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Cooling Average Potential of Evaporative Cooling System in Dry Warm Climate

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Abstract

The high summer temperatures, high solar radiation and common inadequate thermal design of buildings obliges the occupants to recur to the use cooling equipment such as evaporative air-conditioning to achieve acceptable levels of habitability. Evaporative cooling systems require considerable electric energy and a significant constant clean water supply during operation. Therefore, this paper presents the results of a field study aims to quantify in this kind of weather, the potential cooling means having the following strategies: indirect evaporative cooling and shading devices; indirect evaporative cooling, shading devices and thermal mass; indirect evaporative cooling, solar protection, thermal mass and nocturnal radiative cooling; indirect evaporative cooling, thermal insulation and nocturnal radiative cooling; and finally indirect evaporative cooling, thermal insulation, thermal mass and nocturnal radiative cooling. The method consisted of measuring the reduction in air temperature is achieved with each of these cooling strategies, applied in three research modules of same construction features, orientation and dimensions during the summer 2012.Then quantified the cooling average potential by the method proposed by Dr. Eduardo Gonzalez (1989). Finally registration was the water consumption with each of these strategies and estimated required consumption by direct evaporative cooling to achieve the same cooling potential. The results obtained indicate that the IEC/TI/NRC had cooling potential of 822.89 Wh/m^{2}day, followed IEC/SP with 764.19 Wh/m^{2}day and finally IEC/SP+TM 568.60 Wh/m^{2}day.

Keywords: Cooling Potential, Indirect evaporative, water consumption.

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1. Introduction

Chihuahua City is located at the north of the Mexican Republic at 28º 38' North latitude, 106º 06' West longitude and 1425 meters over sea level (figure 1). The climate is prone to extremes and is dry and hot, with an annual average maximum temperature of 26.94°C, an average of 18.9°C and a minimum of 10.87°C, with an annual thermal oscillation of 16.08°C. The average relative humidity is 52.4%, with minimum average of 14.4%. Rainfall is 385.1mm, with dominant winds from the Northeast with an average speed of 3.33m/s. The summer season is characterized for a dry-hot climate, with an average duration of 5 months (May to September).

Fig. 1. Mexican Republic. Source: INEGI, 2004.

The annual average of pluvial precipitation is close to 386 mm, equivalent to 110 billions of cubic meters. 88% of them are evaporated and 12% are drained [1]. This climate presents scarce rain and recurrent periods of drought. In agreement with information of the Comisión Nacional del Agua (CNA), Chihuahua suffered ten years of constant drought from 1993 to 2003.

This extreme climate demands that buildings apply design criteria that are consistent with the surrounding environment, so to satisfy in an adequate manner the needs for comfort of their inhabitants. Regardless, in a lot of cases these needs aren't satisfied, they are aggravated. This situation causes that during the warm season the users solve their air conditioning needs with the continuous use of artificial cooling equipment, usually direct evaporation (DEC), causing the significant increase of energy and water consumption. Unfortunately in this desert region the water resources are limited.

This research paper gives continuity to the results found in the doctorate thesis of Herrera, L. (2009) [2], where the feasibility of achieving water savings of the conventional DEC equipment was demonstrated, through the implementation of bioclimatic strategies in buildings. In this time the research project's objective is to evaluate systems of passive cooling applied to roofs to reduce the energy and water consumption, but they must have efficiency levels similar or better than the conventional system. The results which are presented in this document, were to evaluate the Average Cooling Potential (ACP) of five Passive Cooling Techniques (PCT) based in Indirect Evaporative Cooling (IEC) applied to the roofs of experimental cells in a dry hot climate; measure the water usage that the selected ACP require; and finally to compare these results with the normal performance of a DEC in the same circumstances. As a result of this comparison, the percentage of water savings that can be expected from the use of the evaluated ACP instead of DEC equipment could be determined. The techniques of cooling implemented via pond roofing evaluated are:

1) Experimental cell EC1: Indirect evaporative cooling with shading devices (IEC/SP)
2) Experimental cell EC2: Indirect evaporative cooling with shading devices and thermal mass (IEC/SP+TM).
3) Experimental cell EC3: Indirect evaporative cooling, thermal insulation, thermal mass and nocturnal radiative cooling (IEC/SP+TM/NRC).
4) Experimental cell EC4: Indirect evaporative cooling, thermal insulation, nocturnal radiative cooling (IEC/TI+NRC).
5) Experimental cell EC5: Indirect evaporative cooling with thermal insulation, nocturnal radiative cooling and thermal mass (IEC/TI+NRC/TM).

