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Integration of an innovative dual day-night technique for air conditioning of public spaces

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Abstract. The citizen has lost his place in the streets. Also, streets have become hostile and unlivable due to climate change and unsustainable urbanization. CartujaQanat project was born to mitigate the problems discussed. CartujaQanat is an innovative urban transformation project through which the use of the street as a social activator will be promoted, improving it and involving the city's entire ecosystem in this transformation. This new model of urban governance will serve as a facilitator for introducing these models in their expansion throughout the city to gradually change the appearance and functionality of the street concept and its future evolution in the next 15 years. So, this paper shows a set of solution for climatic control of outdoor conditions for two open public spaces in Seville. These techniques guarantee thermal comfort by the implementation of passive and adaptive bioclimatic solutions. The natural element of thermal dissipation is water, which will allow the air conditioning of spaces by cooling the air. One of the keys to the project is the cooling of water using the natural technique "falling-film". The water is driven from accumulation volumes by fan nozzles on the photovoltaic panels arranged on the installation roof, forming a falling film on them. This innovative technique allows the water to be cooled through a convective-radiant effect during the night thanks to the low temperature of the sky, obtaining promising results of thermal dissipation, whose dissipation heat varies depending on the flow width and length of the film travel. The duality of the system allows the cooling of water at night and the production of electricity during the day in order to guarantee a zero-energy balance in the installation.

Keywords. Falling-film, energy, natural techniques; thermal dissipation.
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1. Introduction

Global warming has caused the rapid growth of hot days and extreme weather, significantly increasing the demand for refrigeration [1]. This situation promotes the need to develop and use natural cooling techniques that reduce energy consumption, support the environment and the ecosystem and provide a satisfactory degree of comfort.

The CartujaQanat project is an innovative urban transformation project through which the use of the street as a social catalyst will be promoted, improved and involving the entire ecosystem of the city (public, private and citizen agents) in this transformation. This project is a continuation of the works started by Servando Álvarez Domínguez et al. [2] at the Universal Exhibition in the city of Seville in 1992, in which it seeks to innovate, improve and above all be able to integrate it into real projects and buildings.

This new urban governance model will serve as a facilitator for introducing these models in their expansion throughout the city to gradually change the appearance and functionality of the street concept and its future evolution in the next 15 years. A set of actions and elements will be developed that, integrated, act as social dynamizes. All this is to improve universal accessibility and ensure that superficial interventions on existing urbanization manage to reconfigure the urban planning. It is, therefore, an innovative urban design experience that will improve environmental comfort, promote social exchange and promote sustainable models of urban growth. The initiative is part of the Seville strategy in the fight against climate change, which has two main lines of action: developing strategies to adapt to climate change at the local level and recognizing the essential nature of the artery of the streets and neighbourhoods [3].

The execution of the project takes place on Thomas Alva Edison Avenue. This avenue is located in the city of Seville, specifically on the island of La Cartuja, where the 1992 universal exhibition took place. Buildings and open spaces were built for the universal exhibition. After the end of the event, some pavilions were dismantled by the exhibition participants, but the vast majority remain today. At present, the island of La Cartuja encompasses part of the infrastructure of the University of Seville, as well as numerous companies or institutions with a scientific - innovative nature.

Over the years, the Cartuja Science and Technology Park has grown, taking advantage of most of the buildings found on the island. However, the main objective continues to be to achieve a higher percentage of occupancy, which is why the growth margin of the said park continues to be enormous. The Expo left an architectural framework for business settlement and numerous public spaces surrounded by dense vegetation that, together with innovative and pioneering natural cooling techniques in the world, fought the extreme temperatures registered in the city of Seville during the summer season. The expensive maintenance of public spaces and the lack of funds caused them to be abandoned, so the vegetation and urban furniture have deteriorated over the years, completely disused by the inhabitants of the city of Seville.

The CartujaQanat project aims to rehabilitate, recover, and thermal condition an existing amphitheatre inherited from Expo 92 and create a new space called Zoco. Both spaces aim to guarantee the thermal comfort of their occupants through innovative natural conditioning techniques and the management of said energy through the use of thermal storage, where the star concept of the project stands out, which are the so-called "qanats."

