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Passive evaporative cooling through water-filled bricks: a preliminary investigation

A Tejero-González[1], F Nocera[2], V Costanzo[2] and E Velasco-Gómez[1]

[1] Dept. Energy Engineering and Fluidmechanics, Universidad de Valladolid, Paseo del Cauce, No.59 (47011) Valladolid, Spain
[2] Dept. Civil Engineering and Architecture (DICAR), University of Catania, Via Santa Sofia 64, 95125, Catania

anatej@eii.uva.es

Abstract. Direct evaporative cooling is widely known to be an energy efficient air-conditioning option for arid and semi-arid climates. However, care must be taken on humidity ranges achieved indoors. Existing literature presents several options for integrating evaporative cooling within buildings for passive cooling applications. This work aims at expanding the current knowledge by focusing on the use of water-filled hollow bricks to implement evaporative cooling of air in contact with the brick's surfaces. A prototype is built and experimentally characterized under controlled air velocity, air temperature and relative humidity conditions. Results on the psychrometric conditions achieved under different geometric arrangements (i.e., with one, two or three rows of four bricks each) are presented and discussed. Insights on likely building integration of the system for passive cooling purposes in farms and agriculture applications are eventually given.

1. Introduction

Evaporative cooling systems are based on the natural conversion of sensible heat into latent heat when non-saturated air is exposed to water. Their simplicity made them the first inexpensive air conditioning equipment [1]. Within the current concern on the energy consumption and the uncertain climate change scenarios, evaporative cooling rises as an energy efficient alternative to either reach indoor thermal comfort or reduce the energy demand of conventional air conditioning [2].

Direct Evaporative Cooling (DEC) can be implemented either from wetted surface materials or with spray nozzles. DEC from wetted surfaces has, however, the advantage of avoiding direct generation of aerosols, though water entrainment may occur at high velocities [3]. Although it would not be applicable for indoor thermal comfort under ambient wet bulb temperatures above approximately 21 °C, it can still satisfactorily relieve indoor conditions in greenhouses, industrial plants and other spaces not dedicated to human occupation [4].

Ceramic materials have several advantages for wetted-media DEC not only because of their capability to hold large quantities of water, but also because they neither degrade when humidified nor suffer from chemical degradation when exposed to the outdoors [5–8]. Indeed, evaporative cooling from ceramic surfaces has been widely used in hot and dry locations worldwide both for improving thermal comfort and for food storing and conservation [9,10]. Moreover, the hygrothermal performance of porous construction materials have been widely studied as well [11–14].

Existing research on DEC has also targeted such materials: Laknizi et al. [15] built an evaporative cooling pad made of clay cylinders achieving temperature drops of up to 6.4 and 7 °C with an increase in the air relative humidity between about 28 and 32 %. Doğramaci and Aydin [8] studied the performance of ceramic pipes as the wetted surface for DEC, as well as other materials. The achieved temperature drops reached 10.7 °C to 4 °C for increased air velocity from 0.1 m/s to 1.2 m/s. Abdullah et al. [16] also used clay cylinders, but covered by jute fiber and integrated in a wind tower to enhance natural ventilation. They achieved temperature drops between 9.7°C and 19.8°C.