2. Method and materials

To evaluate the PCT a descriptive experimental research was done, based on the work method proposed by González, E. (1989) [3] and González, S. (2010) [4] for warm humid climates, consisting of field records of experimental modules with the same dimensions, materials and finishes.

For this project three experimental cells were employed. One functioned as a control cell (CM) without any ACP applied to it, while the other two were denominated experimental cell (EC), to which a metallic pond was installed at the top, and was modified according to each ACP's requirements, with the characteristics described in the works mentioned before were used. For this research, in the CM, air temperatures (Ti) and black globe temperature (Tg) were recorded. In the EC, exterior air (To) and interior air (Ti) temperatures, inferior surface of steel sheet temperature (Ts), black globe temperature (Tg), and indirect evaporative cooling water temperature (TwEEI) were measured.

The EC1 experiment, a ventilated pond made from sheets of galvanized steel was prepared, with a water film of 0.020m high (11 liters) and a shading devices put in place to diminish the incidence of solar rays over the pond (figure 2).

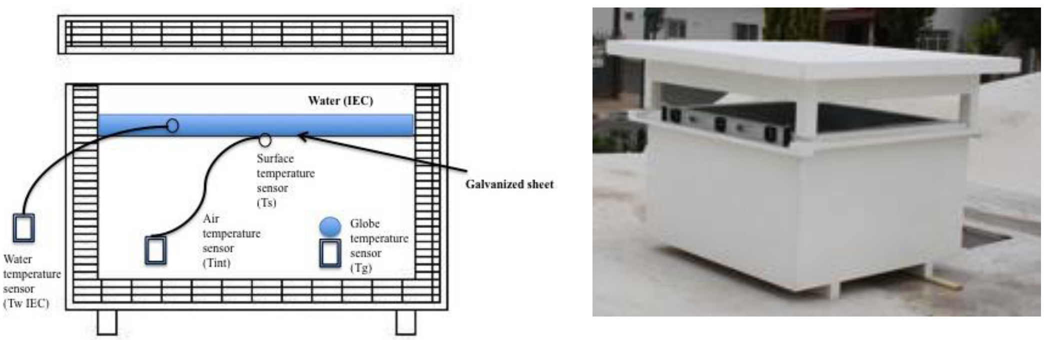

Fig. 2. EC1: IEC/SP

The experiment EC2 is a variation of the former one, but in this case a container of galvanized steel sheets with 30 liters of water (0.701 m high) was installed to act as thermal mass (TM). The water in this case was confined in the container with a galvanized steel sheet cover sealed with acrylic, as to avoid the contact between the water surface and the natural ventilation airflow. Over this container a film 0.020m high of water (11 liters) was poured, functioning as a pond. This second film of water was exposed to the ventilation flow and gave the system IEC. The only change for the EC3 was to remove the cover during the nighttime to bring about the radiative exchange with the sky, a strategy known as NRC (figure 3).

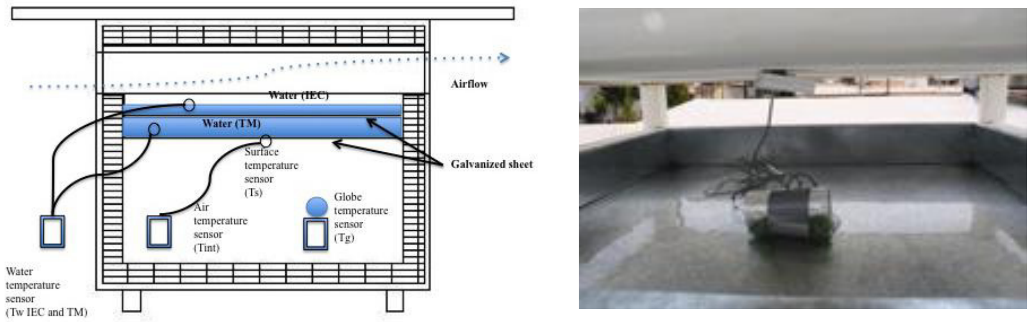

Fig. 3. EC2: IEC/SP+TM

In the EC4 experiment a pond made of galvanized steel sheets, with a water film 0.020m high (11 liters) insulated with a polystyrene plate 0.05m thick during the day and exposed to the air during the night to bring about radiative cooling (figure 4).