This work focuses on corroborating that the falling film technology developed by Servando Álvarez Domínguez et al. [4] - [6] can be adapted to photovoltaic panels using a comprehensive opening fan nozzle solution, showing that the performance is identical, with the addition of solving the details of its implementation in the CartujaQanat project. This natural cooling technique, a falling film, uses water as a heat transfer fluid. Water is propelled from some volumes of accumulation by fan nozzles on the photovoltaic panels arranged on the installation roof, forming a falling water film on them. This innovative technique allows the water to be cooled through a convective-radiant effect during the night thanks to the low temperature of the sky, obtaining promising results of thermal dissipation, whose dissipation power varies depending on the flow width and length of the water film travel. The duality of the system allows the cooling of water at night and the production of electricity during the day to guarantee a zero-energy balance in the installation.

2. Methodology

The present study aims to show the design and evaluation of the integration of the falling film nocturnal dissipation system on photovoltaic panels [6]. The innovative character of this technology requires the development of a simplified model of energy characterization of the system that allows the evaluation of the system's potential under different operating conditions quickly and easily. In the particular case of the Cartuja Qanat project mentioned above, the simplified energy characterization model is required to evaluate the design and cooling potential of the natural cooling water stored in the accumulation volumes (qanats). Finally, about the system's design, the evaluation of the typology and arrangement of the nozzles is required to guarantee the optimal development of the falling film. In line with the previous objectives, this study first shows the description of the experimental prototype of the system under investigation. Second, given the integration of nozzles, the study of these is required, distinguishing the parameters of interest for their research. Third, the fundamentals of the simplified model developed are shown. Finally, the results show the simplified model obtained and the experimental tests associated with the integration of the falling film forming nozzles.

Fig. 1 – Recreation of the souk. Dual day-night technique on top.

3. Experimental prototype

To obtain the model's parameters, an experimental prototype of the falling film system is carried out based on the work of Guerrero et al. [6]. The experimental prototype said, shown in figure X, is described below:

1. Tank: storage tank for the volume of water to be cooled.

2. Water transport: The impulsion pipe conveys the water towards the impulsion nozzle; therefore, a circulation pump is necessary for this section. The return pipe gets the water from the collection gutter back to the storage tank. In this case, a pumping system is not required since the water circulates naturally towards the said reservoir.

3. Nozzle in charge of the impulsion: large opening fan nozzle located on the upper end of the drop panel. The large opening of the nozzle allows the water driven from the tank to bathe the panel thoroughly, forming a homogeneous water film.

4. Photovoltaic panel for lowering the water: a flat surface whose material has adequate characteristics for cooling by night radiation (low reflectivity and transmittance in the atmospheric window, which is equivalent to a high emissivity (approximately 0.90)).

5. Water collection gutter: gutter connected to the bottom of the drop panel. Said element is connected to the water return pipe to the tank.

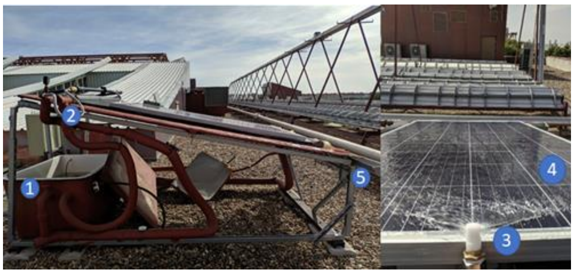


Fig. 2 - Experimental prototype of the falling-film system.

4. Study of nozzles

To determine which nozzle is adapted to the project's needs, a set of these are evaluated. The ideal nozzle for the application in the CartujaQanat project on photovoltaic panels must meet a series of characteristics that guarantee quality and formation of the complete falling water film, low operating pressure, which translates into energy savings on the part of the pressure equipment and a flow rate that optimizes the thermal dissipation of the falling film system. Another point to study and no less important is the arrangement of the nozzle for the photovoltaic panel, which must correspond to the most significant possible travel of the water film developed on the panel and low losses caused by the large opening of the nozzle or direct impact of the jet with the panel.

