EXPERIMENTAL CHARACTERIZATION OF THE OPERATION AND COMPARATIVE STUDY OF TWO SEMI-INDIRECT EVAPORATIVE SYSTEMS

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Abstract

The study described in this paper aims to present the fundamentals in which the operation of two different evaporative cooling systems is based, as well as the experimental results developed to characterise their behaviour in different conditions of outside air. These results will permit to define, according to the ideas of the systems' operation, appropriate parameters to characterise the heat and mass exchange processes that take place as well as to compare them, like cooling capacity, thermal or energetic effectiveness; and afterwards developing this comparative analysis. The first system consists of a bank of ceramic pipes arranged vertically and staggered acting as a heat exchanger (SIERCP). In the second case an evaporative cooler has been manufactured with hollow bricks filled with still water (SIECHB). Both systems are called "semi-indirect" because they are designed to act as either direct or indirect evaporative systems depending on the relative humidity of the outdoor and return air streams. Results show that parameters related to the air humidity should be considered; and that the second system behaves generally as a direct evaporative cooler and provides a better performance.

Keywords

Evaporative cooling; heat recovery; cooling capacity; wet bulb thermal effectiveness; thermal conductance.

1 Introduction

Indoor air quality and thermal comfort are two of the numerous key factors that determine if the environment inside a building is comfortable for the inhabitants and adequate for the activity developed there or not. However, meeting the values expected needs such an important energy consumption that leads to this sector in European countries to consume up to a 20-40% of the global amount, depending on the climatic conditions. Moreover, it is expected that up to a 20% of the energy involved in this field could be avoided maintaining the same requirements [1].

Furthermore, in countries with continental climate, nowadays the energy consumption for cooling the air is becoming more and more important, though in the past most part of the energy consumption was associated to heating during the winter.

The current problems associated to energy provision and consumption, such as dependency on sources, increased cost or the environmental impact of energy use and transformation, favour the development of new technologies in air conditioning, which could permit reducing the energy consumption. Previous research has proved that among the possible passive techniques for cooling buildings, which permit substantial energy savings and reduction in CO_2 emissions, evaporative cooling shows important potential for integration into buildings, especially in dry and hot climates [2].

Evaporative cooling is a natural process that even animals use to lower their bodies' temperature. Some proofs of its practical use, such as images in engravings, can be found in the Ancient Egypt; and the Arabian architecture shows lots of applications to supply fresh air in their buildings, for example, Alhambra's Lions Courtyard in Granada (Spain).

In this context, evaporative cooling arises as an interesting alternative for providing a comfortable environment inside the buildings, with very low energy requirements [3].

Particularly, the devices studied in this paper use porous ceramic materials to retain the water that evaporates into the air to permit the phenomenon of evaporative cooling. Some researchers have already proved the effectiveness of this kind of systems in building applications [4,5]. However, the systems studied here are manufactured with ceramic materials already existing in the market, which are characterised by their low cost and easy availability. Furthermore, hollow bricks are common materials used in the building sector, widening the interest of the application of these air-conditioning systems.

It is important to remember that systems which use evaporating water have an important risk of appearance of Legionnaire's disease. Nevertheless, contrary to cooling towers or evaporative condensers, no cases of Legionnaire's disease have been associated to evaporative coolers, being the particularities of their operation and design the reasons for this fact. Actually, Legionella is not active at the characteristic operation temperatures of evaporative coolers (usually below 20ºC). However, some care must be taken in designing and maintaining the systems to avoid any possible risk [6]. The two particular systems presented here evaporate water from a humid surface; this way, aerosols capable to hold the bacteria are not produced. Moreover, working with relative humidity below 70% reduces the risk of this kind of disease. On the other hand, the small size of the pore of the ceramic materials, although it is an additional resistance to water flow, act as a filter blocking the way to pathogen elements and organic molecules bigger than water that can be found in the return air [7].

In this paper, two different evaporative coolers are studied. Both of them are called "semi-indirect" because they are designed to work either in direct or indirect evaporative cooling mode. Actually, water only evaporates into the outdoor air stream, behaving like a direct evaporative system, when the vapour pressure of this stream is lower than that of the water in the external surface of the ceramic device, capillary transported from the inside. In other case, the system merely behaves like a sensible heat exchanger between outdoor and exhaust air stream, like an indirect evaporative cooler.

The differences between the operation principles of the two systems are described in the following section, and the performance of each one is analysed later to present the comparative study.

2 Description of the two semi-indirect evaporative systems

A semi-indirect evaporative recoveree made with ceramic pipes, (SIERCP) [8]; and a semi-indirect evaporative cooler made with hollow bricks (SIECHB) [9] are compared in this study.

In the first case, the device allows cooling the outdoor air that circulates outside the pipes by enabling the recovery of the energy associated to the return air, which circulates inside the pipes in contact with a stream of water, thus permitting the phenomena of evaporative cooling.

