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The phenomenon of evaporative cooling from a humid surface as an alternative method for air-conditioning

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Abstract
The phenomenon of evaporative cooling is a common process in nature, whose applications for cooling air are being used since the ancient years. In fact, it meets this objective with a low energy consumption, being compared to the primary energy consumption of other alternatives for cooling, as it is simply based in the phenomenon of reducing the air temperature by evaporating water on it. This process can be an interesting alternative to conventional systems in these applications where no very low temperatures are needed, like the case of air-conditioning during the summer. However, the risk of contamination by legionnaire's disease, commonly related to evaporative cooling systems, has led in recent years to the substitution of these devices in the industry by less-efficient systems, like the case of cooling towers or evaporative condensers substituted by air-condensing refrigerating processes.
Therefore, these systems based in the evaporative cooling are rarely used for cooling buildings. To reduce this risk, evaporative cooling is produced from humid surfaces, in such a way that water evaporates due to the difference of vapor pressure between the surface and the air, and thus minimizing the generation of aerosols, responsible for the spread of legionnaire disease. Aerosols are nevertheless produced in conventional systems where water is sprayed or directly in contact with the stream of air; and the problem worsens if the water, which is recirculated, has been still in any moment or its temperature is adequate for the bacteria proliferation.
This paper aims to introduce the thermodynamic basis in which the process is based, as well as the commercial evaporative systems and the problem associated to legionnaire's disease in this kind of systems. Furthermore, three different experimental devices based in evaporative cooling are described, which have been designed and manufactured in the Thermal Engineering Research Group of the University of Valladolid., describing their characteristics of operation and providing the experimental results obtained during their characterization, for outside air conditions typical of hot and dry summers.

Keywords: Direct evaporative cooling, Air-conditioning, Energy efficiency, Legionnaire's disease.

1. Introduction
The environmental impact associated to the use of energy from conventional fossil origin, the energetic and economic dependency on non-renewable sources, lead to the necessity of reducing the energy consumption, maintaining the current targets and necessities of each activity that require the use of energy.

Figures about the energy consumption by fields show that from 20% to 40% of the total energy demand in developing countries is generated in buildings, depending on the climatic conditions [1]. Moreover, due to the high number of users of the building sector, an improvement on the energy efficiency of the systems leads to an important decrement on the energy consumption, thus being this sector one of the most interesting fields to focus the activity to improve the energy efficiency. However, not only the economic savings have to be considered in the study of the improvements in energy efficiency, whose profitability is commonly uncertain, but also the reduction in the environmental impact or in the misused of natural resources implied [2].

Despite the fact that the priority of the new dispositions introduced for energy management, new devices and generators among others, is to reduce the energy consumption in buildings, they must ensure a proper comfort level and well being of their users [3]. Consequently, it should be considered the introduction of systems that permit condition the hygrothermal environment of the rooms, maintaining an adequate indoor air quality and thermal comfort, with low energy requirements, when providing energetic viable solutions to obtain a proper thermal environment in buildings.

There are many sustainable alternatives in the air-conditioning of buildings, which consist in minimizing the energy demand by improving the thermal insulation, taking advantage of the bioclimatic facilities, or using energy resources different from the conventional ones, like solar energy generation, geothermic heat pumps, or evaporative cooling systems, which are the ones studied in this work.

This paper introduces the characteristics as well as some of the experimental results obtained for different prototypes based in the phenomenon of evaporative cooling, and that have been developed in the Thermal Engineering Research Group of the University of Valladolid.

2. History of evaporative cooling

Many examples of the application of the phenomenon of evaporative cooling can be found, such as the metabolic regulation of the human body temperature through the evaporation of sweat from the skin, the use of cooling towers or evaporative condensers, the cooling of pools by the evaporation of the water, etc. Furthermore, it was the most widespread method to cool the environment in ancient years, before developing the principles of refrigeration by mechanical compression or absorption. It is important to note which are the historical background and the development of this technology till nowadays. Originally, this process was firstly applied by humankind in Near East, where the dry and hot climate was favorable to its application. Thus, in paintings from Ancient Egypt (2500 B.C.) it can be seen how slaves fanned big vessels filled with water, which were porous enough to permit this water to pass through the ceramic wall and maintain the surface humid, evaporating into the air [4].

Other paintings from Rome, founded in a wall from Herculano (70 A.D.), show a big Wessel made of leather used to cool the drinking water making use of this process. Similarly, the Persian and American Indians tents were maintained humid to be cooled. Other similar applications of the evaporative cooling are used nowadays, like the water bottles of the soldiers covered with wet cloth; or the drinking jugs, which provide drinking water at a temperature below that of the environment.

Moreover, old buildings from Iran were commonly cooled by this process, as they were partially built underground to avoid solar radiation, while the upper terraces were provided with pools of water cooled in a kind of cooling towers.

During Middle Age, the Islam spreads this technology all throughout the Occidental countries, and evaporative cooling systems start being used in Mediterranean areas. Leonardo da Vinci probably built the first mechanical air-cooler made of a hollow wheel through which the air was conducted, keeping in contact with a water curtain that fell into different chambers, cooling and purifying the air. The system included wood valves to control it, and it was designed to cool the rooms of his boss' wife [5].

The first rigorous analysis of the direct and indirect evaporative systems, considering both the advantages and disadvantages and indicating and establishing some basis about their design, was developed by Dr. John R. Watt, who worked for the Research Laboratory of the U.S. Navy. He built and studied four prototypes of plate evaporative coolers, one of them constituted of two stages; as well as a cooling tower and coil, determining their efficiency and cooling capacity [6].

Currently, the work developed by Dr. Donald Pescod gathers different studies about plate evaporative coolers, being the pioneers in using plastic materials for the plates, and in creating artificial turbulences to minimize the stillness of the air film, reaching really high heat-transfer areas in compact distributions [7]. As the main resistance to heat-transfer can be found in the air on the dry face of the system, the advantage of the higher thermal conductance of metals than that of plastics is negligible. Moreover,

plastic avoids corrosion and is adequate to resist the high pressure differences characteristic of this kind of devices.
In the 80's, the interest in these systems increases considerable, as probes the high number of articles and communications in scientific journals, developing different applications of this technology like the recovering of the energy associated to the return air stream from the cooled rooms.

3. Theory on evaporative cooling
Evaporative cooling is a process of heat and mass transfer based on the transformation of sensible heat into latent heat. The non-saturated air reduces its temperature, providing the sensible heat that transforms into latent heat to evaporate the water. If the process develops in ideal adiabatic conditions, the dry bulb air temperature decreases as this transformation develops, increasing its humidity. This heat exchange continues until the air reaches its saturated state, when the air and water temperature reach the same value, called "adiabatic saturation temperature", being the process known as "adiabatic saturation".
To define this temperature we can suppose a long adiabatic tunnel, in which the humid air is introduced in certain conditions, while water is sprayed inside the tunnel and then recirculated, in such a way that the air becomes saturated (see Figure 1).
The adiabatic saturation temperature, Tad sat, is the temperature that the air reaches when gets to the output of the tunnel, if water is provided and evaporated at that temperature.

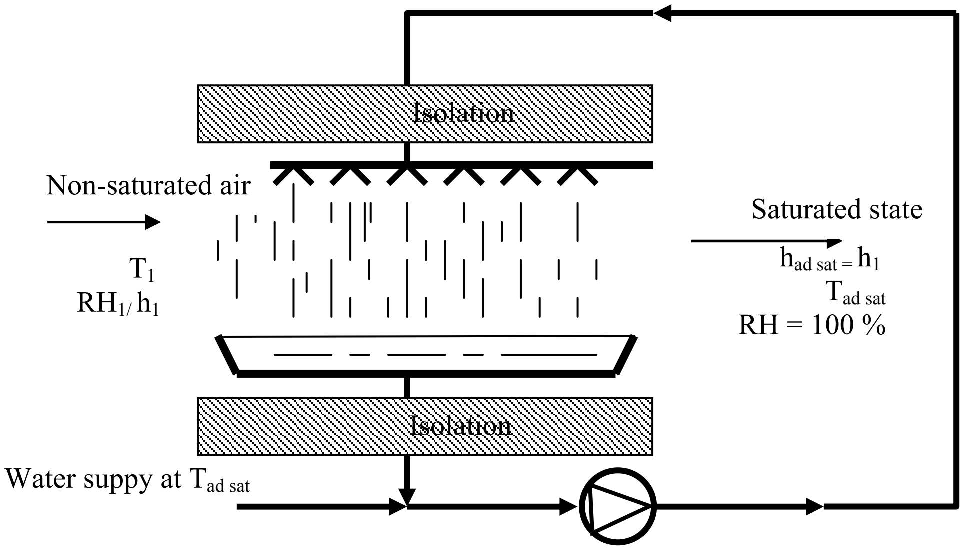

Figure 1. Adiabatic saturation tunnel

In the last stages of the tunnel there will be no mass-exchange because Relative air Humidity (RH) is 100%, and heat exchange neither, as the air and water temperature are the same. Thus, these conditions only depend on those of the inlet air and, consequently, the saturation air temperature can be defined as a thermodynamic property of humid air.
The value of the wet bulb temperature is close to that of the saturated air temperature in the common working conditions of air-conditioning systems. However, they are completely different concepts, as the first one is conceived as the temperature that reaches the bulb of a thermometer when the heat transferred from air, essentially by convection processes, is the same as the heat required to evaporate the water from its surface into the air, due to the vapor pressure gradient between the bulb's surface and the air.
Figure 2 shows the heat and mass flows involved in the process introduced to define the wet bulb temperature.

Heat transferred from air to the bulb by convection:

$$q = h(T_\infty - T_{wb}) \tag{1}$$

where q is the heat flux (W/m^2), h is the convective heat coefficient (W/m^{2}C), T_∞ is the air temperature (C) and T_{wb} is the wet bulb temperature (C).