For this reason, for evaluating each of the nozzles, they are subjected to the following parameters to study:

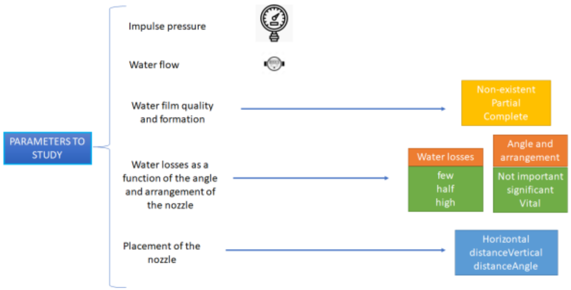


Fig. 3 - Nozzles study parameters.

5. Simplified model

The simplified model used is based on Guerrero et al. [4] - [7], which details the fundamentals of the model summarized here for calculating the water temperature in a solar collector. This simplified model performs a standard treatment of the convective-evaporative transfer, formulating the power dissipated in a falling film system according to equation 1.

$$P_d = Q_{cv-evap} + Q_{rad} \qquad \text{(eq.1)}$$

Where P_d is the total dissipation power of the falling water film system $\left(\frac{W}{m^2}\right)$, $Q_{cv-evap}$ the nocturnal cooling power referring to the heat loss due to convection and evaporating and Q_{rad} the nocturnal cooling power refers to the thermal losses by radiation with the sky.

The cooling power referred to the convective and evaporative thermal losses is formulated according to equation 2.

$$Q_{cv-evap} = h_{cv-evap} \cdot (T_w - T_{wb}) \qquad \text{(eq.2)}$$

Where $h_{cv-evap}$ is the convective-evaporative transfer coefficient of the water film $\left(\frac{W}{m^2 °C}\right)$, T_w is the water temperature (°C) and T_{wb} wet bulb temperature (°C).

The formulation associated with the radiation heat transfer between the water film, the surroundings and the sky is formulated according to equation 3. Since the form factor between the falling film system and the sky is practically unity, they are neglected radiant effects with the surroundings and given that the temperature difference between the water and the sky is less than 100K, it is possible to linearize the formulation developed in equation two so that the cooling power referred to the thermal losses by radiation. The sky is formulated according to equation 4.

$$Q_{rad} \left(\frac{W}{m^2}\right) = h_{rad} \cdot (T_w - T_{sky}) \qquad \text{(eq.3)}$$

$$h_{rad} = 4 \cdot \sigma \cdot \varepsilon \cdot \left(\frac{T_w + T_{sky}}{2}\right)^3 \qquad \text{(eq.4)}$$

Where h_{rad} is the radiant transfer coefficient of the water film $\left(\frac{W}{m^2 °C}\right)$, T_w is the water temperature (°C) and T_{sky} is the temperature of the sky(°C).

6. Results and discussion

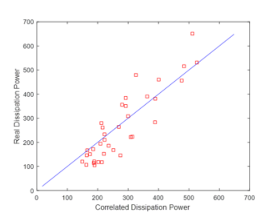
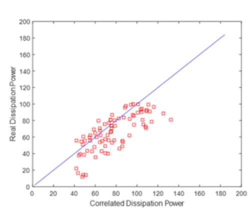
The experimental results obtained in the elaborated works [4] [6] show that the cooling of the water throughout the night presents a change of behaviour characterized by the variation of the thermal conditions of the water and the air. This evolution can be described in two sections:

- Section 1 characterizes the thermal dissipation of the system when the thermal conditions of the air and water cause evaporative cooling phenomena to occur, that is, when the air is not saturated.

- Section 2 characterizes the dissipation of the system given the radiant exchange with the sky once the air saturation has been reached. In this section, the convective transfer of water with saturated air can even counteract heat dissipation from the sky. The slope of the water cooling in said section is more attenuated.