It consists of a bank of 49 ceramic pipes arranged vertically and staggered in 7 columns and 7 rows, whose geometric characteristics are:

- Inside diameter: 0.015m
- Outside diameter: 0.025m
- Wall thickness: 0.005m
- Length T: 0.03m
- Length L: 0.025m
- Pipe length: 0.6m
- Area: 2.3 m^2

It works in a heat-recovery mode, as the return air from the climate chamber whose environment is to be conditioned circulates inside the pipes, while supply air circulates outside. There is also a stream of water that circulates counter-flow with the return air inside the pipes, keeping in contact with this air flow and thus evaporating in it, transforming sensible heat into latent heat. The porosity of the material allows the water inside the pipes to be capillary transported through the pipe walls to its outside surface. If the outside air vapour pressure is lower than that of the water present on the outer surface of the pipes, the system acts as a direct evaporative cooler, allowing humidification of the outdoor air stream. If this is not the case, it acts as an indirect evaporative system, in which the pipes work just as a heat exchanger that allows the recovery of the energy of the return air.

Figure 1 shows a view of the semi-indirect evaporative recoveree, the setting of the whole system and its operation mode. Typical outdoor air conditions of different climates are simulated in an Air Handling Unit, while a heat pump installed inside the climate chamber permits achieving the comfort conditions in those cases in which the evaporative cooling system cannot reach the power requested due to unfavourable climate conditions.

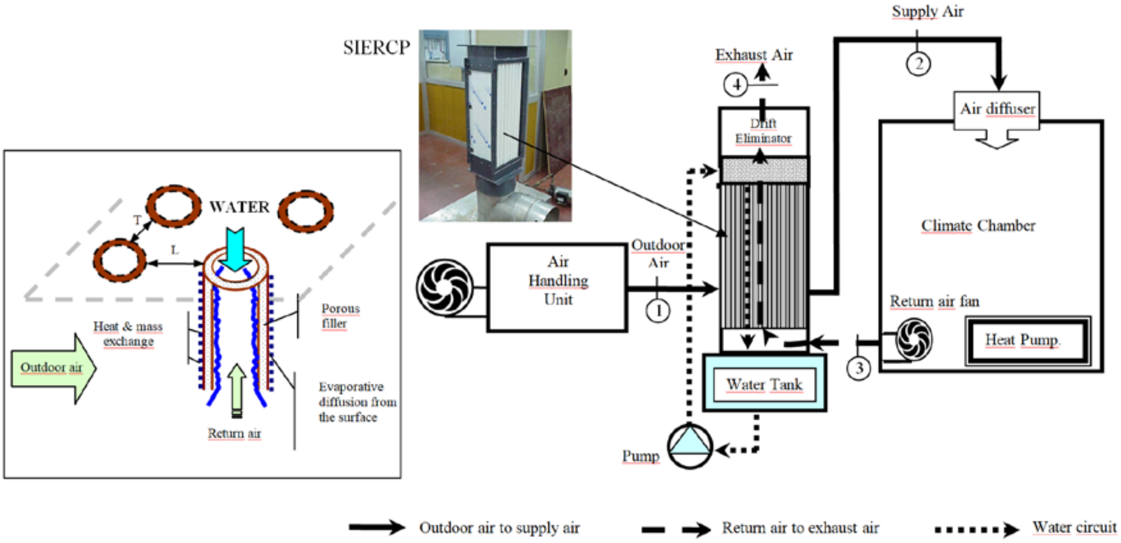

Figure 1. View of the SIERCP, operation and setting.

The other equipment consists of hollow bricks filled with stagnant water, in such a way that the water is capillary transported to the outer surface of the bricks, evaporating into the outdoor air stream if its vapour pressure is higher than that of the outdoor air. This water is previously cooled in a cooling tower, using the return air from the climate chamber. If the vapour pressure of the outdoor air is higher than that of the water in the surface, the system works merely as an indirect evaporative cooler [10].

The dimensions of a hollow brick are:

- Length: 0.198m
- Height: 0.41m
- Thickness: 0.0043m
- Hollow section: 7.92E-4m^2 (0.037 m x 0.021 m).
- Side area: 0.201m^2
- Number of bricks: 12
- Number of shell passes (outdoor air stream): 3.

Figure 2 shows a detail of a hollow brick similar to the ones used, the whole system setting and a view of the evaporative cooler.