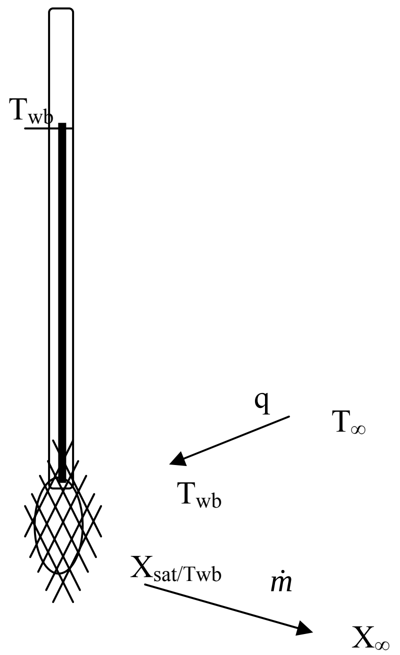

Figure 2. Wet bulb temperature (T_{wb})

Vapour flow from the bulb to the air:

$$\dot{m} = h_m \cdot \rho_{da} \cdot \left(X_{sat/T\,wb} - X_\infty\right) \tag{2}$$

where $\dot{m}$ is the mass flow (kg/m^2), h_m is the convective mass coefficient (kg/m^{2}s), ρ_{da} is the dry air density (kg$_{as}$/m^3), which is the inverse value of the specific volume, X_∞ is the air absolute humidity (kg/kg$_{da}$) and $X_{sat/Twb}$ is the absolute humidity at saturation point of these conditions of wet bulb temperature (kg/kg$_{da}$).

Heat flow required to evaporate the water from the bulb's surface into the air:

$$q = \lambda \cdot h_m \rho_{da} \left(X_{sat/Twb} - X_\infty\right) \tag{3}$$

where λ is the latent heat associated to the phase change (J/kg).

The equations introduced could be more complicated if other kind of exchanges with the environment were considered. The advantage of using the wet bulb instead of the adiabatic saturation temperature is that, although they correspond to different concepts, their value is quite similar and the first one is easier to measure, as only a thermometer whose bulb is maintained humid is required.
It can be demonstrated from the Lewis number (eq. 4) that, for a mixture of dry air and water vapour, the outlet air temperature in an adiabatic saturation tunnel, thus the adiabatic saturation temperature, is mainly the same as the wet bulb air temperature. However, slight differences can be appreciated between both values of temperature.

$$Le = \frac{\alpha}{D} = \frac{h}{\rho \cdot C_p \cdot h_m} \tag{4}$$

where α is the thermal diffusivity (m^2/s), D is the mass diffusivity (m^2/s), Cp is the specific heat (J/kgC) ρ is the density (kg/m^3).
The process of adiabatic saturation controls most of the evaporative cooling systems. This is the basic process in those cases in which the water initial temperature is close to the wet bulb temperature of inlet air, which usually occurs when water is recirculated continuously. Theoretically, water temperature

maintains constant, and consequently all the heat involved in the evaporation process is used to cool the air, not the water.

Nevertheless, in practice water usually gains some external sensible loads in the tank, pumps and pipes. Moreover, the temperature of the water supplied to support the evaporated part and purges, is not necessarily the adiabatic saturation temperature of inlet air. Thus, in an evaporative cooling process the concept of "adiabatic saturation" is only the theoretical limit up to which water or air involved could be ideally cooled.

When the water temperature is considerably over the adiabatic saturation temperature of air, the process is similar to the one characteristic of a cooling tower, where both air and water are cooled simultaneously.

In the direct evaporative coolers, such as the ones called "spray in air stream system", water can be heated by the pump or by gains from non-insulated pipes. When it comes into contact with the air, both provide sensible heat and are cooled when it transforms into latent heat, as water evaporates removing heat from the environment to permit the phase change from liquid to vapor, humidifying the air.

The majority of the systems of direct spray in air stream use non-recirculated water, as it permits reducing corrosion and incrustations. However, in these systems it should always be prevented the generation of aerosols, and usually incorporates an ultraviolet radiation system in order to prevent legionnaire's disease.

There are limits to the cooling achieved by adiabatic saturation. The amount of sensible heat removed cannot exceed that of the latent heat necessary to saturate the air. The cooling possibilities thus depend inversely on the air humidity. Consequently, when relative air humidity is very high, this process is not very effective. The theoretical and real processes of evaporative cooling are introduced following.

3.1 Theoretical evaporative cooling process

The study of the psychrometric diagram lead to a better understanding of the processes analysed. As pointed before, the theoretical process is adiabatic, and is performed following the constant enthalpy line. The air is adiabatically humidified when coming into contact with water, which is recirculated to maintain its temperature at the adiabatic saturation temperature of inlet air. Because the sensible heat load is transferred to the water surface and transformed into evaporation latent heat, the dry bulb air temperature diminishes, while this loose of sensible heat is simultaneously compensated for the vapor absorption, increasing its absolute humidity.

The process develops following a path in the psychrometric diagram that starts in the point of the inlet air conditions, and follows the line of constant enthalpy towards the upleft of the diagram (Figure 3). If air reaches saturation (point B), the maximum cooling of the air will be achieved.

The figure below shows a theoretical adiabatic saturation cycle of the air at high temperature (35 C) and low humidity (20 %) to describe which would be the theoretical cooling level that would be achieved in an ideal adiabatic saturation process. It can be noticed that the maximum temperature that can be achieved, if water recirculated is at the saturation temperature, is 20 C.

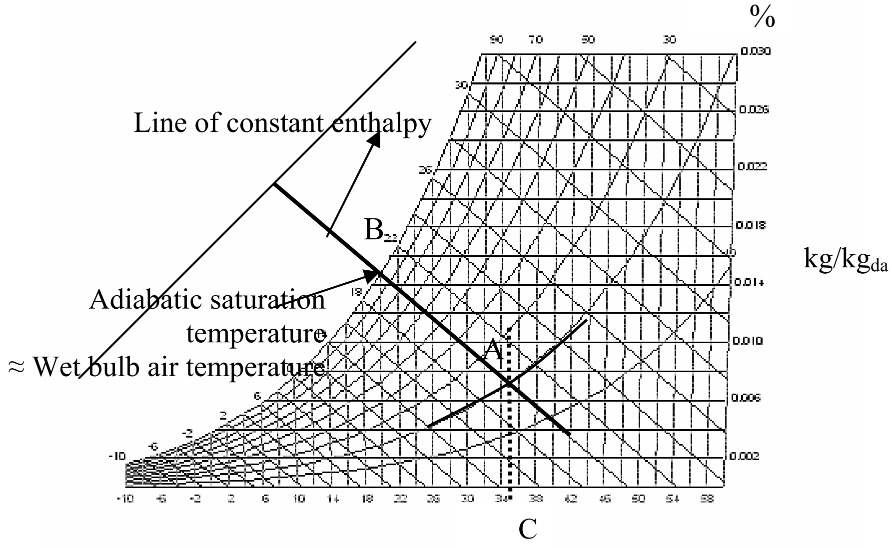

Figure 3. Theoretical evaporative cooling process

3.2 Real evaporative cooling process

The operation of most part of the evaporative coolers differs from the adiabatic case, due to the sensible heat introduced by water. Thus, air is cooled, but its enthalpy and wet bulb temperature increase.

Supposing an hypothetical situation in which water temperature is maintained constant all throughout the process, the air evolution between inlet and outlet will follow the line that connect the inlet air conditions and those of the water, this line represented on the psychrometric diagram.

When in an isolated system water and air are supposed to be in contact, if air gains enthalpy then water loses it, being cooled; while if air looses enthalpy, water would be heated. Thus, in a process where air and water are in contact, water will always tend to adiabatic saturation temperature, as in the case of the adiabatic tunnel described before.

To clarify what has been exposed before, the evolution of an air stream originally at 25ºC and 30% of RH is described for different cases of water temperature. The different possible processes for the air evolution are shown in the Figure 4.

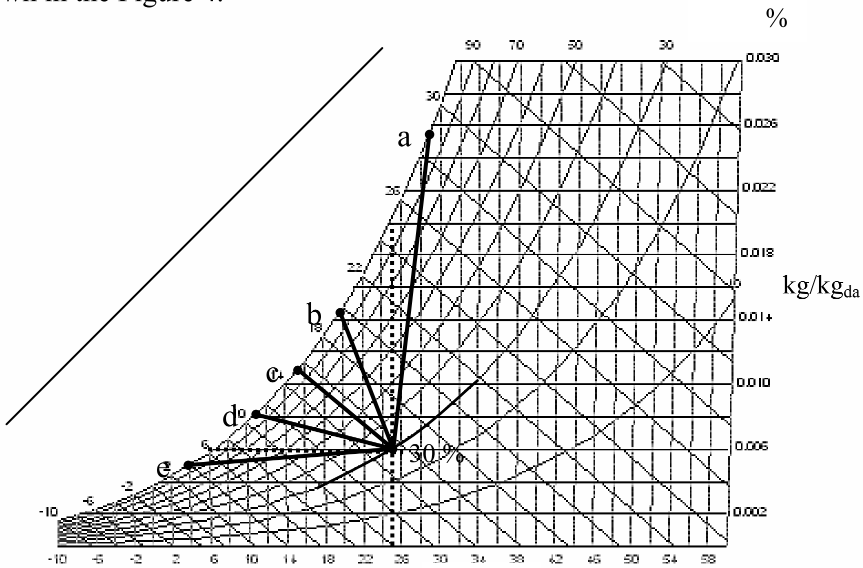

Figure 4. Real evolution for different water temperatures

a- Water temperature is over that of the air.
Air is heated and humidified, gaining enthalpy.

b- Water temperature is between dry bulb and adiabatic saturation temperature of air.
Air is cooled and humidified, gaining enthalpy.

c- Water is at the adiabatic saturation temperature of inlet air.
Air is cooled and humidified maintaining its enthalpy constant.

d- Water temperature is between the adiabatic saturation and dew point temperature of inlet air.
Air si cooled and humidified loosing enthalpy.

d- Water temperature is below that of the air dew point.
Air is cooled and dehumidified, loosing enthalpy.

Commonly, air in the adiabatic evaporative coolers evolves between case b and c represented above.

4. Conventional evaporative cooling systems

The evaporative cooling can be achieved by direct, indirect systems, or combining these two types in various stages (mixed systems) [8].

4.1 Direct evaporative cooling systems

In direct systems, water evaporates directly in the air stream, producing an adiabatic process of heat exchange in which the air dry bulb temperature decreases as its humidity increases. Thus, the amount of heat transferred from the air to the water is the same as the one employed in the evaporation of the water (Figure 5).