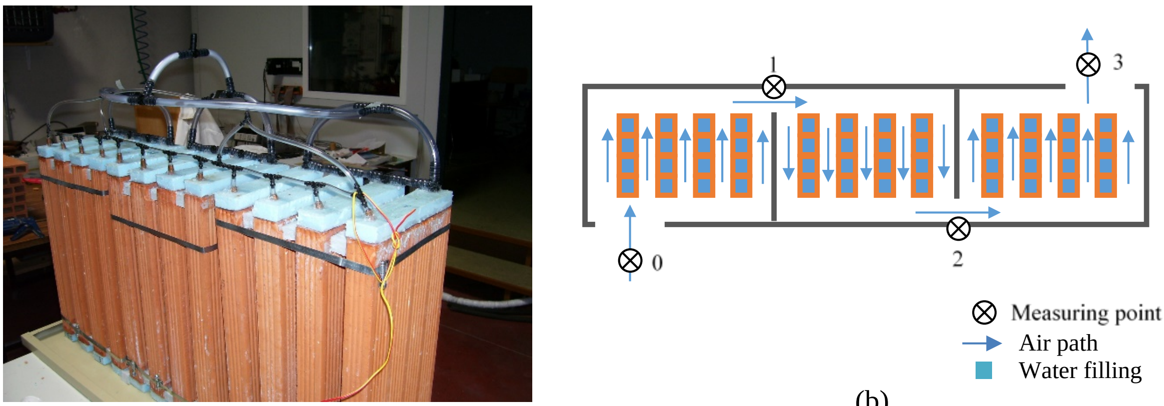
On the other hand, some authors resorted to ceramic surfaces to achieve a semi-indirect evaporative cooling of treated air. Velasco-Gómez et al. [17] proposed a ceramic pipes cross-flow heat exchanger to be integrated as an air window system where the secondary airstream moves inside the pipes counter flow to water. Similar prototypes were designed by Sun et al. [18] and Zeitoun et al. [19], though the latter did not aim at achieving thermal comfort but humidifying the gas turbines inlet air.. Ibrahim et al. [20] designed a hollowed ceramic evaporator and studied the effect that different levels of porosity had on the temperature drop and relative humidity increase.

Existing literature also approaches the integration of DEC wetted ceramic surfaces within passive cooling strategies in both outdoor and indoor spaces. He and Hoyano [6,7] built and characterized a passive wall made of ceramic bricks with the aim of providing shading and evaporative cooling outdoors. A similar system was proposed and studied through laboratory experiments by Chen et al. [21]. Sudprasert and Sankaewthong [22] used rice byproducts to produce porous cylinders to be integrated in agricultural houses and outdoor spaces. Bagasi and Calautit [23] studied the effect of water pots placed in the traditional Arab-Islamic Mashrabiya, which enabled ventilation, daylight and privacy.

Within this context, the aim of this research is to give a first insight on the applicability of DEC from hollow bricks filled with water in farms and agriculture buildings. To this purpose, experimental results conducted on three different configurations of a prototype are provided, where air velocity, air temperature and relative humidity conditions are controlled at the system inlet.

2. Experimental setup

A DEC from wetted surface prototype has been designed and built with hollow bricks typically used for partition walls. A photo and schematic of the prototpye is shown in Figure 1..



(a) (b)

Figure 1. (a) Experimental setup using and (b) schematic of prototype DEC made of hollow bricks.

Bricks are kept filled with water from an upper tank, while air is forced to pass through three paths of four bricks each. Inlet air psychrometric conditions at each test are achieved in an air handling unit equipped with a steam humidifier. Experimental tests are conducted for three air volume flow levels (approximately V_1 = 240, V_2 = 370, V_3 = 530 m^3/h) and five dry bulb air temperatures, To (T_{01}=20, T_{02}=25, T_{03}=30, T_{04}=35 and T_{05}=40 °C). Given the geometry of the device, the inlet air volume flows tested yield air face velocities of approximately 1, 1.5 and 2.2 m/s.

Inlet air humidity is uncontrolled but modified through vapor injection in three steps: no vapor injection, 1.2 kW vapor injection and 2.4 kW vapor injection respectively. Tests without vapor injection at each airflow rate and dry bulb air temperature are repeated once to check the repeatability of results. This design of experiments yielded 60 tests. However, three test conditions at the lowest air volume flow rate V_1 resulted into saturation of inlet air (for 1.2 kW and 2.4 kW vapor injection at 20 °C, and for 2.4 kW vapor injection at 25 °C in order), thus those results were not included in the present study.