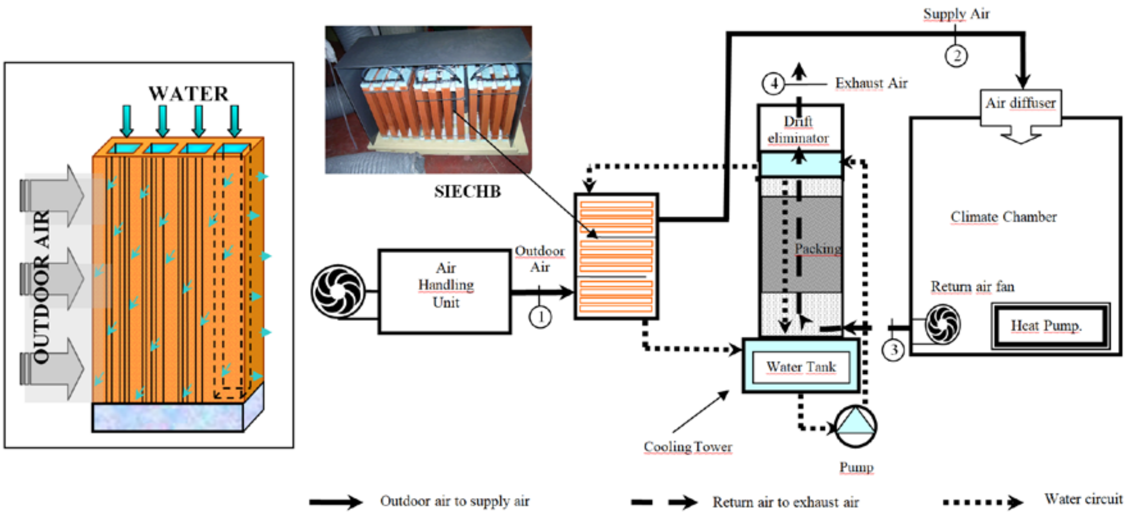

Figure 2. View of the SIECHB, operation, setting and detail of a hollow brick.

The pores of the ceramic materials used in each of the two devices have such a small diameter that they act as a filter between the two streams of air, smaller in the first case (pipes) than in the second (bricks), avoiding contamination of the supply air with possible pollutants from the return air. Furthermore, these materials show a high resistance to corrosion and oxidization.

Figures 3 and 4 show, in the psychrometric diagram, the possible evolution of outdoor air in summer conditions as well as the area of possible supply air conditions achieved, when these semi-indirect systems are used, in the case of tropical and continental climates respectively. In the first one, due to high humidity levels, both systems are expected to operate like indirect systems. In the second case, the low humidity ranges make the system operate approximately like a direct evaporative system.

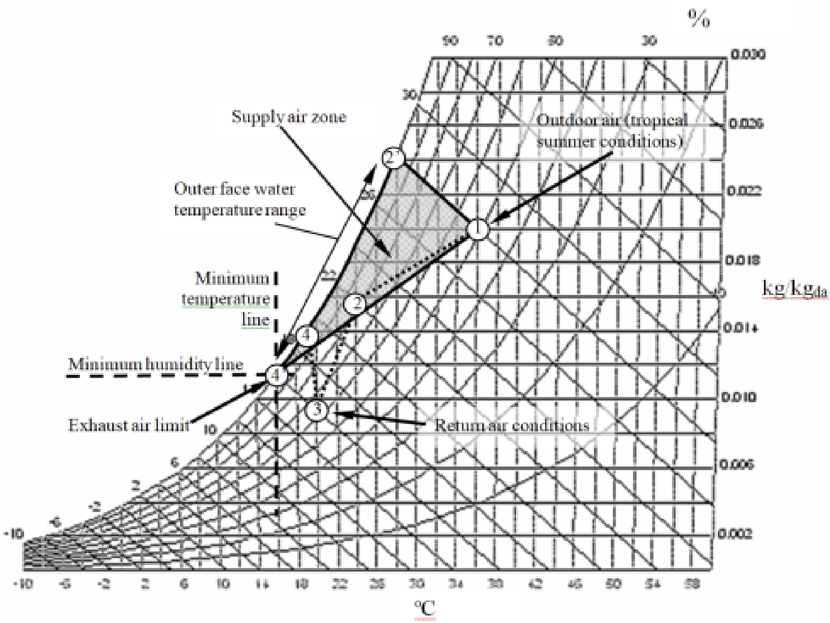

Figure 3. Area of possible evolution of return and outdoor air streams in tropical climates (summer conditions), and evolution followed in a generic test.

As an example of the humid air psychrometric evolution, a generic test has been drawn in figure 4. The state points of this evolution correspond to the ones shown in the two dimensional schemes of the processes shown in figures 1 and 2. Outdoor air (point 1) will adiabatically evolve to the limit conditions theoretically achievable (point 2') in case an ideal direct evaporative cooler is used. However, in the real semi-indirect systems presented, the supply air conditions (point 2) achieved are comprised in the area indicated. Notice that the air supplied to the climate chamber evolves to return air conditions (point 3), due to the heat pump that supports supply air loads as well as those inside the chamber, and thus enables the achievement of the comfort conditions. If there were no heat pump, indoor air would evolve to more humid conditions, like in every direct evaporative cooling system. If return air evolved adiabatically when recovering its energy associated in an evaporative process, exhaust air would reach conditions of point 4'. However, in the real heat-recovering process, conditions closer to point 4 would be more expectable.

