# Experimental assessment of radiant panel for thermal conditioning of open spaces

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**Abstract.** Climate change resulting from the high emission of greenhouse gases has caused a continuous increase in the Earth's temperature, leading to an increase in the demand for refrigeration in the residential sector. Added to this is the heat island effect that generates even worse microclimatic conditions. Based on this idea, the CartujaQanat project was born, which seeks to recover life on the street by providing up-to-date solutions to combine the knowledge obtained from experience, tradition, innovation, and research. These solutions include reducing solar radiation, lowering the temperature of surrounding surfaces, and lowering the air temperature. Furthermore, this study explores a new concept of radiant solution adapted to outdoor spaces to improve thermal comfort and determine the radiant effect it provides since only radiant heat flux is relevant in open spaces with a low level of confinement of air. For this, the proposed solution is evaluated in a test cell to obtain its thermal behaviour under different operating conditions. Thanks to the experimentation carried out, it has been possible to obtain an inverse model to analyze the thermal behaviour of the solution. The inverse model obtained achieves high precision in its estimates and the possibility of fractioning the radiant and convective heat flux rate, allowing to evaluate the system's different operating conditions and know the solution's impact in open spaces. Thanks to this control of surface temperatures, an increase in thermal comfort by 40% is guaranteed. In addition, it prolongs the time of use of the open space, allowing attendees to be in comfort conditions for a longer period.

**Keywords.** thermal comfort, radiant system, open spaces, thermal adaptation.
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## 1. Introduction

The original concept of EXPO’92 [1] had as its main purpose that open spaces were the differential and cohesion component between the different pavilions of the venue. The function of the open spaces was not limited to a simple transition between the various pavilions. Still, they were spaces with their personality that favoured their use as outdoor leisure places where numerous activities were carried out. For this, it was necessary to develop innovative climate control techniques [2] to combat the high temperatures in the city of Seville in the summer, allowing those attending the venue to stay outside of the pavilions and carry out numerous activities in a situation of thermal comfort.

The climate control strategies developed depending on numerous factors and on the different characteristics of each outdoor space and its function. The longer the stay, the greater the intensity of conditioning. Actions that included confinement, solar control, surface cooling and air cooling were progressively used in many ways, including the later popularized micronization systems.

To recover the spirit of the climate conditioning works developed for EXPO’92, the CartujaQanat project was born. New technologies, materials, and modern and innovative design tools are introduced. From the social point of view, the project aims to be a catalyst, allowing citizens to enjoy open spaces during the warm months. High temperatures make practically any activity impossible.

The project takes place on Avenida Thomas Alba Edison, on Isla de la Cartuja (Seville). A new semi-confined space is being built, and an existing one is being rehabilitated, an amphitheatre located on the avenue itself and dating from the EXPO’ 92. The new space is known as the souk. The amphitheatre will be naturally conditioned to offer comfort conditions during the hottest months, obtaining a thermal jump of up to 10 ° C less than the outside temperature than the conditioned open spaces. As heat transfer fluid, water will be used, stored in two Qanat and cooled during the night thanks to the nocturnal use of environmental sinks [3]. During the day, this water is used to cool the air to be introduced in both spaces [4].

This work deals in detail with the characterization and applicability of a radiant panel. To do this, experimentally the results obtained from numerous experiments are analyzed and a simplified model is proposed, which allows determining the total heat flux absorbed from a series of input data.

In addition, the different modes of operation existing in the CartujaQanat project that allow the conditioning of the two rooms mentioned above are explained.

## 2. System description

### *2.1 System*

The radiant solution of this study is a modular solution, which facilitates the coupling of successive modules in parallel (figure 1). A module consists of meanders made by machine from multilayer composite pipe placed on a metal structure attached to the ceiling. Each module has dimensions of 1.6 m long by 0.33 m wide. The configuration adopted for the experiments presents 10 steps the tube for each module. The linear length of a 10-tube module is approximately 18 m with an outer diameter of 16 mm and 2 mm thick.