Dry bulb air temperature and relative humidity are measured at the system inlet (point 0) and after each bricks path (points 1, 2 and 3 of Figure 1 respectively). The temperature sensors used are 4-wire Pt100 from RS with accuracy of ±0.1°C and range from -50 to +250°C, while capacitive RH sensors from Honeywell are used for measuring the air relative humidity (accuracy ±2%, range 0-100%). Air volume flow (V) is determined by measuring the pressure drop (ΔP) at orifice plates that were previously calibrated with a calibration nozzle model TG-50 from Tecner Ingenieria. The air flow $\dot{V}$(m^3·s^{-1}) is thus determined at the system's inlet (0) according to equation 1:

$$\dot{V} = K_V \cdot \sqrt{\Delta P} \tag{1}$$

Where the constant K_V is equal to 0.0065 and ΔP is the inlet/outlet pressure difference in Pa.

The performance of the system is evaluated using its saturation effectiveness, defined in Equation 2 as follows:

$$\varepsilon = \frac{T_0 - T_1}{T_0 - T_{WB0}} \cdot 100 \tag{2}$$

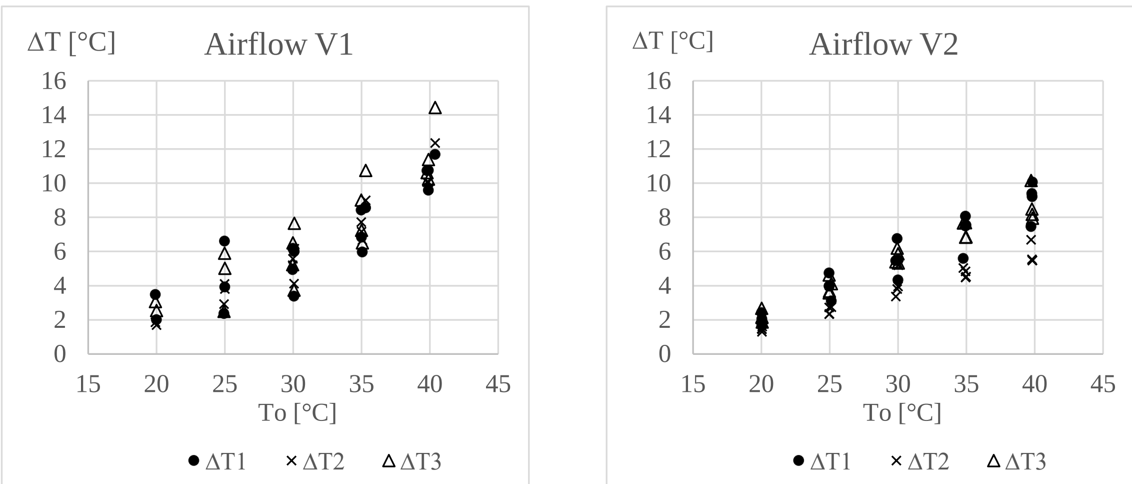
Here, T (°C) refers to dry bulb air temperature and T_{WB} (°C) corresponds to the wet bulb air temperature, while 0 identifies the inlet air conditions and 1 the air conditions measured after the first four-bricks row.To further substantiate the performances of the proposed system, the cooling capacity (CC) of the system is calculated according to equation 3:

$$CC = \dot{m} \cdot C_p \cdot (T_0 - T_1) \tag{3}$$

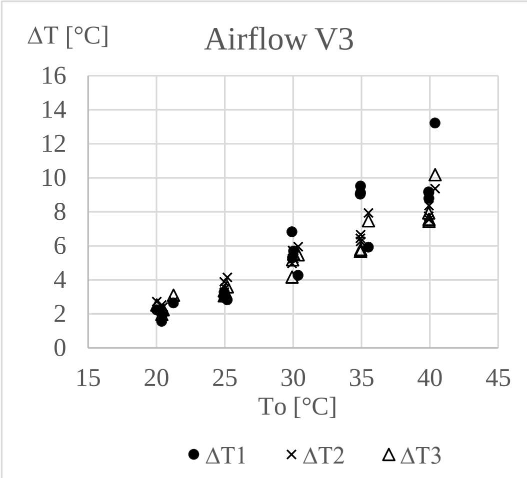
Being Cp the specific heat of humid air (J·kg^{-1}·K^{-1}).