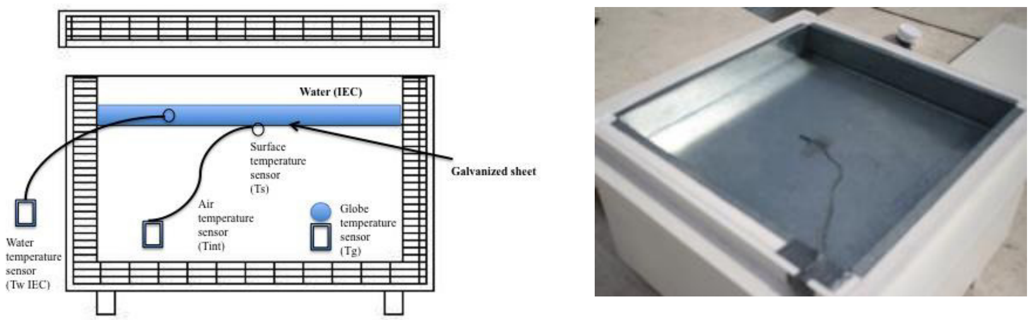

Fig. 4. EC3: IEC/TI+NRC

The experiment EC5 is a variation of the preceding one, but in this case a container of galvanized steel sheets with 30 liters of water (0.701 m high) was installed to act as thermal mass (TM) equal the EC2 (figure 5).

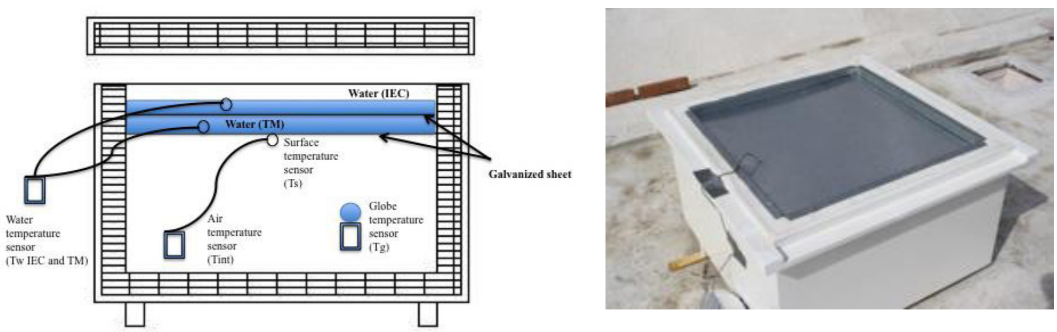

Fig. 5. EC4: IEC/TI+NRC

The average cooling potential (ACP) is defined as "the amount of energy per time and surface unit, able to be removed from the system, obtained as an average value during a 24 hour period" [5], and obtained through the next equation:

$$ACP = HLC * \frac{(TOPmc - TOPme)}{A} * 24 \qquad (1)$$

ACP= Average cooling potential Wh/m^{2}day

CPC = Heat loss coefficient = 1.50 W/m^{2}K [3]

$\overline{T}_{op}mc$= Average operative temperature of the control module for 24 hours, ^{o}C

$\overline{T}_{op}me$ =Average operative temperature of the experimental module for 24 hours, ^{o}C

A = Roof area (0.67 x 0.67m)= 0.4356 m^2

To estimate the water consumption that a conventional DEC equipment needs to reach the same temperature as the interior of the modules with an applied ACP, the method proposed by IMPCO (1999) [5] and proved by Herrera, L. (2009) [2] was used, who found a correlation of r=0.8 between field records and the calculations. This consumption refers to the water volume evaporated each hour in a DEC equipment to reach a given temperature. In this case the average of all the modules Top was used as a "design" temperature to be reached by the DEC equipment. The equation is as follows:

$$evap = \frac{Ecap * (Text - TOP\text{int}) * eff}{1222} \qquad (2)$$

$evap$ = Water volume evaporated each functioning hour by a DEC equipment, Lts/hr

$Ecap$ = DEC equipment capacity in cubic feet per minute = 3,800 cfm

$\overline{T}_{ext}$ = Average hourly temperature of exterior air in ºC

$\overline{T}_{op\,\text{int}}$ = Average operative hourly temperature inside the module in ºC

eff = Filter cooling efficiency = 0.50 (Herrera, L., 2009) [2]

Given that the IMPCO formula is solved for a space to be cooled with a useable surface of 38m2, the result obtained from equation 3 was adjusted to the surface corresponding to the interior space in the experimental modules, which is de 0.64 m2 (0.80 x 0.80 m), through the next procedure:

$$Vw = \frac{Evap * 0.64}{38} \qquad (3)$$

V_w = Water volume evaporated each hour by a functioning EED equipment in an experimental module.

