hourly behaviour and which can be integrated into the official tool in Spain for energy certification of buildings (HULC) using the protocol created for the calculation of singular elements such as this.

The results obtained on demand are shown in Figure 12. It can be seen that the refrigeration needs are strongly reduced with a drop of more than 80% with respect to the initial case.

![Cooling demand modification by the use of the evaporative cooling active roof.](image)

It is important to mention that for the calculation of the cooling demands, an interior temperature of 25°C is assumed. However, if indoor air temperatures of up to 27°C were accepted, the cooling demand would be practically negligible. For this case, air temperatures of 27°C may be perfectly acceptable since the ceiling is a cold surface, which will be approximately 2.5°C below the air temperature, so there will be an operating temperature of approximately 26°C that is a value in which a high percentage of the occupants will be in comfortable conditions.

6. Conclusions

The potential of evaporative active cooling roof in a building in Cádiz has been studied through simulations and with a previous reference experiment.

The results and previous experiences show that the use of this element of the envelope has the ability to remove heat from the interior since it maintain a surface temperature of approximately 2.5°C lower than that of the indoor air. This lower surface temperature has the added benefit of lowering the operative temperature, which increases comfort levels.

The simulations carried out show that the cooling demand on the top floor of the building studied is reduced by approximately 80%, which added to the fact that the operative temperature is reduced due to the effect of the cold surface, leads to the conclusion of that the demand for refrigeration, for practical purposes can be considered zero.
7. Acknowledgments

This study has been funded by the European Union’s Horizon 2020 Research and Innovation program under Grant Agreement No 768576 (RECO2ST project).

8. References