3. Results

Figure 2 shows the average dry bulb air temperature drops achieved during steady-state operation for each airflow level with respect to the inlet dry bulb air temperature. Results measured at points 1, 2 and 3 during each test are thus plotted to analyze the effects of driving the air through just one, two or three rows of bricks respectively. Average values and standard deviations obtained are gathered in Table 1.



(a) (b)



(c)

Figure 2. Temperature drop measured at point 1, 2 and 3 for (a) airflow level V1, (b) airflow level V2, and (c) airflow level V3.

Table 1. Average and standard deviation of measured temperature drops.

		V1			V2			V3		
		ΔT1	ΔT2	ΔT3	ΔT1	ΔT2	ΔT3	ΔT1	ΔT2	ΔT3
T_{01}=20°C	Average	2.7	1.8	2.8	4.1	2.5	3.7	3.9	3.9	3.8
	Standard dev.	1.0	0.1	0.4	4.0	2.0	2.9	3.3	2.5	2.4
T_{02}=25°C	Average	4.3	3.6	4.5	3.9	2.5	4.0	3.0	3.7	3.3
	Standard dev.	2.1	0.6	1.8	0.7	0.2	0.5	0.2	0.4	0.2
T_{03}=30°C	Average	5.1	5.3	5.8	5.5	4.1	5.7	5.5	5.5	5.1
	Standard dev.	1.3	0.9	1.7	1.0	0.8	0.4	1.1	0.4	0.6
T_{04}=35°C	Average	7.4	7.6	8.4	7.2	4.7	7.2	8.4	6.8	6.2
	Standard dev.	1.3	1.0	1.9	1.1	0.3	0.5	1.7	0.8	0.9
T_{05}=40°C	Average	10.7	10.5	11.7	9.0	5.8	8.7	10.1	8.2	8.3
	Standard dev.	0.9	1.2	1.9	1.1	0.6	1.0	2.1	0.8	1.3

It appears that the maximum temperature drops achieved after the first path are 11.7 °C, 10.1 °C and 13.2 °C for airflow levels V1, V2 and V3, respectively, while it can also be seen that the temperature drop achievable increases for warmer inlet air conditions and decreases for larger airflows due to the lower residence times. However, there are no clear differences between the temperature drops achieved after one, two or three paths through bricks (ΔT1, ΔT2 and ΔT3); consequently, one single brick row would be enough. This can be explained by the fact that relative humidity measurements taken after each row of bricks show that the air does not get further humidified when passing through the second and third groups of bricks. For instance, at the highest airflow rate V3, T_{05} and no vapor injection, the air relative humidity values after the first, second and third group of bricks (points 1, 2 and 3) are 42%, 37% and 41% respectively, which falls within the uncertainty introduced by the accuracy of the sensors. Figure 3 reports such information at both the inlet (panel a) and after the first row of bricks (point 1) with varying to the inlet dry bulb air temperature and air flow rate values.