Therefore, given the clear distinction of water cooling trends, the simplified characterization model parameters are obtained ($h_{cv-evap}$ and h_{rad}) in both sections. The proposed sectional model is shown below and the results of its experimental validation (Table 1). The values of the parameters obtained are valid for a dissipation area of 2.4 m^2 and a water circulation flow for cooling it of 1440 l/h.

Tab. 1 - Proposed simplified model (reference operating conditions) [4]

Section 1: Unsaturated air (Radiation+Convection+Evaporation)	Section 2: Saturated air (Radiation+Convection)
$P_d = 33.11 \cdot (T_w - T_{wb}) + 5 \cdot (T_w - T_{sky})$	$P_d = 3.44 \cdot (T_w - T_{wb}) + 5 \cdot (T_w - T_{sky})$
	

Given the definition h_{rad} according to equation 4, said radiant transfer coefficient varies with the temperature of the water and sky. According to the experiments' results, the values of h_{rad} obtained vary between 4.8 y 5.3 $\frac{W}{m^2 °C}$, so that the value of h_{rad} obtained from the experimental adjustment in both sections is within the expected range. In addition, the proposal made in detailed studies of the combined effect of heat and mass transfer has been revised. The proposed convective-evaporative heat transfer coefficient takes a value of 33.11 $\frac{W}{m^2 °C}$. This value, as discussed in the previous section, is understood as the net effect of the sum of convection and evaporation with the air. So if the approximation of the convective coefficient [7] is taken in the range of wind speeds measured between 0 and 2, we have a value that can range between 3-5 $\frac{W}{m^2 °C}$. In turn, the execution of the correlations [4] returns a value of the evaporative transfer coefficient between 18 and 45 $\frac{W}{m^2 °C}$. Therefore, the value of 33.11 can be considered within the expected range, and it is even proved that evaporation dominates the heat transfer with the surrounding air.

As mentioned above, the parameters' values are valid for a dissipation area of 2.4 m^2 and a water circulation flow for cooling of 1440 L/h. To analyze the variation in night-time dissipation power when modifying these operating conditions, its evolution is experimentally analyzed by varying the L/h·m^2 of system operation. Figure 3 shows the results obtained where an asymptotic behavior of the increase in night dissipation power can be observed from approximately 600 L/h·m^2

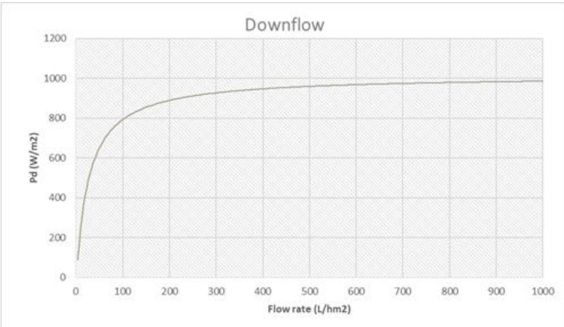


Fig. 4 - Variation of dissipation power as a function of operating conditions [4]

Taking as a reference the test conditions of the experimental prototype (600 L/h·m^2), the variation of the correction factor as a function of the operating conditions is shown in Figure 4.

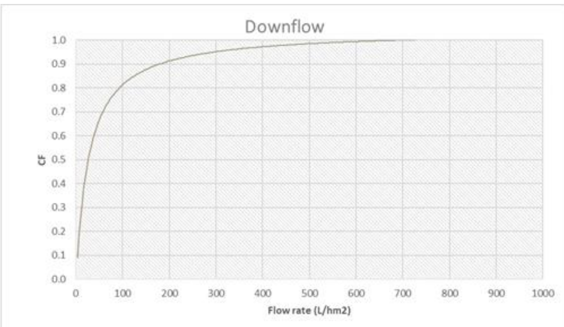


Fig. 5 - Correction factor for dissipation power as a function of operating conditions [4]

Therefore, the estimated night-time dissipation power corrected for the variation of the operating conditions of the reference system is formulated according to equation 5:

$$P_{d\_c} = P_d \cdot CF \qquad \text{(eq.5)}$$

Where P_d is the estimated night-time dissipation power for the reference system operating conditions as shown in table 1 and CF is the corrective factor associated with the variation in operating conditions $(\frac{L}{h \cdot m^2})$.