The measuring was done during the summer season of 2012 (June to September). Each studied ACP was monitored during 72 consecutive hours (3 days), with data entries every 15 minutes. The monitoring equipment were data loggers of the HOBO kind from Onset Computer Co., models H08-004, H08-032-08 and U12-013 provided with dry bulb temperature sensors (Tbs), wet bulb temperature (Tbh), black globe temperature (Tg), and a TMC6-HD cable for the water temperature register (Tw). The measurements obtained with this equipment can be considered as class I according to the ISO 7726 norm [6], based on the precision and range of operations with which they work.

3. Results

3.1. Experiment EC1: IEC/SP. The recorded operative temperature inside the EC1 (TopIEC/SP) was always inferior to the exterior temperature (To) (an average of 9.9ºC) and the operative temperature of the control cell (TopCM) (an average of 8.8ºC). This difference is accentuated in the case of maximum temperature, when in the EC1 average temperature is 11.7 ºC lower than the exterior and 14.6ºC lower than what the CC recorded. The difference between the minimum temperatures is less, 7.1ºC against the exterior and 4.6ºC with the CM. The Top of the EC1 runs very closely to the pond water temperature (TwIEC), an average of 1.6ºC above (figure 6).

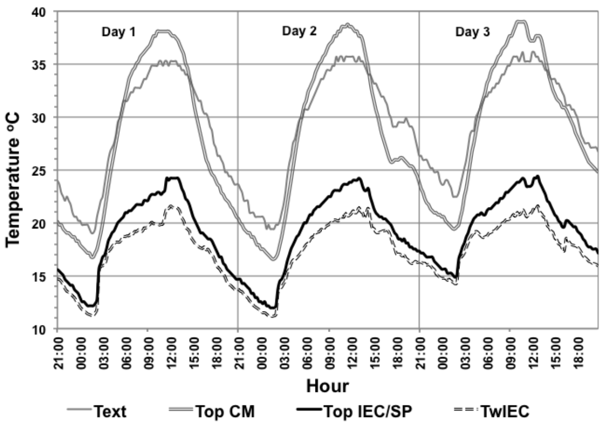

Fig. 6. Data recorded in EC1.

3.2. Experiment EC2: IEC/SD+TM. The recorded operative temperature inside the EC2 (TopIEC/SP+TM) was always inferior to the exterior temperature (To) (an average of 7.5ºC) and the operative temperature of the control cell (TopCM) (an average of 8.0ºC). This difference is accentuated in the case of maximum temperature, when in the EC2 the average temperature is 11.7ºC lower than the exterior and 15.9ºC lower than what the CM recorded. The difference between the minimum temperatures is relevant, 3.6ºC against the exterior and 1.3ºC with the CM. The Top of the EC2 runs very closely to the pond water temperature (TwIEC), an average of 1.3ºC above, while it runs 1ºC above (TWTM) (figure 7).

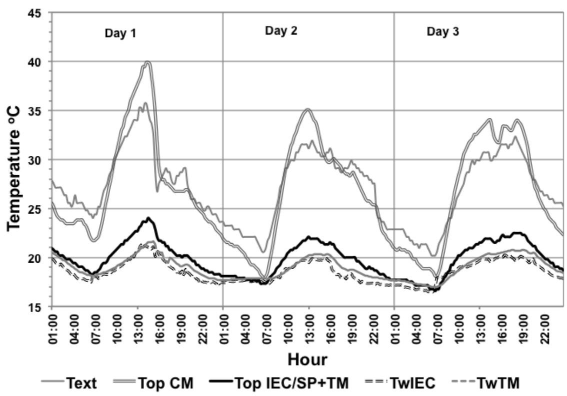

Fig. 7. Data recorded in EC2.

3.3. Experiment EC3: IEC/SD+TM/NRC. The recorded operative temperature inside the EC3 (TopIEC/SP+TM/NRC) was always inferior to the exterior temperature (To) (an average of 5.9ºC) and the operative temperature of the control cell (TopCM) (an average of 2.1ºC). This difference is accentuated in the case of maximum temperature, when in the EC3 the average temperature is 8.6ºC lower than what the CM recorded. The difference between the minimum temperatures is less, but relevant, 3.6ºC against the exterior and 1.9ºC with the CM. On the other hand, the Top of the EC3 runs very closely to the pond water temperature (TwIEC), an average of 0.2ºC above (figure 8).