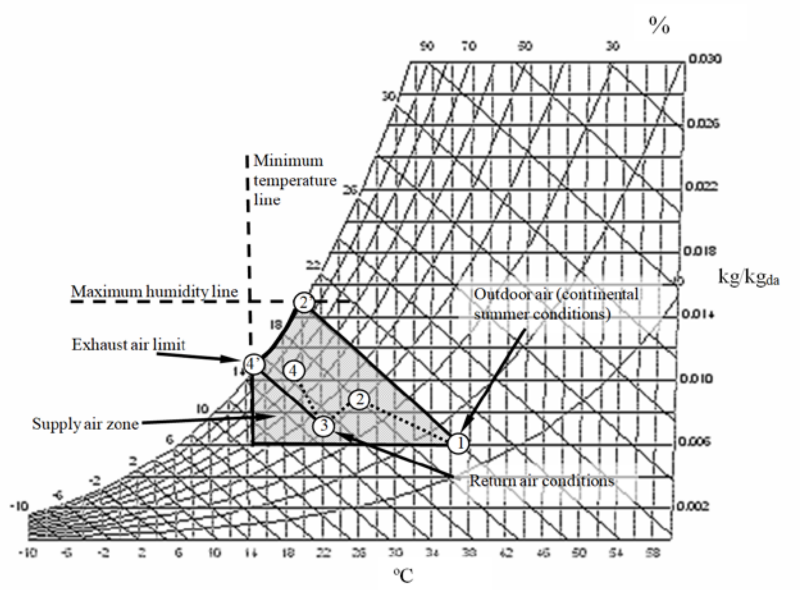

Figure 4. Area of possible evolution of return and outdoor air streams in continental climates (summer conditions), and evolution followed in a generic test.

No outdoor conditions for tropical climates have been tried in the particular study, so the evolution of a generic test shown in figure 3 corresponds to the information that can be found in other experimental studies performed on the SIERCP [7].

3 Experimental results

Both systems have been experimentally characterised testing them in a specific setting for each one. Different tests have been performed for each device, varying the most relevant factors in the process: the outdoor air flow rate, dry bulb temperature and relative humidity. Five levels of temperature are considered: 20, 25, 30, 35 and 40ºC. The volume flow rate for the SIERCP is set in three levels: 290, 410 and 515 m^3/h, whereas for the SIECHB this factor is set in 180, 360 and 540 m^3/h. This difference of flow rate settings between the two cases is caused by the difference in pressure drop, not being possible for the air handling unit to provide the same volume flow. The reason for this is the presence of restricted positions available for the AHU volume flow controller, which need to be considered to permit repeatability of the experimental tests. Therefore, despite the attempt to obtain similar flow rates by establishing the most appropriate position of the volume flow controller, this cannot be achieved in any case.

In order to make an adequate comparative analysis between the two systems, only tests concerning similar levels of relative humidity at each level of dry bulb temperature are compared at the same time. These values of relative humidity, whose tests associated are selected for being the ones that give the best results, happen to be the corresponding ones for a given absolute humidity characteristic of the laboratory; that is to say, no extra humidification for outdoor air is tried in the particular experimental processes chosen. Taken this into consideration, for an outside air-dry bulb temperature level of 20ºC, the relative humidity will be set around 55%, while for 25, 30, 35 and 40ºC relative humidity varies around 45, 35, 25 and 20% respectively.

Measurement error expected for volume flow rate is ±5 m^3/h., considering the experimental error, the error related to the orifice plate used for the measurement and that of the nozzle used to calibrate. Accuracy of more than ±5% cannot be either provided for relative humidity data, due to the precision of the measuring probe.

Once the defining factors are established and the corresponding experimental measures are gathered, different parameters can be defined to describe the behaviour and performance of the systems, depending on the possibility of considering the wet bulb temperature instead of the dry bulb temperature. However, it can be expected that the thermal effectiveness, which is defined considering only dry bulb temperatures, would not give an interesting view of the performance of the systems, as humidity is such a relevant factor in this study. Consequently, the wet bulb thermal effectiveness is also introduced.

In addition, in the definition of the parameters it can also be considered the wet bulb temperature of return air instead of outdoor air wet bulb temperature.

Notice that the criteria for considering one particular parameter instead of any other in the characterization of a system are based in its operation principles. Thus, it can be expected that for the SIERCP, the parameters would be better defined in relation to the return air, as it behaves as a heat-recoveree; while for the SIECHB, those defined in relation to the outside air could be more reliable. These hypotheses will be checked in the analysis of the experimental results.

In addition to the parameters that will be presented later, it can also be interesting to compare the supply air temperature in relation to outdoor air temperature. This evolution is shown in figure 5.

The calculated parameters are defined below:

The cooling capacity of each system is given by the expression:

$$\mathrm{CC} = \dot{\mathrm{m}}(\mathrm{h}_1 - \mathrm{h}_2) \tag{1}$$

The thermal effectiveness is defined as [10]:

$$\varepsilon_T = \frac{\dot{m}_1(T_1 - T_2)}{\dot{m}_2(T_1 - T_3)} \tag{2}$$

The wet bulb thermal effectiveness in relation to return air [10]:

$$\varepsilon_{3wb} = \frac{\dot{m}_1(T_1 - T_2)}{\dot{m}_2(T_1 - T_{3wb})} \tag{3}$$