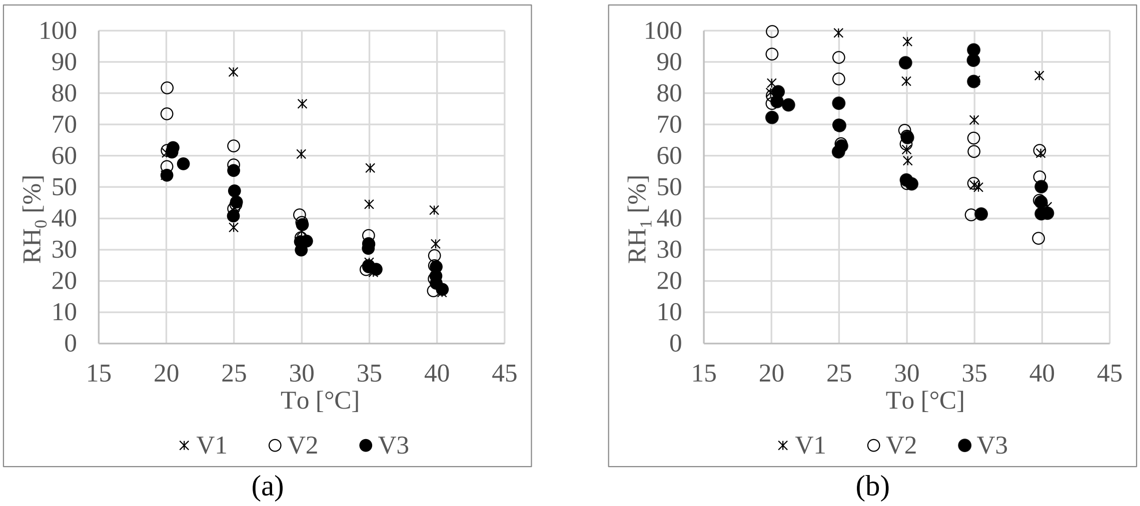


Figure 3. Air Relative Humidity at (a) the system inlet (point 0) and (b) outlet after one path through bricks (point 1) for different airflows and air inlet air dry bulb temperatures.

The calculated saturation effectiveness is shown in Figure 4. As expected, it decreases for higher airflows due to the lower air residence times and is not affected that much by the inlet air psychrometric conditions.

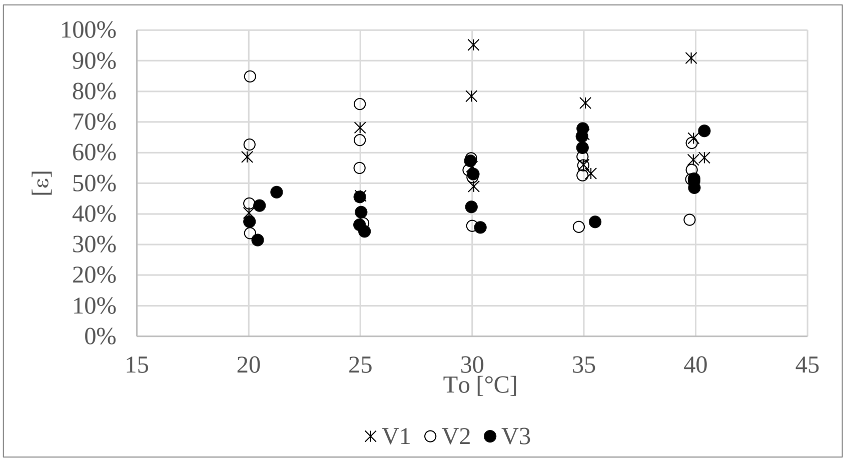


Figure 4. Saturation effectiveness after one path for different airflows and air inlet conditions.

Results reported in Figure 5 show instead the cooling capacity of the system. As it is possible to observe, higher airflows imply larger cooling despite the decrease in the temperature drop achievable.

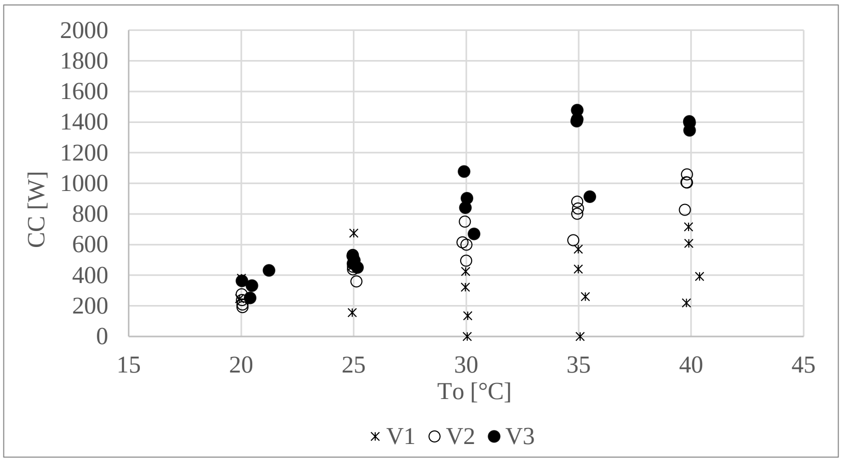


Figure 5. Cooling capacity after one path for different airflows and air inlet conditions.