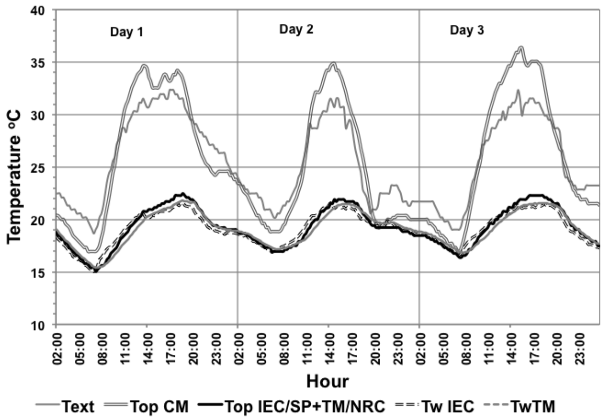

Fig. 8. Data recorded in EC3

3.4. Experiment EC4: IEC/TI+NRC. The recorded operative temperature inside the EC4 (TopIEC/TI+NRC) was always inferior to the exterior temperature (To) (an average of 8.43ºC) and the operative temperature of the control cell (TopCM) (an average of 8.2 ºC). This difference is accentuated in the case of minimum temperature, when in the EC4 the average temperature is 10.3ºC lower than the exterior and 7.1ºC than what the CM recorded. The difference between the maximum temperature is less, but relevant, 4.0ºC against the exterior and 7.4ºC with the CM. On the other hand, the Top of the EC4 runs very closely to the pond water temperature (TwIEC), an average of 1.4ºC above (figure 9).

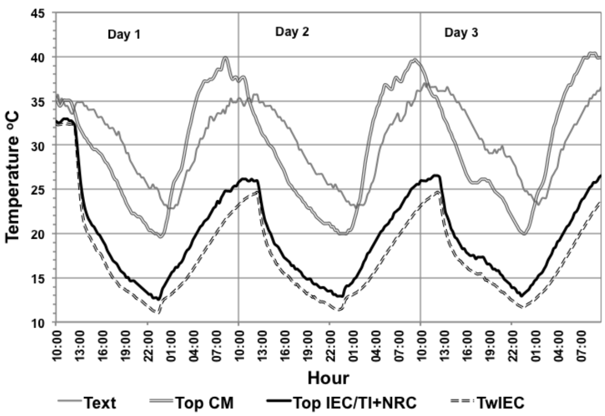

Fig. 9. Data recorded in EC4.

3.5. Experiment EC5: IEC/TI+NRC/TM. The recorded operative temperature inside the experimental module EC5 (TopIEC/TI+NRC/TM) was always inferior to the exterior temperature (To) (an average of

6.7 ºC) and the operative temperature of the control cell (TopCM) (an average of 7.4 ºC). This difference is accentuated in the case of maximum temperature, when in the EC5 the average temperature is 9.9 ºC lower than the exterior and 13.9 ºC lower than what the CM recorded. The difference between the minimum temperature is less, 3.6 ºC against the exterior and 1.9 ºC with the CC. The Top of the EC5 runs very closely to the pond water temperature (TwIEC), an average of 0.7 ºC above, while it runs 0.8 ºC over the (TwTM) (figure 10).

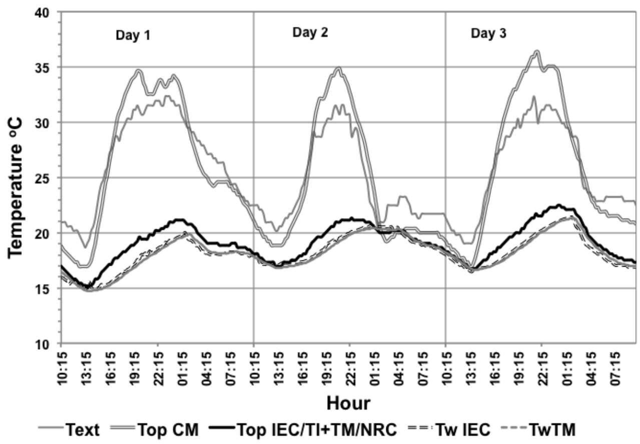

Fig. 10. Data recorded in EC5.

4. Average cooling potential (ACP)

The average cooling potential (ACP) was obtained from the average operative temperature values inside the control modules and the experimental modules, each from the experiments and the analysis. The analysis was done every 24 hours and then the three obtained results were averaged to determine the corresponding ACP of each PCT experiment.