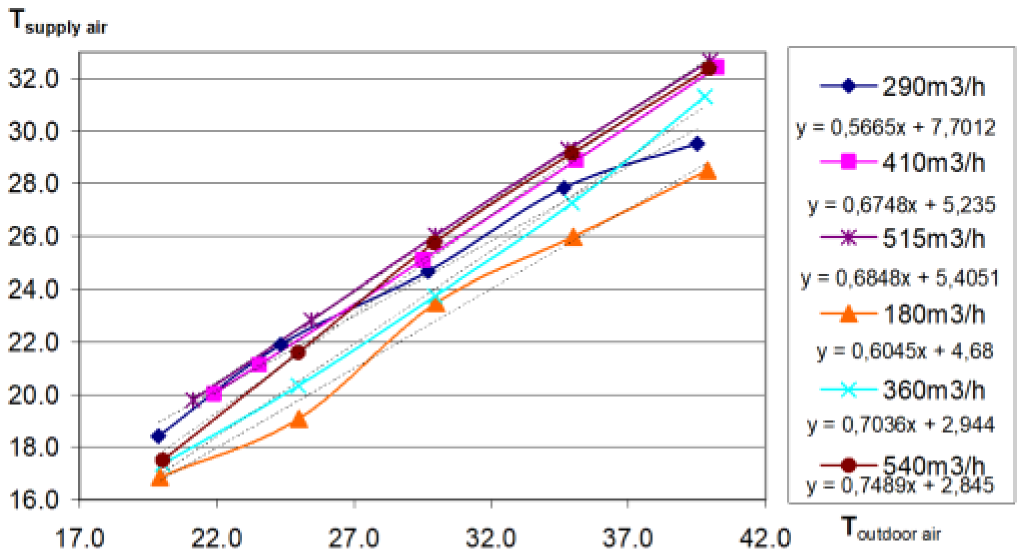

Fig. 5. Supply air dry bulb temperature variation with outdoor air-dry bulb temperature.

While related to the outside air wet bulb temperature the following expression is considered:

$$\varepsilon_{1wb} = \frac{\dot{m}_1(T_1 - T_2)}{\dot{m}_2(T_1 - T_{1wb})} \tag{4}$$

Another interesting parameter could be the thermal conductance, which is the product of the heat transfer coefficient and the area involved and can be conceived as the inverse of the thermal resistance of the wall of the heat exchanger. This value is obtained from the logarithmic mean temperature difference, and as can be seen in the expressions proposed for its calculation, related to the return air or the outside air wet bulb temperature in each case:

$$USF_1 = \frac{CC_1}{\Delta T_{im_1}} \tag{5}$$

$$USF_3 = \frac{CC_3}{\Delta T_{im_3}} \tag{6}$$

Where the logarithmic mean temperature differences are defined as:

$$\Delta T_{im_1} = \frac{(T_1 - T_{1wb}) - (T_2 - T_{1wb})}{\ln\left(\frac{(T_1 - T_{1wb})}{(T_2 - T_{1wb})}\right)} \tag{7}$$

$$\Delta T_{im_3} = \frac{(T_1 - T_{3wb}) - (T_2 - T_{3wb})}{\ln\left(\frac{(T_1 - T_{3wb})}{(T_2 - T_{3wb})}\right)} \tag{8}$$

The values of these parameters, calculated from the experimental results, are gathered in table 1 for the SIERCP and table 2 for the SIECHB, except for the cooling capacity, which will be shown later.

As can be seen from the values obtained for the thermal effectiveness, this parameter cannot be considered in a fair study of the device performance. As it is defined in relation to the return air dry bulb temperature, and this is not a lower or upper limit for outside air dry bulb temperature, this parameter turns to be negative if the outside air temperature is lower than that of the return air; and over 1 if the supply air temperature reached is below than that of the return air.

Table 1. Measures and values of the parameters defined for the SIERCP

T_1[a] [ºC]	T_2[a] [ºC]	T_3[a] [ºC]	T_{1wb}[b] [ºC]	T_{3wb}[b] [ºC]	ε_T[b]	ε_{1wb}[b]	ε_{3wb}[b]	USF_1[b] [W/K]	USF_3[b] [W/K]
Q=290 m³/h									
19.9	18.4	22.8	15.9	16.8	-0.50	0.36	0.47	37.5	52.4
24.3	21.9	22.8	17.3	17.2	1.55	0.34	0.34	33.9	33.7
29.7	24.7	22.9	18.6	16.8	0.74	0.45	0.39	47.7	39.0
34.7	27.9	23.4	20.3	17.5	0.60	0.47	0.40	49.3	38.9
39.5	29.5	23.5	21.5	17.2	0.62	0.55	0.45	60.9	44.7
Q=410 m³/h									
21.9	20.0	22.7	16.7	17.0	-2.36	0.36	0.38	53.0	57.1
23.5	21.1	23.1	16.1	16.2	5.51	0.32	0.33	45.0	46.4
29.5	25.1	23.4	18.9	17.1	0.72	0.41	0.36	60.4	49.6
35.1	28.9	24.1	20.5	18.4	0.57	0.43	0.37	60.9	51.2
40.2	32.4	23.7	21.3	16.9	0.47	0.41	0.33	56.8	43.3
Q=515 m³/h									
21.1	19.8	24.0	16.2	17.3	-0.46	0.27	0.35	46.1	63.6
25.4	22.8	23.3	16.2	16.1	1.24	0.28	0.28	45.4	44.7
30.0	26.0	23.3	18.8	17.4	0.58	0.35	0.31	59.5	51.4
34.8	29.3	24.0	20.4	17.4	0.51	0.38	0.32	64.9	51.0
40.0	32.7	24.3	21.1	17.5	0.46	0.39	0.32	64.6	51.8

On the other hand, the wet bulb thermal effectiveness provides a better reference for the performance analysis, as it is defined in relation to the wet bulb temperature, which better reflects the performance of an evaporative system due to the physical basis of this phenomenon. In fact, it can be seen how this value is approximately constant whatever the outdoor air-dry bulb temperature is.