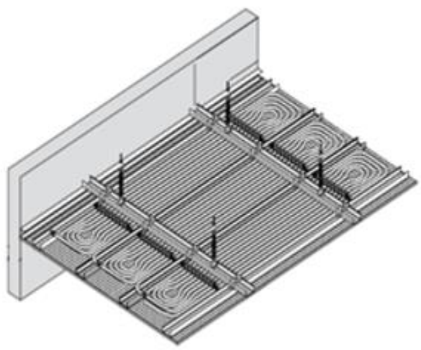

**Fig. 1 –** Three module coupling.

### *2.2 Experimental facility*

The experimental prototype to test the radiant solution deals with a modular solution, which facilitates the coupling of successive modules in parallel. It takes place in a test cell, located at the Eduardo Torroja Institute of Construction Sciences in the city of Madrid, Spain.

The proposed experimental prototype consists mainly of the radiant solution, a heat pump to cool or heat the water accumulated in the buffer tank and a pump in charge of driving the water from the buffer tank to the radiant solution through a collector of supply and return of the two available circuits.

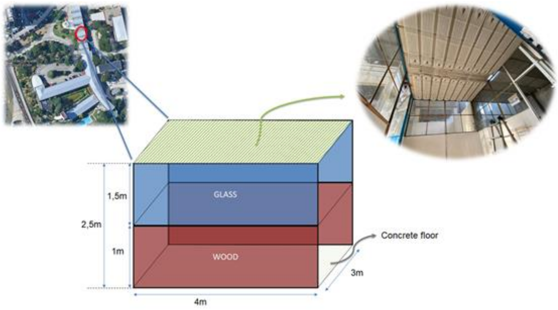


**Fig. 2 -** Layout.

The described System is fully monitored by multiple calibrated sensors coupled to a DAQ.

## 3. Methods: characterisation model

### *3.1 Theoretical basis*

The theoretical basis of the radiant system described are based on an energy balance. If the energy balance is carried out in an active roof system, wholly isolated from the top, the variation in water-energy refers to the thermal gains due to convection and radiation with the conditioned space ($Q_{cv} + Q_{rad}$).

Therefore, the energy variation of the water that circulates through the radiant cover is formulated according to equation 1:

$$m_w \cdot \rho_w \cdot Cp_w \cdot \frac{dT_w}{dt} = Q_{cv} + Q_{rad} \qquad \text{(eq.1)}$$

Where $m_w$ is the flow of water that circulates through the radiant cover, $\rho_w$ the density of water, $Cp_w$ the specific heat of the water, $\frac{dT_w}{dt}$ the difference in temperature between the inlet and outlet of the water of the radiant system, $Q_{cv}$ is the convective heat flux between the surface and the surrounding air, $Q_{rad}$ is the radiant heat flux between the surface and the rest of surface.

### *3.1 Model*

To predict the convective and radiant heat flux for the tested system, a model is formulated that allows determining the heat flux as a function of the discharge temperature, the projected air of the radiant roof based on the number of modules and the impulsion flow. Among the parameters to highlight of the model:

- The heat flux referred to as the radiant thermal gains are linearized, so the hypothesis is made that the representative temperature difference is less than 100K. Therefore, the error made when linearizing the radiation heat flux is acceptable [5].

- The convective heat coefficient is modelled based on the Morgan correlation for a long horizontal cylinder [6]:

$$h_{cv} = k \cdot LMTD_{cv}{}^{n} \qquad \text{(eq.2)}$$

Where the coefficients K and n are the parameters to be determined based on the data obtained from the experimentation of the experimental prototype.

# 4. Results

### *6.3 Identification of parameters and validation*

The experiments have been carried out for different water flow rates. As a first result, the variation of absorbed heat flux is obtained as a function of the water flow.

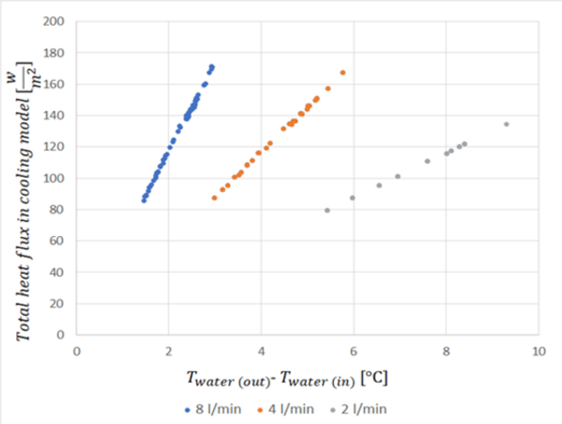


**Fig. 3 -** Total heat flux.

As this flow increases, the thermal jump between the water inlet and outlet is less.