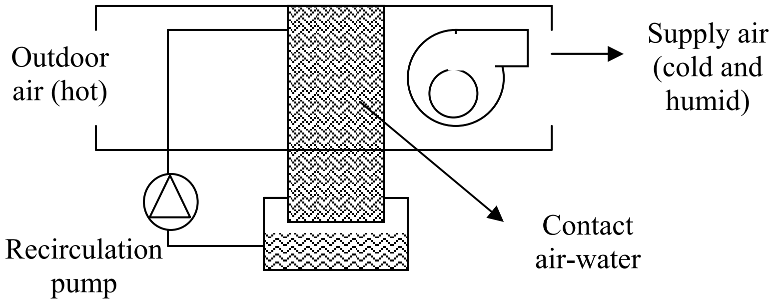

Figure 5. Direct evaporative cooler

The direct evaporative systems used for cooling rooms consist of at least a humidifier, a fan (generally a centrifugal one, to supply the required pressure with low noise), a tank of water and casing. A recirculation pump is also needed.
The direct evaporative systems aim to increase the area through which the mass-exchange is produced between the air and the humid surface, given that the vapor mass flow in air needed to evaporative cooling that air is directly proportional to that area.
Although it is more improbable that drops of water were swept away by the air stream than the presence of aerosols when atomizing, it is always necessary to dispose a proper drift eliminator in the outlet of this air stream. Nevertheless, special care should be taken to provide a right maintenance of the evaporative systems to avoid bacterial contamination like the legionnaire's.
According to the specific characteristics of the humidifier, the direct evaporative cooling systems can be classified into different categories considering the different proceedings to put air and water into contact, such as the case of the rotary devices with a lower water tank. But the most common ones in market are the Rigid Cooling Media Pad and the direct pulverization systems.

A.- Rigid cooling media pad: these systems are made of rigid corrugated plates, as shown in Figure 6, made of plastic, impregnated cellulose, fiberglass, etc. The air and water streams are usually disposed cross flow.

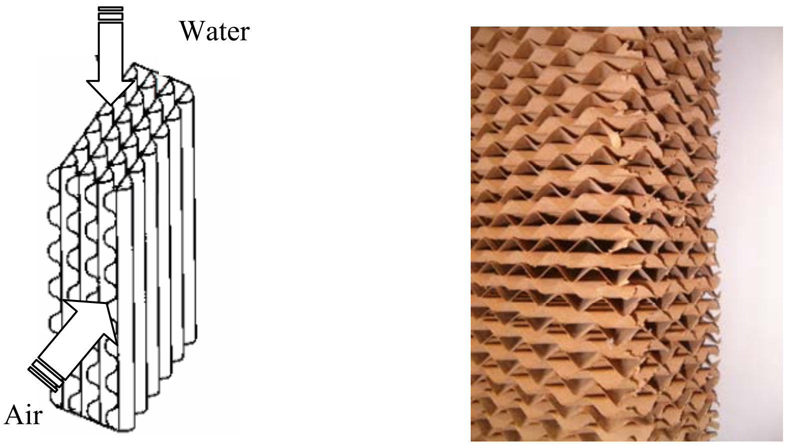

Figure 6. Rigid cooling media pad

B.- Direct pulverization: In these devices humidification is achieved by pulverizing water in the primary air stream. Although the effectiveness of these devices is very high, there are many problems related to the possible bacterial contamination, such as legionnaire's disease, which force to assure a due maintenance and cleanness of the systems, avoiding sweeping away drops of water from the cooling system. Thus, humidifiers from wet surface are preferably selected, with less tendency to originate aerosols, such as the one made of rigid pads. The configuration of how these systems, traditionally used as humidifiers, should operate is shown in Figure 7.

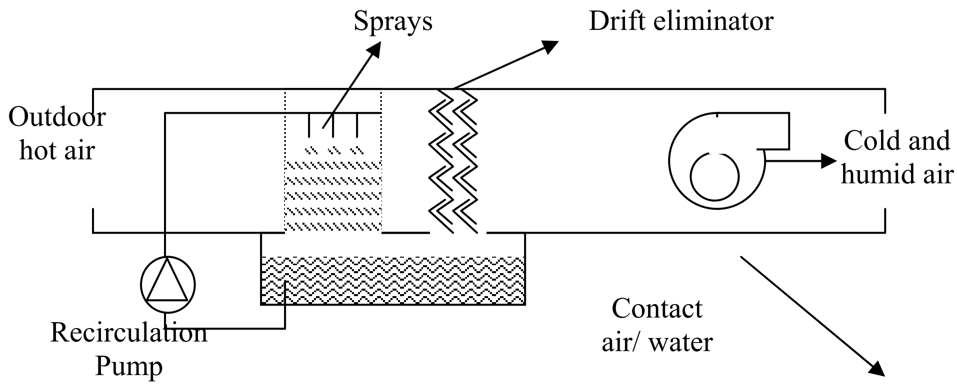

Figure 7. Direct pulverization evaporative cooler

The most common direct evaporative spray cooler system is the one used in hot and dry climates to condition outdoor areas. It consists of a pump that provides water with due pressure, and nozzles to pulverize it directly into the environment. Water comes from urban supply and is not recirculated, which reduces the risk of legionnaire's disease. This system is shown in Figure 8.

Figure 8. (a) Spray system for cooling outdoor areas

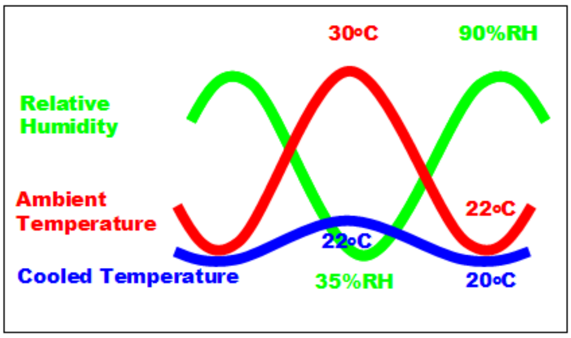

Figure 8. (b) Air conditions obtained with spray systems

4.2 Indirect evaporative cooling systems

In the case of indirect evaporative cooling, water evaporates in a secondary air stream which exchanges sensible heat with the primary one in a heat exchanger. In this way, the outdoor air stream is cooled when keeping into contact with the surface through which the heat exchange is produced, without modifying its absolute humidity; whereas at the other side of this surface the secondary air stream is being evaporative cooled. Thus, this process is called indirect and is mainly used in those applications where no humidity addition is allowed in the supply air, as well as no risks of contamination, as no mass exchange is permitted between the two air streams (Figure 9).

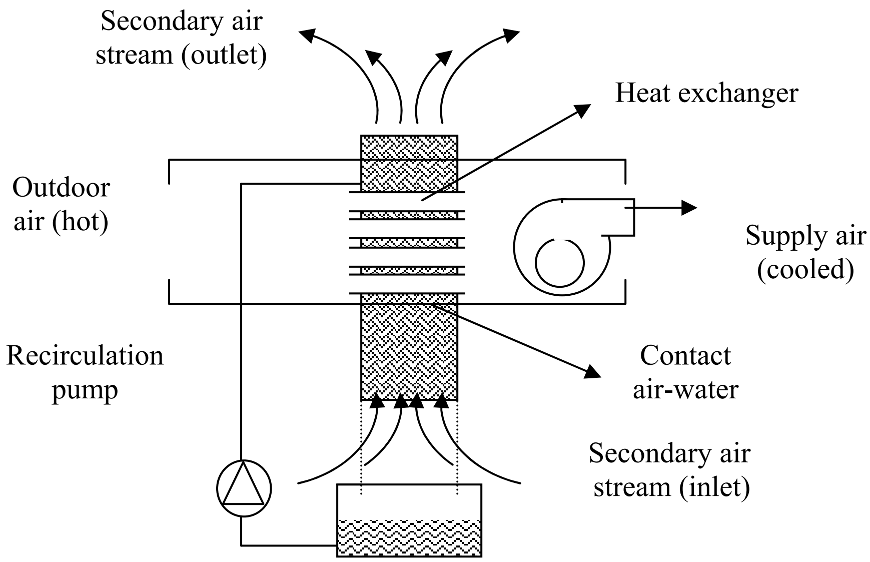

Figure 9. Indirect evaporative cooler

The different psychrometric evolutions that can follow the air streams in a direct or indirect evaporative system are shown in Figure 10.

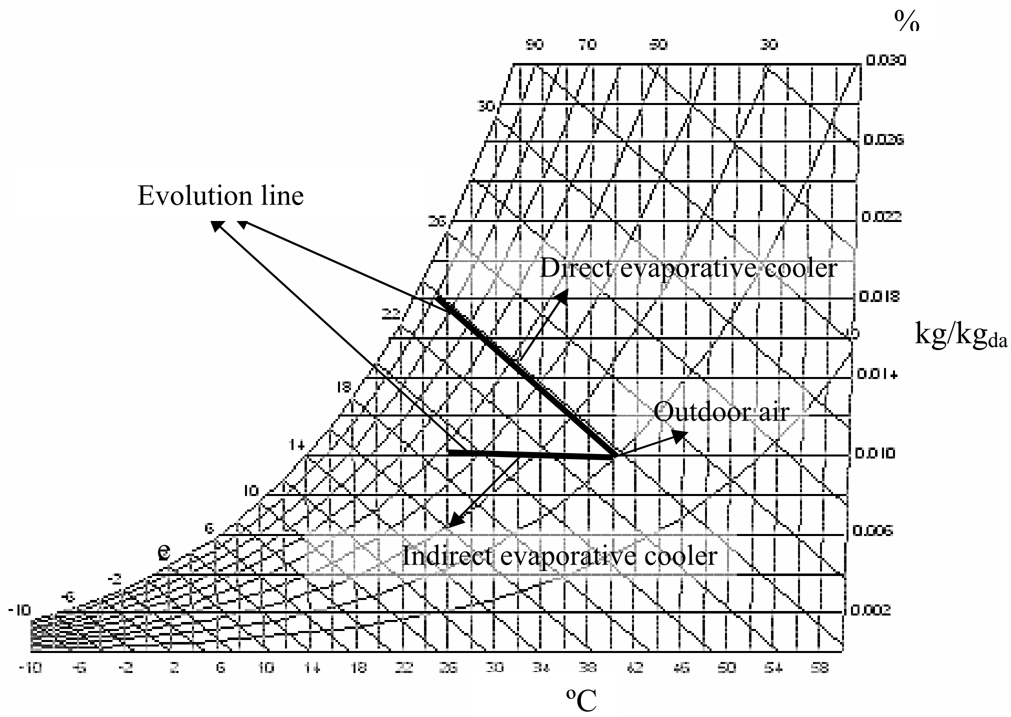

Figure 10. Air evolution in direct and indirect systems

The indirect evaporative cooling systems can be considered as energy recovering systems if a return air stream from the room cooled is used as a secondary air stream in the process, taking advantage of either its lower temperature or humidity. It can also be used a mixed stream of outside and return air. Consequently, some authors distinguish between heat recovering or heat regenerating cycles according to the following ideas:

a) Conventional indirect evaporative cooler: it has been already introduced. It combines a heat exchanger and an adiabatic saturation system, making use of outdoor air exclusively for both the primary and the secondary streams. The primary air stream is cooled through a heat exchanger.