However, it can also be noticed that for the SIECHB this parameter defined in relation to the return air does not give very clear results, as for low values of the outdoor air temperature, the wet bulb temperature of the outside air is lower than that of the return air, and thus the values of the wet bulb thermal effectiveness are over 1. This is caused by the particular operation of this second device, where the return air does not directly affect, and thus it seems to be better characterised in relation to the outdoor air.

The parameter defined as thermal conductance depends only on the material; therefore, the values obtained should be approximately constant. Nevertheless, only the results in relation to the outdoor air wet bulb temperature show an adequate behaviour for the

SIECHB. Thus, for defining this parameter in the case of the SIECHB we will also consider the values in relation to the outdoor air-dry bulb temperature.

Table 2. Measures and values of the parameters defined for the SIECHB

T_1^a [ºC]	T_2^a [ºC]	T_3^a [ºC]	T_{1wb}^b [ºC]	T_{3wb}^b [ºC]	ε_T^b	ε_{1wb}^b	ε_{3wb}^b	USF_1^b [W/K]	USF_3^b [W/K]
Q=180 m³/h									
20.0	16.9	22.3	14.8	17.6	-1.29	0.60	1.29	47.2	-
25.0	19.1	21.9	16.1	17.3	1.93	0.66	0.77	55.3	73.9
30.0	23.5	23.7	19.7	20.3	1.03	0.63	0.67	48.9	54.7
35.0	26.0	23.4	20.8	20.0	0.77	0.63	0.60	48.3	43.8
40.0	28.5	23.3	22.1	20.0	0.69	0.64	0.57	48.0	39.8
Q=360 m³/h									
20.0	17.4	21.8	15.3	17.8	-1.53	0.56	1.17	85.5	-
25.0	20.3	22.3	17.2	18.4	1.74	0.59	0.70	90.7	122.4
30.0	23.8	23.4	19.2	19.4	0.95	0.57	0.59	84.0	87.1
34.9	27.3	23.8	20.5	19.5	0.69	0.53	0.50	72.4	65.8
39.8	31.3	24.9	22.4	20.7	0.57	0.49	0.44	61.9	54.3
Q=540 m³/h									
20.0	17.5	21.2	14.9	17.2	-2.20	0.49	0.89	104.8	350.1
25.0	21.6	22.8	16.8	18.2	1.57	0.41	0.50	79.5	103.3
29.9	25.8	25.2	18.9	19.7	0.89	0.38	0.41	69.0	76.4
34.9	29.2	26.0	20.4	19.9	0.65	0.40	0.38	72.0	68.9
39.9	32.4	26.5	22.0	20.4	0.56	0.42	0.39	75.9	68.0

Although for the SIERCP any of the two definitions of the wet bulb thermal effectiveness and thermal conductance could be chosen for the study (as the results show an acceptable behaviour of the four parameters), those related to the return air wet bulb temperature are considered, because they provide slightly better results and seem to be more reasonable according to its operation fundamentals.

The relevant parameters selected above are the only ones represented in the following section, in order to compare the behaviour of the two devices. Figure 6 shows the cooling capacity in the two cases. Figure 7 and 8 represent the wet bulb thermal effectiveness and the thermal conductance, respectively, in relation to the outside or the return air wet bulb temperature, as appropriate.

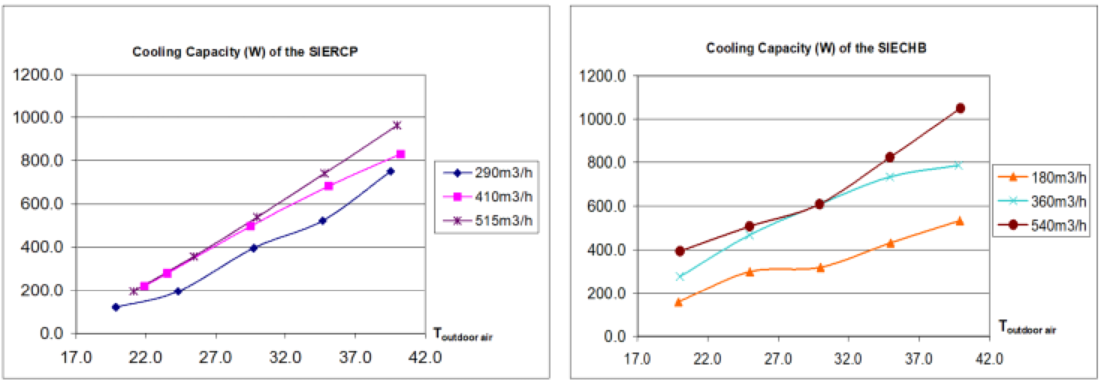

Figure 6. Cooling capacity variation with outdoor air-dry bulb temperature for the SIERCP and the SIECHB