To determine the absorbed radiant heat flux it is necessary to know the emissivity of the material. The manufacturer's data indicates that the emissivity is 0.85.

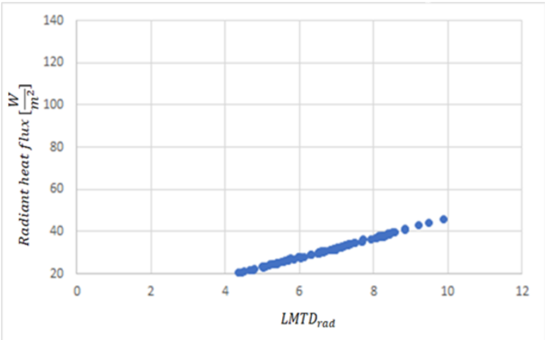


**Fig. 4 -** Radiant heat flux.

To determine the absorbed radiant heat flux it is necessary to know the emissivity of the material. The manufacturer's data indicates that the emissivity is 0.85. The absorbed radiant heat flux results vary linearly with the LMTD, which implies that the radiant transfer coefficient has a constant near value of 4.6 $\frac{W}{m^2 \cdot °C}$.

The following figure shows the results of the evolution of heat transfer by convection.

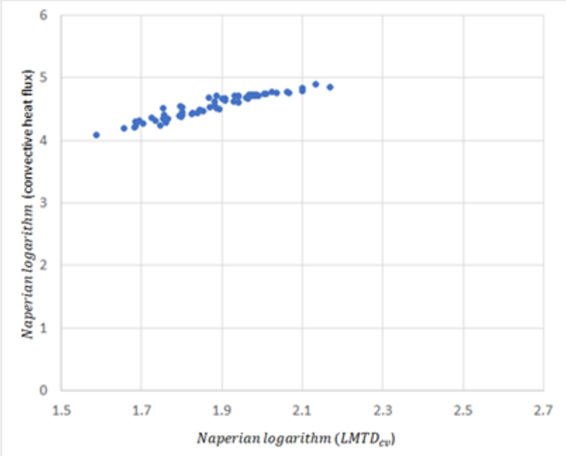


**Fig. 5 -** Obtaining model parameters.

It is possible to adjust the expression (eq. 2) using data from figure 5. Experimental data is divided into two groups: group 1 identifies the coefficients (40% of the experimental data) and group 2 validates the expressions (60% of the data). The coefficients for the cooling mode are

$$h_{cv} = e^{1.8127} \cdot LMTD_{cv}{}^{0.4596} \qquad \text{(eq.3)}$$

To verify that the expression obtained is valid, the model is run with a series of input data. The data obtained from the model are the water outlet temperature and the total heat flux absorbed. These are compared with experimental data to confirm the quality of the model obtained.

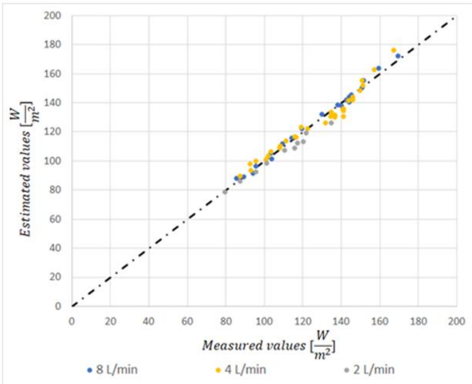


**Fig. 6 -** Estimated vs measured values – Heat flux

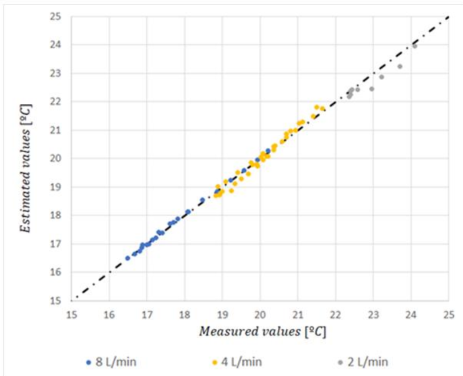


**Fig. 7 -** Estimated vs measured values – Water outlet temperature

Both the estimated total heat flux and the temperature of the water at the outlet show errors not exceeding 2% with respect to the experimental data. Therefore, the quality of the model is confirmed.