b) Regenerative indirect evaporative cooler: it consists of an indirect evaporative cooler in which part of the primary air stream at the outside of the system is used as secondary air stream, which permits reducing the water temperature in the evaporative cooling process of the system, as shown in Figure 11:

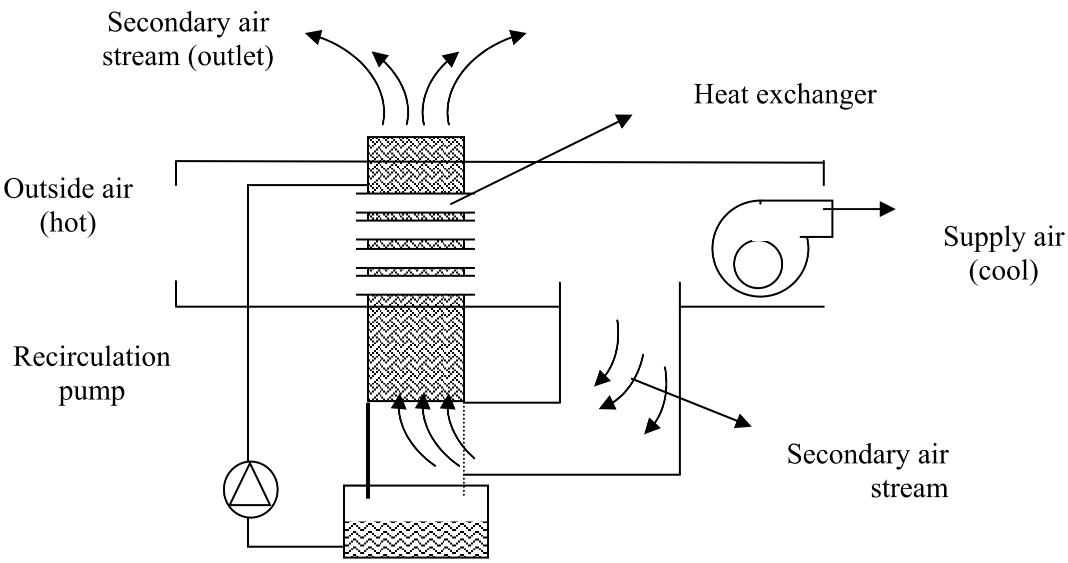

Figure 11. Configuration of a regenerative indirect evaporative cooler

c) Heat recovering indirect evaporative cooling: it consists of an indirect evaporative cooler, in which a stream of return air from the room is used as a secondary air stream, taking advantage of the lower temperature and absolute humidity of the air in comfort conditions, which permit reaching lower temperatures than in the case of using outdoor air only (Figure 12).

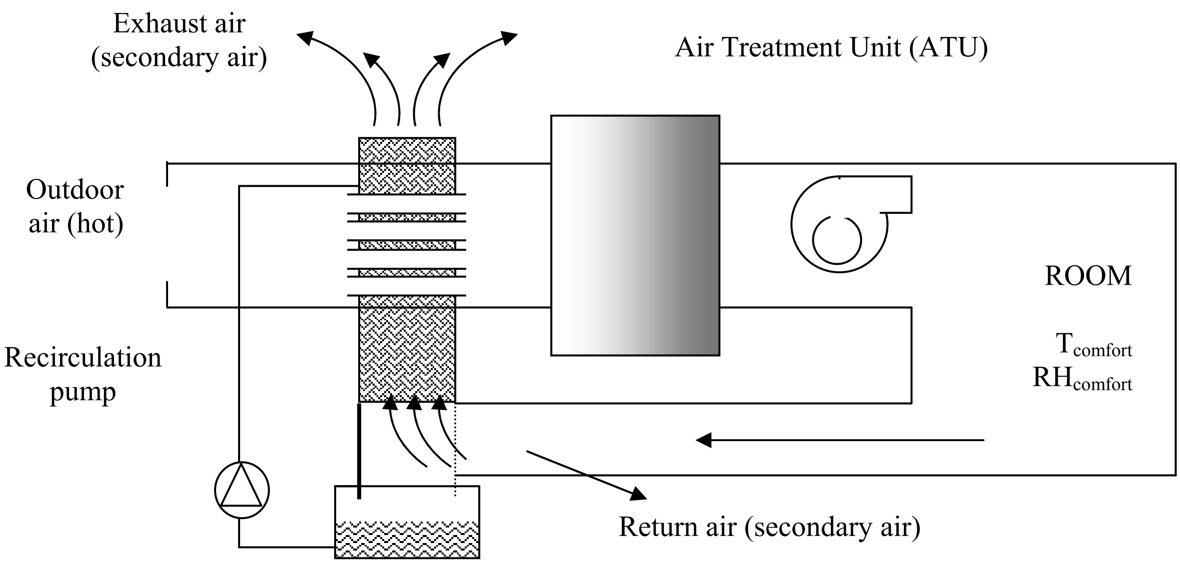

Figure 12. indirect evaporative cooler in a heat-recovery configuration

The elements in an indirect evaporative cooler are: the heat-exchanger, were primary air is cooled; the atomizing nozzles; the recirculation pump; air filters; impulsion and return fans and a casing made of stainless steel or plastic to avoid corrosion.

As in the case of the direct evaporative cooler, the main parameter when designing an indirect system is the heat-exchange surface that separates the air stream from the water to be evaporated. These surfaces absorb heat from the primary air stream and transfer it to the secondary air in the evaporative cooling process. They can be made either of metal or plastic and must easily conduct heat, maintain the two streams separated and resist to corrosion.
Among this group of systems there are devices made of either tubular or plate heat-exchangers.

4.2.1 Indirect system with tubular heat-exchanger
The first reference to this kind of system comes from 1908, from a patent of a German inventor called Elfert. Subsequently, models made of a window air cooler have been developed, which permitted obtaining outdoor air that passed inside a bank of fine horizontal tubes with the aid of a fan, while water was sprayed on the outerwalls. More modern designs of these systems used plastic tubes that resisted corrosion better. Figure 13 shows the operation configuration of this kind of devices.

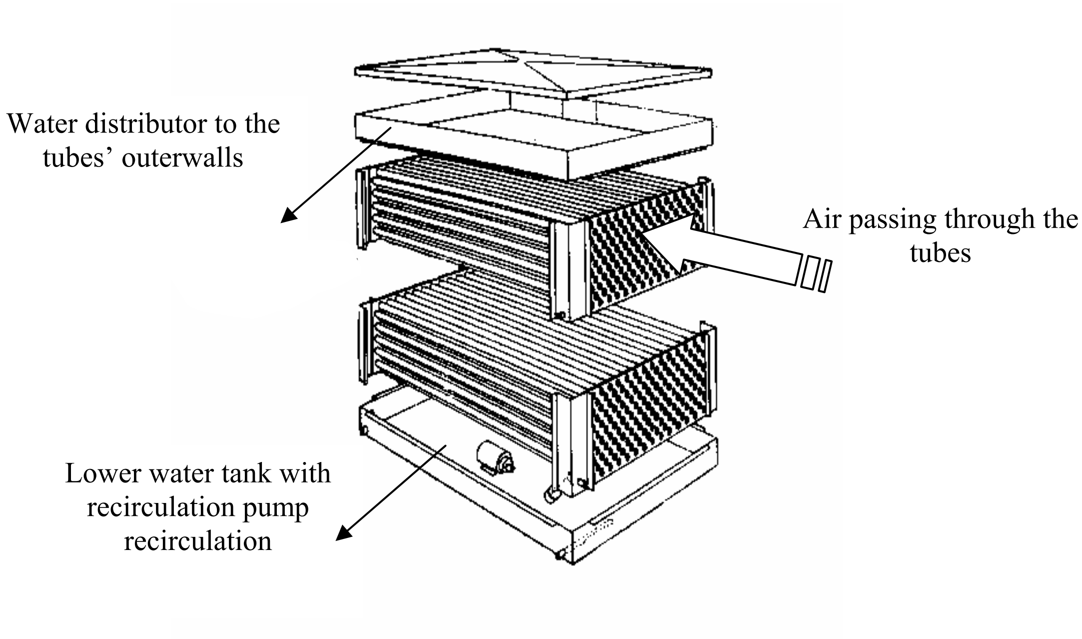

Figure 13. Tubular indirect evaporative cooler

4.2.2 Indirect system with a plate heat-exchanger
This is undoubtedly the most used indirect evaporative system. The first reference known to this system comes from 1934, and that design suggested two stages. In the first stage return air is cooled in two spray humidifiers (direct evaporative cooling). Afterwards, this air is used in a plate heat-exchanger to cool outdoor air which will be supplied into the cooled room. Humid air is thrown outdoors. One advantage of this system is that water does not take into contact with the exchange surface, thus not originating incrustations. However, these are really large devices, and heat-exchange between gas mediums require great areas of transference, so they are not used.
Another system, more cheap and compact, was designed by Dr. Pernot and later by Dr. John R. Watt. It is constituted by a vertical plate heat-exchanger combined with a direct evaporative cooler. Outdoor air and sprayed water circulate on one side of the plates, being evaporatively cooled; while a fan made dry air circulate through the other side, permitting sensible heat exchange as shown in Figures 14 and 15. These systems do not recover return air associated energy, but use outdoor air previously filtered for both the cooling tower and the supply stream, and do not present problems of incrustations. As liquid is used in one side of the heat-exchanger, the convective coefficients are higher, being also higher the global heat transfer coefficient and reducing the necessary surface for the heat exchange.