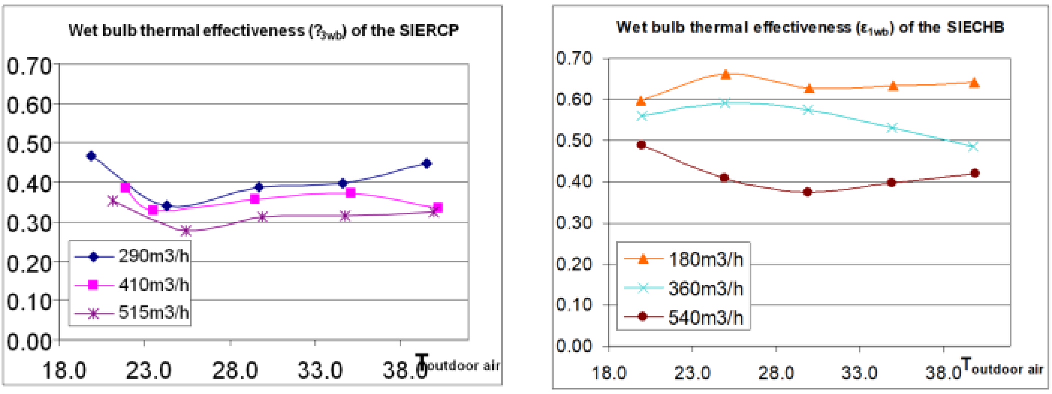

Figure 7. Wet bulb thermal effectiveness variation with outdoor air-dry bulb temperature for the SIERCP and the SIECHB

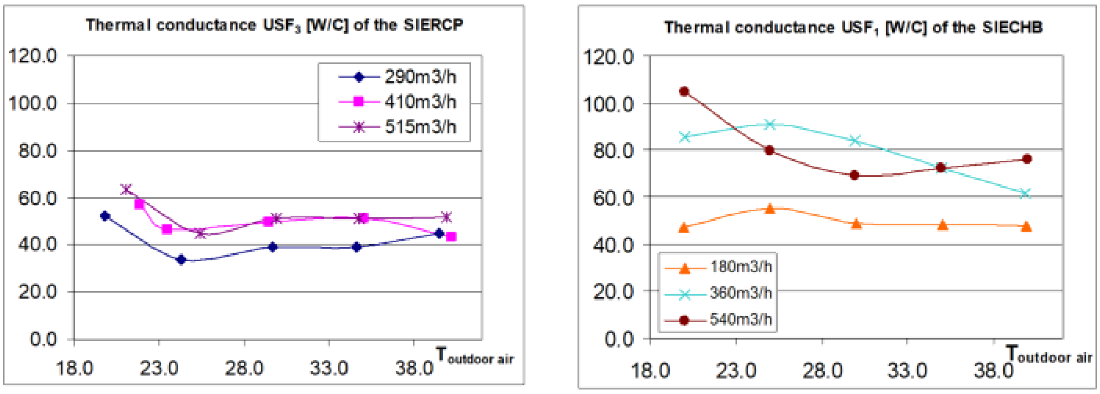

Figure 8. Thermal conductance variation with outdoor air-dry bulb temperature for the SIERCP and the SIECHB

4 Discussion and comparison

Similar conditions have to be considered in the two systems to make this comparison properly. To solve the problem related to the independence of the experimental process developed in each case, a set of different tests is considered. Three levels of volume flow are considered in each case, selecting for each of the three groups those tests performed at each level of established temperature whose relative air humidity measured adjusts to a certain value characteristic of the outdoor air. This enables to compare tests at the same level of temperature and relative air humidity.

Results in figure 5 evidence that the temperature difference between supply and outdoor air increases when the inside air temperature increases, being the growing ratio over 0.5 in every case. Furthermore, they tend to converge for low values of outdoor air-dry bulb temperature. Again, this is related to the physical principles of evaporative cooling, because higher temperatures at a constant level of specific humidity, give conditions further from their saturation point. Moreover, for higher values of the volume flow this difference of temperatures diminishes, because more volume of air needs to be conditioned by the system.

The temperature difference achieved in the case of the system made with hollow bricks is generally higher, even for higher values of the volume flow, because the pore diameter of this material is bigger and thus permits a higher water flow by capillarity. This dependency of the performance of ceramic evaporative systems on porosity corresponds to the results obtained in previous works [4,5].

This behaviour is more clearly shown in the results concerning the parameter defined as "cooling capacity". It can be perceived in figure 6 how the cooling capacity increases with the outdoor air-dry bulb temperature, because the relative air humidity decreases in this case. Actually, not only the results show the same tendency in relation to the temperature already noted in previous works, but also the values obtained are of the same order of magnitude [4].

This parameter also increases for higher levels of air flow, for they are directly proportional. The graphs also show a slight better performance for the SIECHB.