As a result, it was observed that the experiment EC4 was the one that performed better with an index of 822.89 Wh/m2day, followed by EC1 with 764.60 Wh/m2day, then EC5 with 532.78 Wh/m2day. All TEP were upper the 500 Wh/m2day (table 1). It's also timely to mention that the galvanized sheet of the roof pond wasn't painted white, which lessens the cooling ability during the nocturne radiative exchange (Givoni, B., 1994) [7].

Table 1. Average cooling potential (ACP) calculated from the data obtained in each experiment. Source: prepared by the authors

Experiment	*ACP (Wh/m^{2}day)*
EC1	764.19
EC2	568.60
EC3	514.60
EC4	822.89
EC5	532.78

4.1. Evaporated water volumes

The TEP with good performance regarding ACP with natural ventilation, are also the ones that use the most water: EC1 with a 0.163 lts/hr and EC2 with 0.133 lts/hr. Instead, the ACP with insulation don't have such a high consumption: EC4 and EC5 with 0.028 and 0.2 lts/hr each (table 2).

Table 2. Evaporated water volumes in each experiment. Source: prepared by the authors.

Experiment	*Total (lts)*	*Average (lts/hr)*
EC1	11.71	0.163
EC2	9.54	0.133
EC3	5.64	0.078
EC4	2.00	0.028
EC5	1.40	0.020

The water volume that would be required in a DEC equipment to reach the average operative temperature achieved through the ACP was estimated through the pair of formulas 3 and 4.

The relationship between the equivalent performances from the water volumes to evaporate of table 3 doesn't result linear regarding the values of "design" of the reached by the ACP, because in the calculating process there intervenes the average exterior temperature (To) that was recorded during each experiment (table3).

Table 3. Water volumes calculated for DEC equipment with a design temperature equivalent to the average of the Top registered in each experiment. Source: prepared by the authors.

Experiment	$\overline{T}_{op}$ *(ºC)*	*Equivalent volumen of wáter to evaporate*	
		Total (lts)	*Average (lts/hr)*
EC1	19.11	18.96	0.228
EC2	19.85	13.55	0.163
EC3	19.25	20.63	0.247
EC4	19.55	12.16	0.147
EC5	19.07	11.76	0.142

4.2. Water savings

Once the evaporated water volumes were known, both by the work of the PCT in the experimental modules, and the estimated equivalent by the DEC equipment, a water savings percentage was calculated for each PCT (table 4).

Table 4. Water savings by PCT in comparison with the ACP achieved. Source: prepared by the authors.

Experiment	*ACP (Wh/m2día)*	*Water volume by PCT evaporate (Lts/hr)*	*Equivalent volume of water to evaporate by DEC equipment (Lts/hr)*	*Saving Water (%)*
EC1	764.19	0.163	0.263	38.23
EC2	568.60	0.133	0.188	29.59
EC3	514.60	0.078	0.287	72.66
EC4	822.89	0.028	0.169	83.55
EC5	532.78	0.020	0.163	88.10

It's evident that the PCT that contribute to the biggest water savings are associated with the TI and NRC with savings beyond the 80 % (EC3 with 48.9 % and EC5 with 88.10 %). This is because a big part of the cooling job is done without the need to propitiate the change of state of water, instead it's done through radiative exchange, and so the water performance is superior. Instead, the TEP with a smaller potential for water savings are those that make the TM and airflow part of the buffering-cooling job (EC4 with 83.55 % y EC5 con 88.10 %). Nonetheless it's important to note that all the TEP indicate water savings.

Conclusions

This research reaffirms that in arid climates, evaporating water is the best cooling technique possible. This is because such techniques don't need to add great quantities of humidity to the environment or speed up the airflow in the interior space. The evaporation is conditional only to the one done in a natural way, based on low and passive energies that have a smaller volume than what a conventional DEC needs to evaporate to achieve the same results.

This research reaffirms that the pond roof, as any other body exposed to the night sky, looses heat by long wave radiation emissions, and reaches a maximum cooling and water savings potential, product of a clear sky and low specific humidity characteristic to this arid climate.

The water contained as thermal mass wasn't efficient as a cooling technique because its thickness was insufficient. Nevertheless, though it reduces the ACP value, it amplifies the duration of the average temperature, always close to the roof pond water's temperature.

The roof pond technique as an strategy for water saving applied to arid dry climates shows that their cooling efficiency could completely replace the use of conventional direct evaporation cooling equipment with less use of water.

It's necessary to expand the research of these techniques of roof ponds and apply them to inhabited buildings to find which of them has the greatest commercial use viability.

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