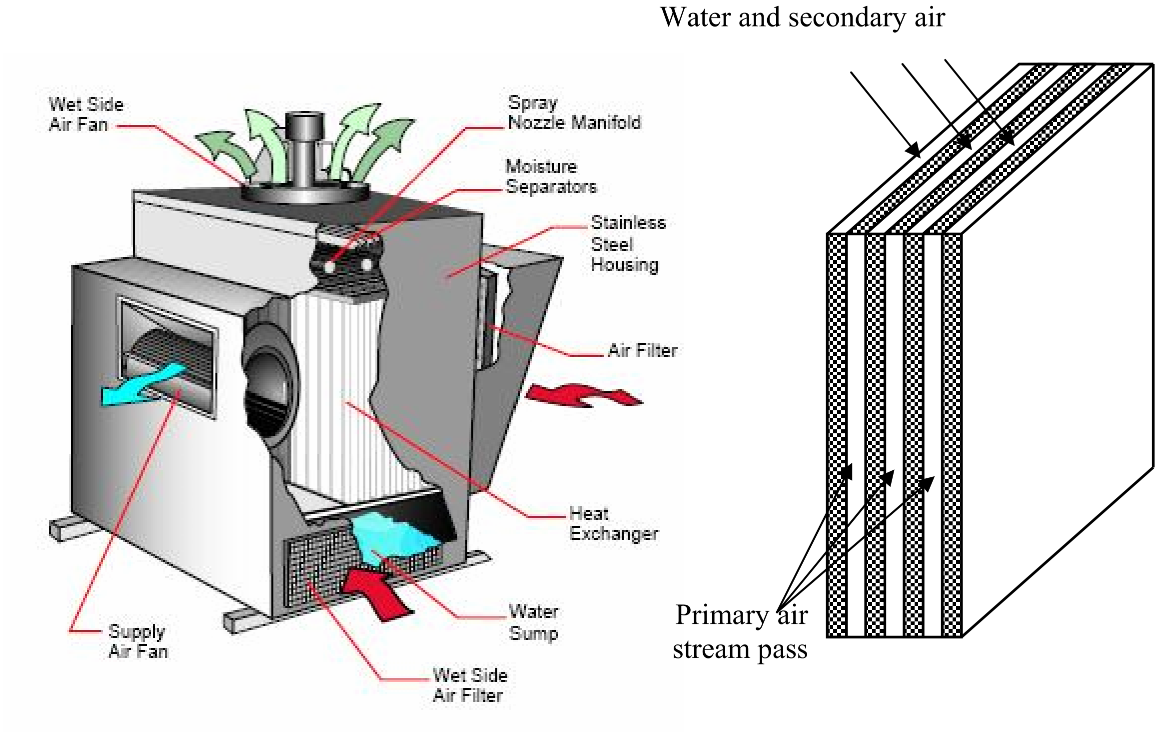

Figure 14. Configuration of the plate indirect evaporative cooler

The main resistant to heat transfer is produced in the dry air side, where there is no liquid phase, the advantage of using metal instead of plastic to manufacture the plates is negligible, and thus its use spread rapidly. Moreover, plastic also prevents from corrosion and is structurally adequate to support the possible pressure differences.

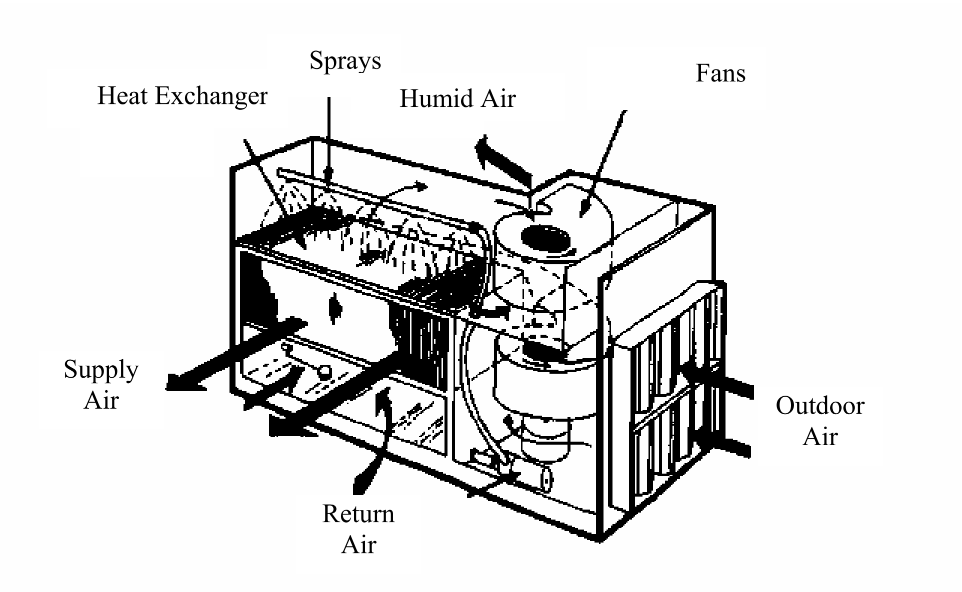

Figure 15. Indirect plate evaporative cooler, developed by Pescod

Outdoor air enters through the filters on the right side, and is driven by the fan through the horizontal paths of the plate heat-exchanger, where it is cooled. The return air, sucked by the upper fan, passes through the humid area of the heat-exchanger, corresponding to the vertical paths, where water is sprayed, and then it is expelled to the outside. Water is recirculated with the aid of a pump from the lower tank to the spraying nozzles.

4.3 Mixed evaporative cooling systems

The mixed systems aim to combine the two cases described (direct and indirect) through a sequence of stages, in order to improve the efficiency and stretch the possibilities of the application of this phenomenon in humid climates (Figure 16).

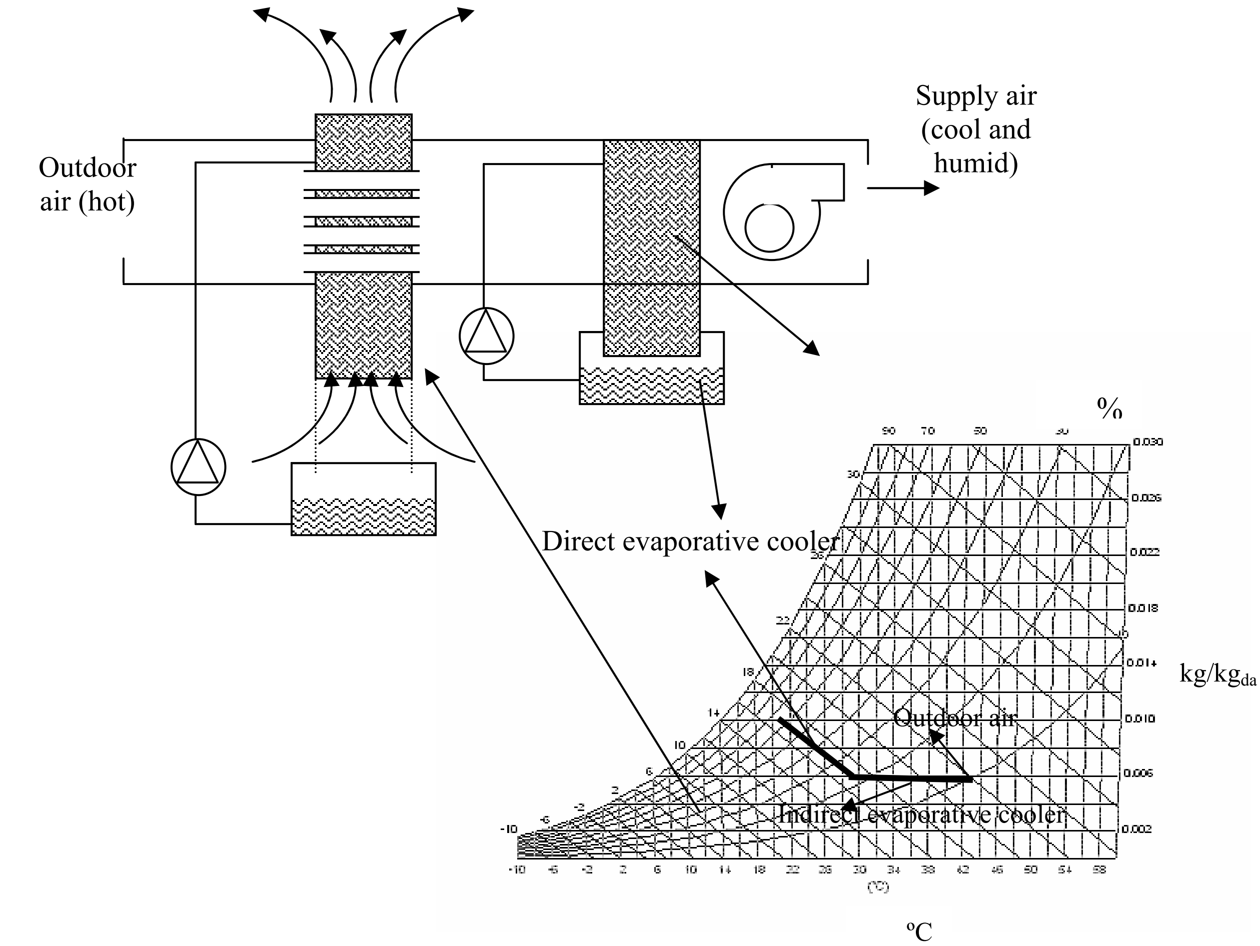

Figure 16. Configuration and psychrometric evolution for a mixed evaporative cooler

In summer, in dry and hot air conditions, the supply air from the indirect evaporative coolers presents a dry bulb temperature over 21ºC and its relative humidity below 50 %. Thus, it can be interesting introducing an additional direct evaporative cooling process that decreases this temperature, though it also increases the air humidity.

Usually a high relative humidity in supply air is acceptable, if it is capable to eliminate the sensible loads of the room. To meet this target, two evaporative coolers are connected in series, the indirect system in the first place and then the direct one.

The operating characteristics are given by the device installed in each stage. Thus, plate heat-exchangers are commonly used in indirect stages, cooling the secondary air with sprayed water; while in direct evaporative stages the Rigid Cooling Media Pad.

Some applications of the direct/ indirect combination are shown following.

4.3.1 Mixed system of multiple stages

It is possible to design compact coolers of multiple stages, in each of which the air stream is divided into two new streams. One of these streams is used in an evaporative cooling system to generate cold water that feeds a battery of finned tubes where the other stream is cooled. This stream of cold air is divided again into two new ones, succeeding in cooling the primary air in a sensible way, without modifying the initial humidity, using part of the cold air to evaporatively cool the water.

The configuration of the process can be seen in Figure 17.