## 5. Applicability

Thanks to the previously exposed model, it is possible to estimate the thermal performance of the radiant panel in any operating condition. In the case of the souk, a newly built room in the CartujaQanat project, it is possible to determine the number of modules needed to install and size the cold-water production system. Figure 8 shows the souk and the installation site of the experienced radiant panel.

Since the radiant panel system studied has been assimilated its operation to that of a heat exchanger, the use of the NTU efficiency method is proposed for the applicability of the model. The results shown below have been calculated using a mean air temperature of 25 ° C, a mean radiant temperature of 24 ° C and an inlet water temperature of 15 ° C.


**Fig. 8 -** Design of climatic outdoor conditioning system by radiant surface in the souk.

In the first place, the efficiency of the system is evaluated for the three water flows studied based on the number of modules installed. If the water flow is the minimum, the maximum length per m2 of active surface is required to achieve the same efficiency as the other cases. This result allows deciding if it is more interesting a low operation cost (pumping cost) or a high initial cost.

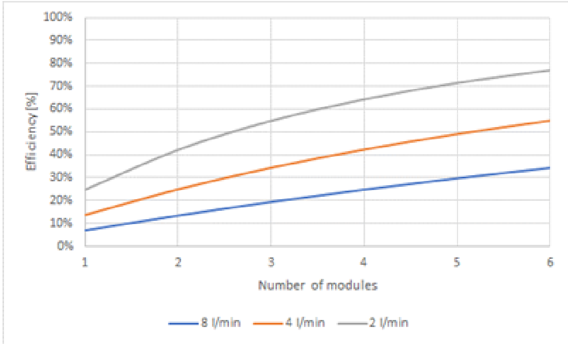


**Fig. 9 -** Efficiency vs number of modules.

The following result shows the variation of the efficiency as a function of the NTU

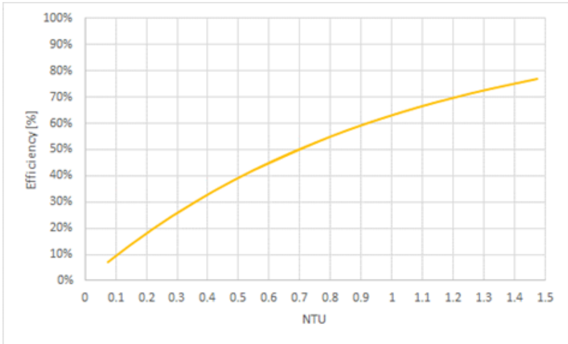


**Fig. 10 -** Efficiency vs NTU.

It follows that a higher NTU implies a greater linear length of tubes through which a low flow circulates.

In addition to the results before, ε-NTU procedure allows evaluating the results for a known solution (108 m of radiant exchanger and water flow of 2 $\frac{l}{min}$). The total absorbed heat flux is represented for different given radiant LMTD as a function of the convective LMTD.

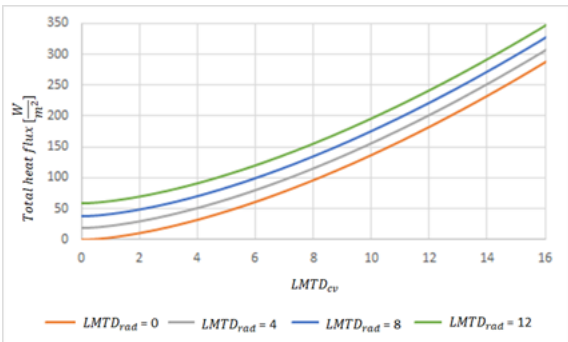

**Fig. 11 -** Total heat flux based on different DTLMs.

Thanks to this result, a pre-design of the radiant panel and the necessary auxiliary equipment is possible.