The wet bulb thermal effectiveness, defined in relation:

- to the wet bulb temperature of the return air stream for the system made of ceramic pipes, and
- to the wet bulb temperature of the outdoor air stream for the system made of hollow bricks,

is maintained approximately constant with the outdoor air temperature, being lower for higher levels of volume flow. This can be explained considering that, the lower the volume flow is, the most part of it is evaporatively cooled. Notice that the effectiveness is better for the SIECHB even for the highest volume flow studied (figure 7), whatever the airstream considered in the definition of the wet bulb effectiveness, as can be seen in tables 1 and 2.

Previous works have been developed on cooling towers as well as on conventional indirect systems working in different climate conditions, which have also stated the study of the thermal effectiveness related to the adiabatic saturation temperature (approximated by the wet bulb temperature). The results obtained establish that for similar outdoor air conditions the values of the thermal effectiveness are similar. However, the performance of the ceramic evaporative systems is slightly lower due to their dependence on the water flow through the porous surface, which depends on the porosity and vapour pressure, thus not being susceptible of being controlled [11,12].

One further parameter has been considered for comparatively describing the systems, called "thermal conductance". As it is a characteristic parameter of the material of the system wall through which the thermal exchange is made, it should not vary importantly despite the variation of the outdoor air-dry bulb temperature. Thus, figure 8 show how this is mostly true, as it varies in about 30W/K in the most unfavourable case, which happens to be the test for the SIECHB at 360 and 540m^3/h. In the other cases this parameter only varies in a range of scarcely 20W/K.

However, in every case this value is higher for the SIECHB, which implies that it is capable of evaporating more volume of water. Thus, it could be said that the evaporative cooler made of hollow bricks mainly behave like a direct evaporative system, in which the water temperature does not contribute to the cooling capacity of the device.

5 Conclusions

During the development of the study, it has been explained why the two evaporative systems analysed could be called “semi-indirect”. It is an important point to consider the fact that these systems have been designed to be able to behave either like direct evaporative coolers or mere heat exchangers. However, it has been proved that the evaporative cooler made of hollow bricks behaves like a direct evaporative system in all the cases performed.

The main difference between the behaviour of the two systems is that the first one permits the recovery of the energy associated to the return air from the climate chamber, which directly circulates inside the equipment; while in the SIECHB the energy associated to this air passes through a cooling tower whose water fills the bricks, so the cooling capacity only depends on the outdoor air conditions.

These differences in their behaviour show that particular considerations had to be taken into account when defining their characteristic parameters. Thus, it has been proved that it is reasonable to consider, as reference values, the measures of the interesting properties in the return air stream for the evaporative recover system, or in the outdoor air stream for the evaporative cooler. Following this idea, two different definitions for the wet bulb thermal effectiveness and thermal conductance were proposed.

Both the representation of the supply air dry bulb temperature in relation to the outdoor air dry bulb temperature, and the cooling capacity for the two systems, support the fact that, for a constant absolute humidity, the higher the outdoor air dry bulb temperature is, the higher is the temperature drop achieved.

The results for the cooling capacity provided by the SIECHB are slightly better than those of the SIERCP.

The wet bulb thermal effectiveness of the systems presents no important relation with the outdoor air-dry bulb temperature, and approximately maintains a constant value. The performance of the SIECHB appears to be better in this case either.

The value of the defined thermal conductance increases for higher values of the air volume flow, consequence of the increase in the convective coefficients for heat and mass exchange between the air and the humid surface.

The overall conclusion is that the evaporative system made of hollow bricks shows a better performance than the one made of ceramic pipes, due to the better behaviour of the ceramic material in the heat and mass exchange.

Another key idea is the fact that the performance of these systems improves when the outdoor air temperature increases, usually related to low values of relative air humidity, due to the process of evaporative cooling.

Nomenclature

CC: Cooling capacity (W).

h1: dry air specific enthalpy of outdoor air (kJ/kg_{da}).

h2: dry air specific enthalpy of supply air (kJ/kg$_{da}$).

ε_T: thermal effectiveness.

ε_{1wb}: wet bulb thermal effectiveness, in relation to the outdoor air wet bulb temperature.

ε_{3wb}: wet bulb thermal effectiveness, in relation to the return air wet bulb temperature.

m_1: air mass flow of outdoor airstream for supply (kg/s).

m_2: air mass flow of return airstream, later exhaust air (kg/s). Mass flow of outdoor and return air is considered equal.

T_1: outdoor air-dry bulb temperature (ºC).

T_{1wb}: outdoor air wet bulb temperature (ºC).

T_2: supply air dry bulb temperature (ºC).

T_3: return air dry bulb temperature (ºC).

T_{3wb}: return air wet bulb temperature (ºC).

ΔT_{lm_1}: Logarithmic mean temperature difference, in relation to the outdoor air wet bulb temperature (K).

ΔT_{lm_3}: Logarithmic mean temperature difference, in relation to the return air wet bulb temperature (K).

USF_1: thermal conductance in relation to outdoor air flow (W/K).

USF_3: thermal conductance in relation to return air flow (W/ K).

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