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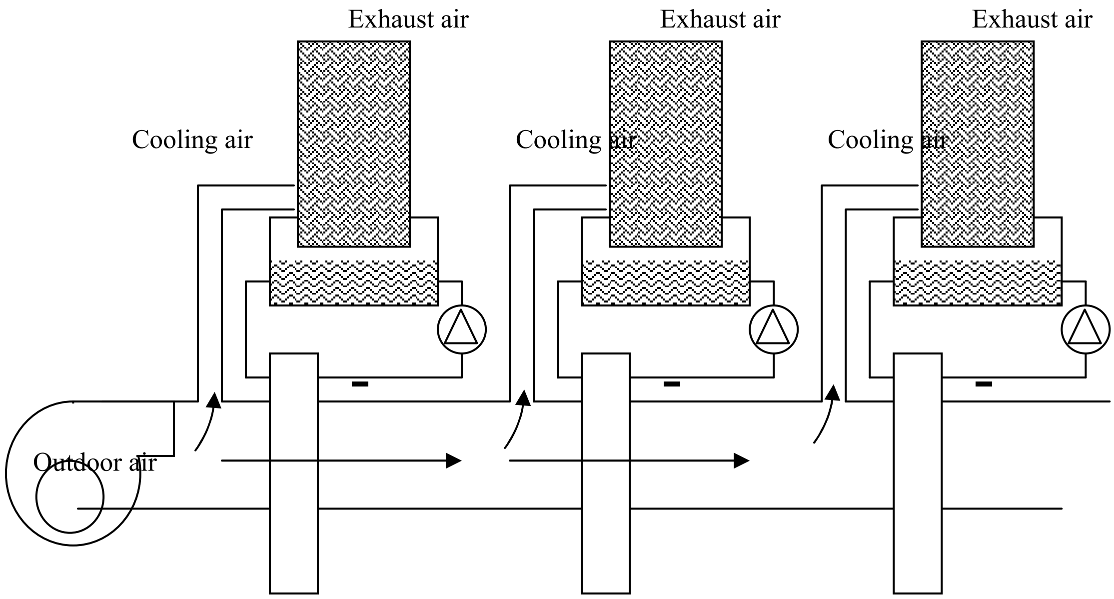


Figure 17. Mixed cooler of multiple stages

This system requires moving high air volume flows to be able to make the due extractions to evaporative cooing the air in the devices that operate like cooling towers. It consists of various indirect evaporative coolers, and permit to sensible cooling part of the air, theoretically up to the dew point temperature of outdoor air.
When absolute humidity of outdoor air is too low, also low supply temperatures can be achieved with various stages, although it must be taken into account that each intermediate stage implies its own power consumption, reduces the amount of treated air and provides smaller temperature differences between the air and water in the direct evaporative cooling process.
Finally, it should be noticed that mixed systems described usually only permit sensible cooling and humidifying, and cannot normally dehumidify the mixture of outdoor and return air unless outdoor air temperature were below 15ºC. This is an important difference with respect to the conventional cooling systems, which can cool and dehumidify whatever the conditions of outdoor air are.

4.3.2 Combination of an evaporative cooler with other cooling systems

In places where wet bulb air temperature is high, an evaporative cooler cannot succed in reaching the comfort conditions of indoor air alone.
In many applications, it is combined with another system such as a direct expansion coil (DX), resulting into a more economic solution than installing an only system.
In 1986, Anderson tested an air conditioning system using a direct and an indirect evaporative cooler combined with an expansion battery, and compared it to a system composed only of a DX, such as the one shown in Figure 18.
Some operation parameters, initial investment and energetic consumption of both systems are gathered in the Table 1.
To control the cooling capacity in each stage of a system, it is common to follow the next steps: indirect evaporative cooler, direct evaporative cooler and finally the DX coil.
If an electric consumption of about 0.1 €/kWh for a combined system like the one described is considered, the return time expected is 3974 hours. If the system is supposed to work 1000 hours a year, the return time estimated for the additional investment is between 4 and 8 years.

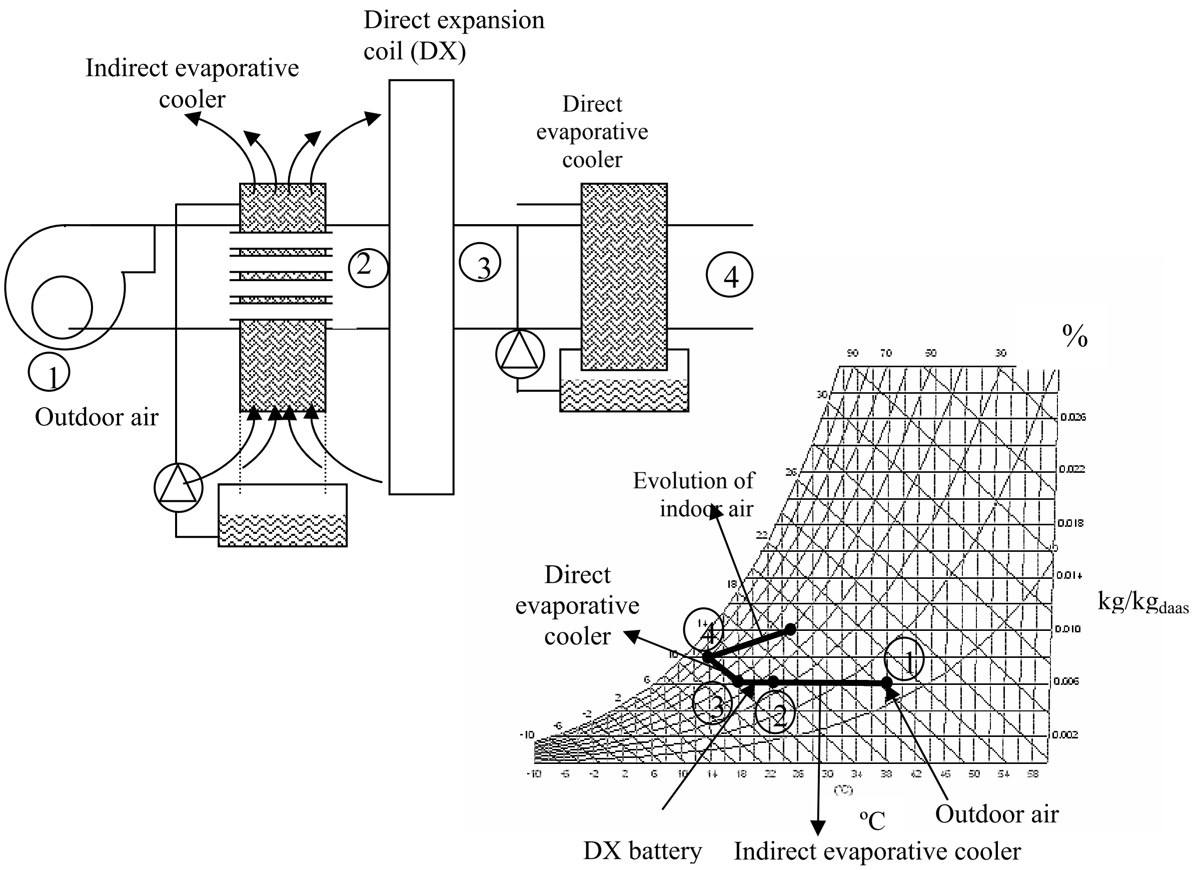


Figure 18. (a) Configuration and operation of a combined system of evaporative coolers

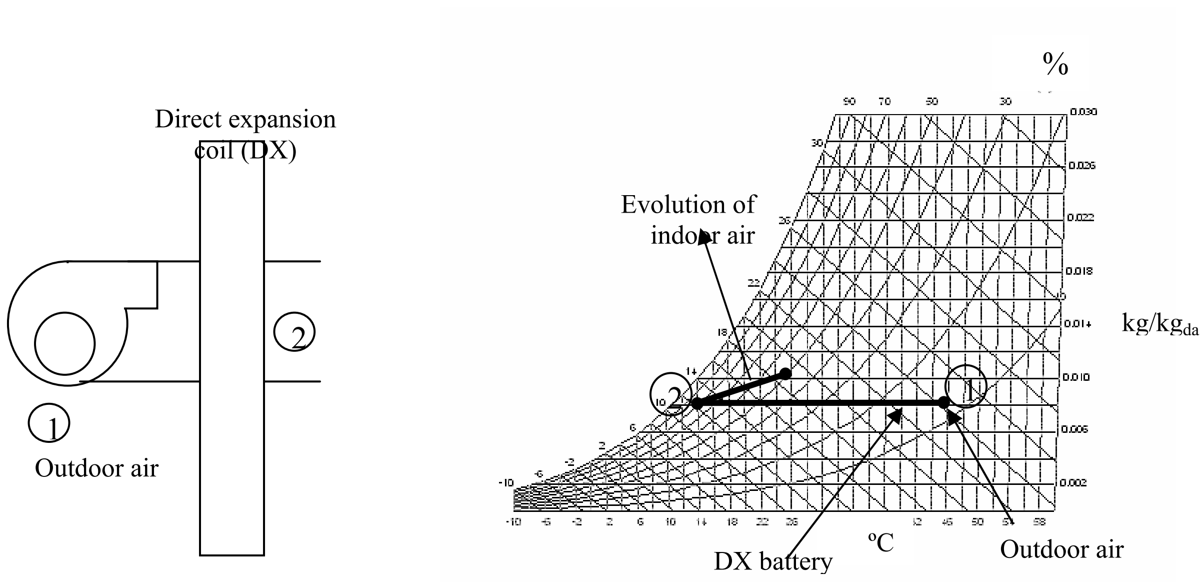


Figure 18. (b) Configuration and operation of a single direct expansion coil

Table 1. Comparative study of a simple direct expansion system and a combined system with direct and indirect evaporative cooling

Outdoor air	T_{da} = 38 C
	T_{wb} = 21 C
Supply air	T_{dry} = 14 C
	T_{wb} = 13.5 C
Indoor air	T_{dry} = 25 C
	T_{wb} = 50 C
Fan effectiveness	0.6

Indirect evaporative cooler effectiveness	0.7
Indirect evaporative cooler effectiveness	0.9
EER	2.63
Air ventilation ratio	15 %
Combined system costs / Simple system costs	2.25
Electric consumption of the combined cooling system	0.313
Electric consumption of the DX battery	0.509

4.4 Design criteria
Some criteria must be considered when designing this kind of cooling systems.

4.4.1 Design of direct evaporative coolers
The main parameter considered when evaluating the performance of direct evaporative coolers is the Saturation Effectiveness (ε_s), which can be defined as [9]:

$$\varepsilon_S = \frac{T_{11} - T_{12}}{T_{11} - T_{h11}} \tag{5}$$

where ε is the saturation effectiveness, T_{11} is the outdoor air temperature, T_{12} is the supply air temperature and T_{h1} is the outdoor air wet bulb temperature.
The value of the Saturation Effectiveness depends on the following factors:

1- Air velocity through the cooler: For a specific cooler, with a particular area and water flow, an increment in the velocity would result in:
- A higher air volume flow.
- A higher effect of evaporative cooling, which can be calculated as:

$$Q = \dot{m}_a \, Cp_a (T_{11} - T_{12}) = v \cdot S \cdot \rho \cdot Cp_a (T_{11} - T_{12}) \tag{6}$$

where Q is the sensible heat (W), v is the air velocity (m/s), S is the area section (m^2) and ρ is the density (kg_{da}/m^3)

In the majority of the direct evaporative coolers, velocity must not exceed 3 m/s to prevent generation aerosols. In other case it would be necessary to dispose a drift eliminator, which increases slightly the pressure drop.