## 6. CartujaQanat operating modes

The operating modes of the installation for the natural conditioning of the rooms are:

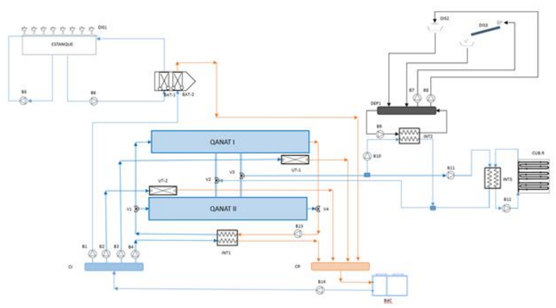

**Fig. 12 -** CartujaQanat hydraulic diagram

Mode 1. Nocturnal cooling of the water of the Qanats: The CartujaQanat project stands out for the use of natural thermal dissipation, thanks to the use of environmental heat sinks. For this, there are two dissipation systems, one placed on the aqueduct, which is made up of numerous nozzles placed along it in charge of cooling the water through the evaporative effect. On the other hand, there is a dual and innovative system such as the falling film on photovoltaic panels, in charge of producing the electrical energy of the installation during the day, which consists of throwing the water on the surface of these, obtaining a great evaporative cooling - radiant by using the sky as a heat sink.

Mode 2. Buried ducts: The new Qanat concept integrates buried ducts specially designed for cooling air during the day. The ground in the ducts is regenerated overnight using mode 5. The air from the buried ducts is strategically blown into the souk. In the event that the cooling is not sufficient, a water-fed terminal unit from the Qanats is available (mode 6).

Mode 3. Submerged ducts: The Qanats accumulation volume has 4 submerged ducts at two levels of depth. The air introduced through the upper ducts circulates from left to right, while through the lower ones it does so from right to left. With this, a better distribution of the blown air is achieved in the conditioned space.

Mode 4. Radiant roof: Installed in the souk, it aims to keep the roof temperature practically constant over 26-27 °C, thus guaranteeing the thermal comfort of the attendees.

Mode 5. Regeneration of the buried ducts: The air coming from outside at night is at a lower temperature than the ground, so its journey through the ducts gives the ground heat, cooling it. If the outside temperature is not low enough to cool the ground, a regenerative system is available by Qanat which performs an evaporative pre-cooling of the air to be introduced.

Mode 6. Terminal cooling: At the outlet of the buried conduits there is a battery powered by water from the Qanats.

Mode 7. AHU amphitheater: The conditioning of the amphitheater is given by the impulsion of cooled air through the air handling unit. The batteries receive the water from the cooled pond by means of mode 8, cooling the air as it passes and distributed in the amphitheater evenly from the front.

Mode 8. Pond dissipation system: The pond dissipation system consists of a set of nozzles on the surface of the pond at a certain height, which drive the water at high pressure, thus achieving the evaporation of part of the drop and therefore, cooling pond water.

At the technology level, the qanats stand out. The reinterpretation of the Qanat made for this project as a cold-water storage element and cold air production. The Qanats used are 40m long and are thermally insulated from the outside using low conductivity fillings and a vegetated surface treatment. 140 $m3$ of water (70m3 per Qanat) is naturally cooled every night from 25ºC to 19°C. This water is used to: cool 48600 $m3/h$ of air using buried and submerged ducts (mode 2 and 3); and cool the bottom surface of the souk using high density non-inertial radiant panels type Thermatop mode 4).

## 7. Conclusions

Obtaining a simplified model has allowed the development and evaluation of the radiant solution proposed for the CartujaQanat project. Results show that the radiant effect accounts for 40% of the system's energy consumption in summer conditions. On the other hand, it is possible to maintain the temperature of the surface practically homogeneous, guaranteeing the exchange of heat with the assistants.

The experimental facility has allowed thermal characterisation by a simplified model. Validation results confirm the high quality and precision of its estimations. The developed model allows obtaining the exchanged heat flow and the return temperature of the water as a function of the environmental conditions surrounding that active surface and the design and operation parameters of that solution.

The experimental results have tested the proposed system's efficiency and have allowed knowing the convective and radiant effects in detail. In addition, the proposed model provides the thermal response of the solution to variations in its design or operating conditions. So, different examples have been described in the discussion section. Furthermore, this application includes the usefulness of the model for decision-making in design phases or even optimal management of such solutions. Finally, it is possible to design the integration of the radiant system into a new space using the model developed.

## 8. Acknowledgement

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