The correction factor associated with the variation in operating conditions is formulated according to equation 6:

$$F = 1 - a \cdot \exp\left(-b \cdot Flow\ rate\ (\tfrac{L}{\mathrm{h \cdot m^2}})^c\right) \qquad \text{(eq.6)}$$

The data graphed in figure 4 allow to identify the model presented in eq. 6. From this identification an almost perfect fit is obtained (correlation coefficients above 0.99, with a maximum relative error of less than 1%) with the values of the coefficients shown in table 2.

Tab. 2 - Coefficients of the correction factor calculation model CF=f (L/h· m²) [6].

Correction factor coefficients CF (ver eq. 8)	Best value	95% Confidence bounds
a	1.273	(1.237, 1.308)
b	0.1647	(0.1527, 0.1768)
c	0.5312	(0.5187, 0.5437)

After multiple experimental checks, it is determined that the following configuration is optimal, minimizing water losses due to side-impact and obtaining the best possible use of the panel surface:

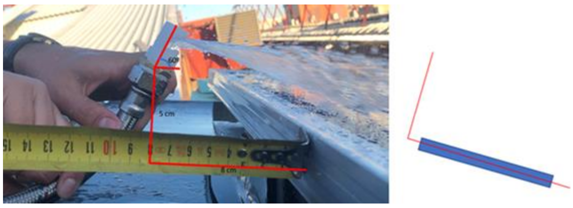


Fig. 6 - Optimal nozzle arrangement.

As seen in the image, the optimal configuration places the nozzle 8 cm away from the panel (axes shown) and at the height of 5 cm up to the head of the nozzle used. Regarding the angle, an inclination of 60º for the horizontal is estimated, guaranteeing that all the water is poured onto the panel and avoiding more significant losses due to the flight of the flow directly to the outside.

From the different tests carried out, the conclusion is drawn that the optimal nozzle to perform the desired function on the photovoltaic panels placed on the roof of a house must present the following technical data and placement on the panel:

Tab. 3 - Technical data of the selected nozzle

Nozzle	Pressure	Flow	Water film	Loss	Optimal Layout		
CW04	0.7 bar	16 l/min	Full	Low	8 cm horizontal	5 cm height	60° angle

- ➢ This placement of the nozzle allows that for lower pressures (up to 0.5 bar) it is guaranteed that the water is deposited on the panel in the same way, only varying the beginning of a fully developed falling water film.

- ➢ The lateral leak "only" is important in the panels placed on the sides on the roof of the souk since in consecutive panels, the water hits and jumps to the adjacent panel without generating losses. It is important to install lateral gutters to collect this water and avoid possible leaks between panels. For safety, implement channels under the photovoltaic to redirect potential losses to the central gutter.

- ➢ Regarding the panel used, it is proposed that these do not have a frame to avoid problems in the transition of the water film between consecutive panels, guaranteeing the continuity of the film as if it were a single panel.

7. Conclusions

The studies carried out at a theoretical and practical level allow natural cooling to implement a falling water film using wide-opening fan nozzles for their impulsion on the photovoltaic panels as thermal dissipation technology in the Cartuja Qanat project.

As demonstrated experimentally, the falling water film technique has a high cooling potential due to convective, radiant and evaporative transfer. Together with this, the low consumption of necessary water stands out, which is 7 and 8 times less than in the conventional evaporative cooling system. Therefore, the enormous interest of said technology in the project is demonstrated.

The results obtained on photovoltaic panels are similar to the enormous cooling potential of this nighttime natural dissipation technology, proposed by Guerrero et al. [5], which corroborates the integration of innovative dual technology, day-night, which combines electricity production during the day for the energy supply of the installation and the enormous thermal dissipation capacity of the falling film on the panels during the night.

8. Acknowledgement

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