2- Relation water/air (M_w / M_a): This is the relation between the mass flow of atomized water and air flow. A high value shows a higher contact area between air and water and thus higher ε_s.

3- Configuration of the humid surface: A humidifier that provides a higher area and time of contact between air and water permits obtaining higher values of ε_s.

In these systems water recirculation is generally used to save water and improve economic results. The recirculated water temperature is close to the wet bulb air temperature. Given that air comes into direct contact with the atomized water, this process permits cleaning the air by removing particles of dust into it. However, if there are great amounts of dust or particles into the air, an additional filter should be used to prevent the fouling of the humidifier and the nozzles.

4.4.2 Advantages and disadvantages

The main advantages of evaporative coolers are their low cost and high effectiveness, permitting a wide range of applications and versatility in the buildings, dwellings, commercial and industrial sectors. They can be specially applied in dry and hot climates, as the minimum cooling temperature for the air depend on its the wet bulb temperature.

It is convenient sometimes to humidify the air, in which cases the direct evaporative cooling is an interesting solution. On the other hand, conventional air-conditioning systems usually dry up the air for being controlled only by the return temperature level and not by the required humidity levels. When it is not possible to humidify, indirect evaporative systems in a regenerative or recovering configuration are preferred. However, direct evaporative devices act like filters, removing dust particles in air.

The main disadvantage is the fact that when water evaporates at the temperature of the environment, bacteria such as legionnaire's can develop into the air stream supplied to the room. This requires an effective bactericidal treatment, which would incur in more complicated control systems. Currently, a study developed by the ASHRAE has cast doubt on this supposing, making more interesting the idea of considering and analyzing the use of these devices.

Another disadvantage is the water consumption associated to the operation of these systems, which is a scarce resource in dry and hot climates, where these systems best work. However, the reduction in electric consumption implies compensation in the global amount of water consumed. This is due to the fact that conventional power plants with an average performance of 40% require removing the remaining 60% heat in a cooling tower. Thus, the electric energy used in conventional systems also implies great water consumption [10] [11].

5. Legionnaire's disease

The bacteriological contamination, mainly by legionnaire's bacteria, has become the main disadvantage of the evaporative cooling systems. Therefore, this implies that in many cases the use of these devices is avoided, despite their high energetic effectiveness, because of the maintenance costs and risks of contamination. Thus, systems like cooling towers or evaporative condensers are being replaced by other less efficient ones. The risk of contamination by Legionnaire's bacteria makes necessary a due maintenance of evaporative coolers that permit the use of such efficient systems ensuring the security of people who develop their activity close to it.

In the case of direct evaporative cooling systems, this contamination can be produced in the primary air stream, which is supplied to the conditioned rooms. For this reason, indirect evaporative systems are preferred, despite their lower effectiveness, because they use a heat-exchanger that avoids the contamination of supply air, though it is necessary a specific treatment of the secondary air, where evaporative cooling is produced.

As a consequence of this problem, this paper includes some information about legionnaire's disease, to provide some general concepts of interest for the use of this kind of cooling systems.

Legionnaire's disease, discovered in 1977 after the pneumonia outbreak declared in 1976 among the attendants to a congress of the American Legion veterans, is composed of a group of bacillus bacteria, either spherical or elongated depending on the environment conditions. It already existed on Earth before humankind, and gathers over 42 species, not all of them virulent; being the serogroup 1 of Legionella Pneumophila the most frequent in supply water and the one that produces most infections.

Several enchained events must be produced to make the contagion possible. They are represented in Figure 19.

Existence of a virulent strain of legionnaire's bacteria in a plant from supply water or aerosols generated in contaminated plants nearby.

Uncontrolled conditions in plants are consequence of a default in the maintenance. The bacteria feed from organic waste in water, and take refuge in incrustations and biofilm. Incrustation problems and dirtiness combined with the optimal temperature range for the operation between 20 and 45 C, let the bacteria spread in the water up to high concentrations [12].

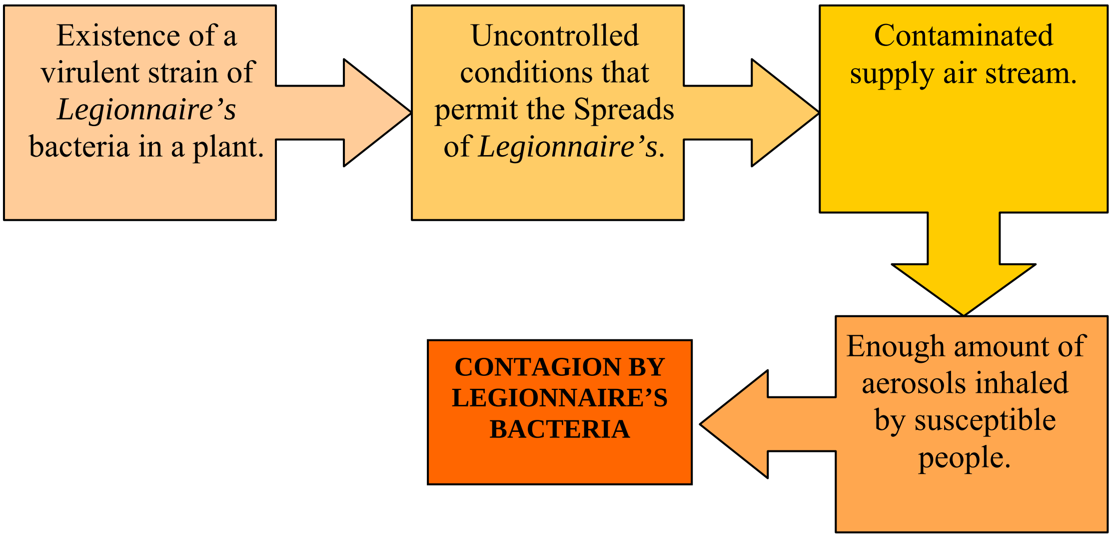


Figure 19. Required steps for contamination by Legionnaire's disease

When devices such as cooling towers, evaporative condensers, adiabatic humidifiers, etc. operate generating aerosols, if these are concentrated enough and reach the respiratory system of susceptible people (elderly, smokers, people with respiratory problems, etc) the contagion by legionnaire's disease can be produced and must be clinically treated. Death of the patient only occurs in some cases.
If any of the upper steps is missed; that is to say, if there is no dirtiness, incrustations or the due thermal level that permits the spread of the bacteria, there are no aerosols in supply or exhaust air stream, etc., legionnaire's disease does not appear.
Evaporative systems cannot be sterilized by thermal processes, like in the production of domestic hot water. So other kind of solutions must be applied, such as chemical biocides (hypochlorite, chlorine-dioxide, etc.) or other treatments to inerting bacteria like metallic toxins, ultraviolet radiation, or titanium dioxide photocatalysis.
Treatments with biocides are effective only if the installation is clean and there are no incrustations or stagnant water areas where bacteria can shelter from the disinfectant, as shown in Figure 20. A disinfecting treatment in a dirty installation will not be effective [13].

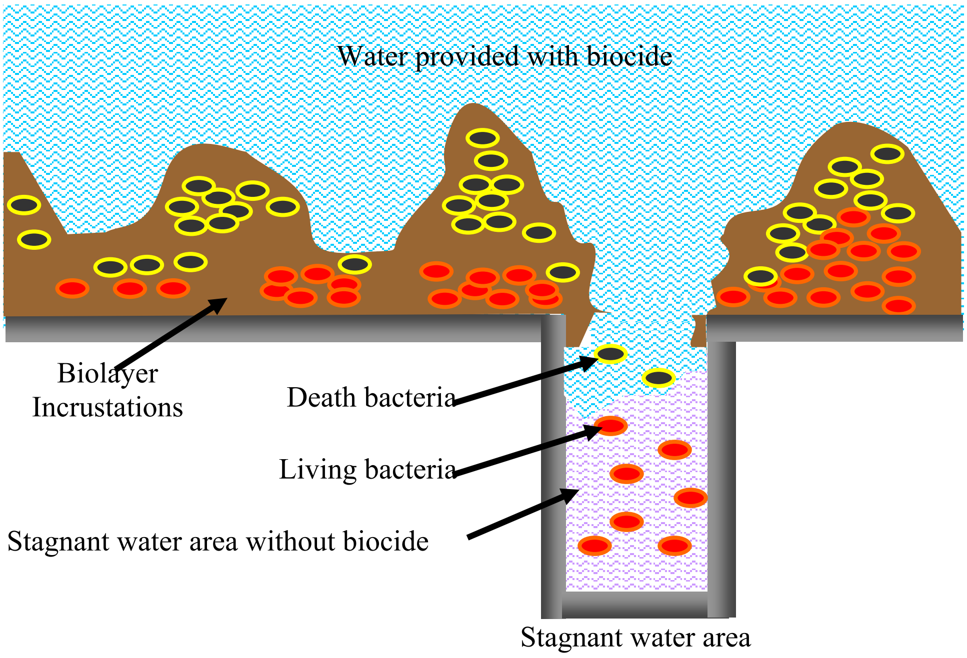


Figure 20. Protected zones where legionnaire's bacteria take shelter

Incrustations and biofilm formed, characteristic in inadequately maintained installations, come from the material ported by the air or generated by the deterioration of the metallic elements in contact with water; but they mainly come from the salt content in supply water, so it is very important to establish an adequate level of water purges to ensure lower values of salt concentration than those of saturation.

There are many disinfection processes. One example is the ultraviolet radiation that inerts supply water by modifying the bacteria genetic code, thus avoiding their proliferation. Another possibility is the titanium dioxide photocatalysis that oxidizes organic material in the supply water. These treatments are efficient if there is no possibility of bacteria contamination downstream, and it must be probed that incrustations are not produced in the ultraviolet lamps, which could avoid the bacteria exposition to the radiation.