4. Discussion of the results and prospective applications

Results from this study showed that the saturation effectiveness of the proposed DEC system decreases with increasing airflows: e.g., for an inlet air temperature of 40 °C, it drops down from around 90% to less than 70 % when passing from 240 m^3/h to 530 m^3/h. On the other hand, the effectiveness is not affected significantly by the inlet humid air conditions, and this aligns with previous research [6-7]. Nonetheless, the higher air flow rates strongly benefit the cooling capacity of the system, which passes from 200 W for an air flow rate of 240 m^3/h to 1400 W for an air flow rate of 530 m^3/h under the same inlet air temperature of 40 °C.

More interestingly, this research showed that the simplest configuration made up of a single row of clay bricks continuously filled with water from the top provides dry bulb air temperature drops similar to those obtainable when two or three rows of bricks are implemented. In fact, the maximum temperature drop has been achieved for the highest inlet air temperature of 40 °C and the lowest air flow rate of 240 m^3/h tested, and ranged between 10 °C and 12 °C for the one row and three rows configurations, respectively.

Potential applications of the proposed DEC system may take place in farms, e.g. in breeding batteries to relieve animals from excessively high air temperatures while also improving the working conditions of farmers, or in other production or transformation activities where indoor air conditions do not need to be strictly controlled (as already reported by Sudprasert and Sankaewthong [22] for a silkworm rearing house). A further utilization of the system may be envisaged for improving comfort conditions outdoors by creating sort of “cool islands”, i.e. semi-open precincts closed on three sides by water-filled bricks and shaded on top for avoiding direct sunlight on people. Such a system would bring the benefits of typical evaporative cooling systems [24,25], but without the issues linked to the use of active systems such as nozzles and spray devices. Implementation of the system in such constructions do not necessarily need mortar joints (i.e., a wet joint), but can be safely constructed with dry joints (e.g., metallic brackets or punctual joints) to avoid the issues you highlighted while also speeding up the building process. Further research on this configuration would be needed.

These findings, and the precise applicability of the system, need to be confirmed in a real-scale experimental setup in order to assess:

- The role played by the extension of water-filled bricks;
- The water consumption rate under different inlet dry bulb air temperature and relative humidity values;
- The role played by direct solar radiation impinging on the system;
- Integration of the system within the target constructions.

5. Conclusions

The experiments conducted on the hollow bricks filled with water prototype have provided useful insights on the capacity and prospective applications of Direct Evaporative Cooling that suggest further detailed investigations:

- No significant differences in the cooling capacity of the system have been detected under laboratory conditions when implementing one, two or three brick rows for the air to pass through and cool down. Consequently, the simplicity and affordability of a unique path is preferred.
- Saturation effectiveness does not depend on the inlet air psychrometric conditions, but the temperature drop achieved strongly does. The maximum temperature drop achieved for a single air path through the water-filled bricks amounts to 11.7 °C, 10.1 °C and 9.1 °C for air flow rates of 240 m^3/h, 370 m^3/h and 530 m^3/h respectively and an inlet air temperature of 40 °C. The corresponding cooling capacities amount to 0.8, 1.1 and 1.5 kW, in order.
- Potential applications of the DEC system, to be investigated in real-scale mock-ups, may range from agricultural and production buildings in the form of external walls to small precincts outdoor in order to relief workers and pedestrians respectively from harsh conditions.
- Hollow clay bricks are widespread and more affordable than the ceramic prototypes specifically designed and typically studied in the literature for evaporative cooling purposes. Moreover, water filling from an upper tank instead of capillary soaking ensures the entire brick being wet and thus higher cooling capacities.

Acknowledgements and funding

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