Finally, systems to filter air and water have been introduced to avoid the bacteria supply and spread. It is important to study the variation in the pressure drop in this kind of treatments, to avoid increasing excessively the consumption of the circulation devices such as pumps and fans.

6. Experimental evaporative cooling devices developed by the Research Group and experimental results

The Thermal Engineering Research Group of the Energy Engineering and Fluidmechanics Department of the University of Valladolid has developed its work with the aim of improving the energetic efficiency in buildings, reducing the amount of energy required to provide the optimal thermal conditions inside habited spaces.

Most devices introduced below have been developed to work in a heat-recovery mode in air-conditioning systems, taking advantage of the exhaust air cooling capacity.

6.1 Evaporative cooler made of ceramic pipes

This device is a semi-indirect evaporative cooler made of ceramic pipes arranged vertically, whose aim is to take advantage of the possibilities to filter water of the ceramic material. The air stream that has to be cooled circulates outside the pipes, while the exhaust air from the room circulates inside, in contact with water introduced through the upper end of the pipes. Thus, the air inside the tubes is evaporativelly cooled.

Figure 21 show the configuration of the device operation, as well as some images of the prototype.

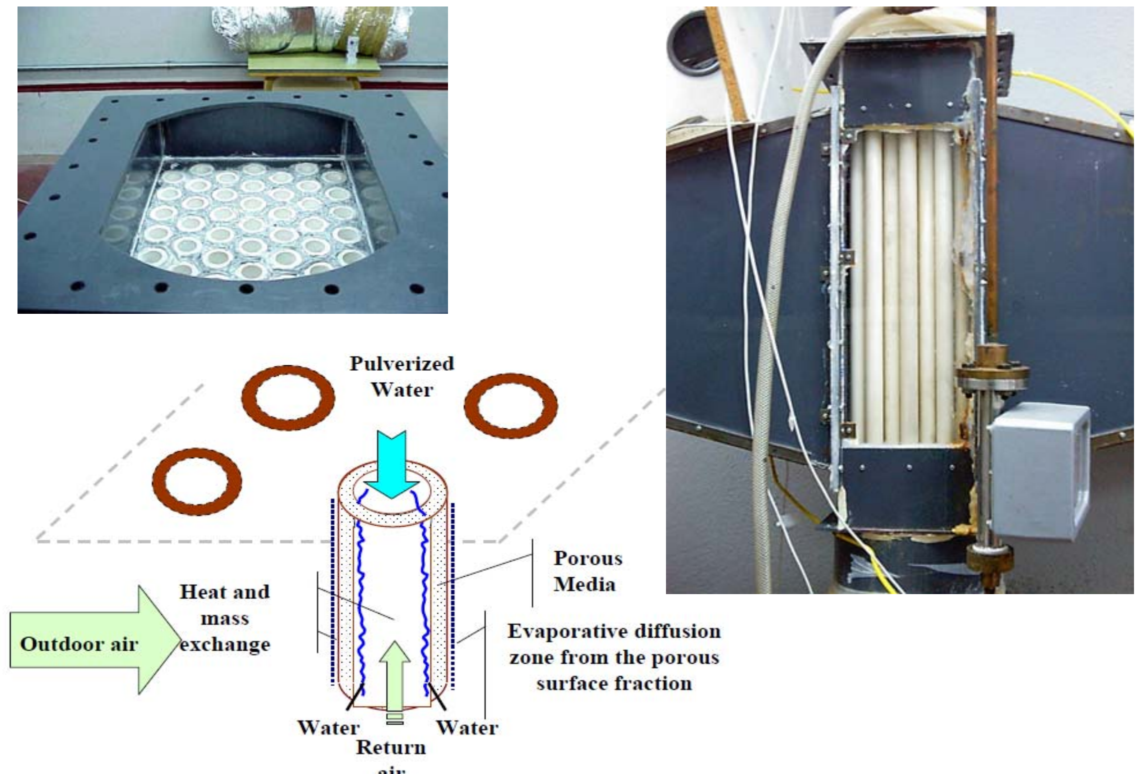
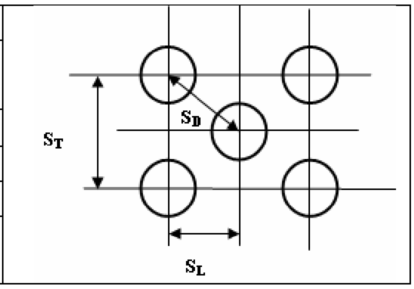


Figure 21. Operation configuration and images of different parts of the experimental system

The geometrical characteristics are gathered in Table 2.

Table 2. Geometric characteristics of the ceramic evaporative recover

Inside diameter (di)	15 mm	Pipe length	600 mm
Outside diameter (de)	25 mm	Area (Ao)	2,3 m^2
Wall thickness (δ)	5 mm	Disposition	Staggered
Length T (S_T)	30 mm	No. of columns	7
Length L (S_L)	25 mm	No. of rows	7
Length D (S_D)	29.15 mm	No. of pipes	49



Depending on the characteristics of outside air, the device has been designed in such a way that it can behave either as a direct evaporative cooler. If outside air is dry, taking advantage of its evaporative cooling capacity; or as an indirect system if outside air is humid and its dew point temperature is over that of wet bulb of the air that circulates inside the pipes. Thus it has been called “semi-indirect”. The second case is characteristic of tropical climates, and this situation can result into condensation of part of the outside air humidity, due to the low humidity of the stuffy air inside the conditioned room.
Figure 22 shows a photograph of the ceramic wall when the system operates under condensation conditions, as well as the evolution zone of outside air while passing through the device. It is delimitated by the adiabatic saturation lines of outside and exhaust air (used for the phenomenon of evaporative cooling). It can be observed that in some cases in this zone supply air at the outlet of the system has a lower absolute humidity than the one it had at the inlet.

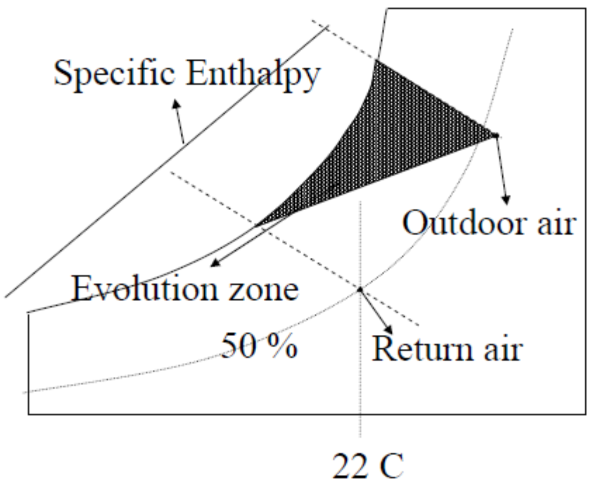


Figure 22. Photograph of the device and operation evolution working as an indirect evaporative cooler under condensation conditions

However, the most common operation way of this system is as a direct evaporative cooler. Figure 23 shows the experimental results of the device operation evolution when outside air is characteristic of a dry and hot climate, corresponding to that of continental climates during summer season. The operation parameters established to design the experimental test are: 41 C of outside air temperature, relative humidity: 16 % and air volume flow provided: 500 m^3/h.
Results show that the system can cool outside air, taking advantage of its low humidity, from about 41 C to 33 C. This important difference is due to outside air cooling capacity, as its relative humidity is too low (16 %), being increased up to around 26 % at the outlet.

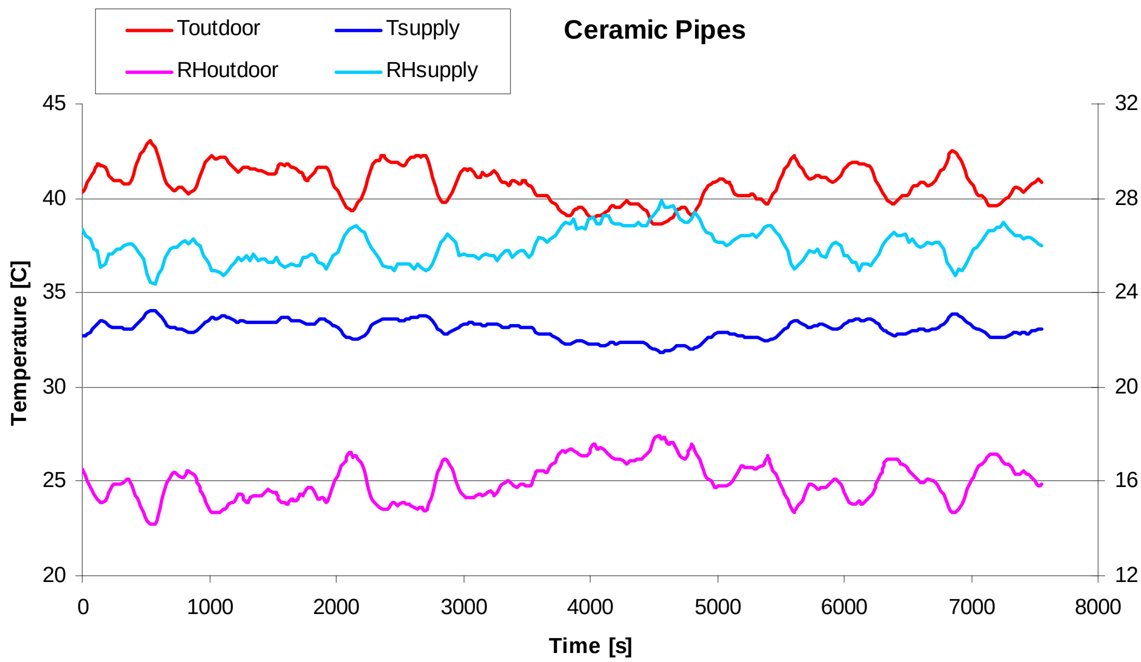


Figure 23. Characteristic test for the device operating as a direct evaporative cooler

The humidification limit of this system is established by the capacity to capillary transport water through the ceramic wall of the pipes. An increase in the amount of water capillary transported would result into higher cooling and humidifying of the air while passing through the bank of tubes. The capillary flow can be increased by using a more porous material.

The characterization of the experimental device was performed by an experimental design, considering factors such as air volume flow, inlet air temperature and relative humidity range. Some of the most characteristic experimental results obtained about the operation of the device can be looked up in the references [14].

6.2 Evaporative cooler made of hollow bricks.

Another device made of hollow bricks was designed and manufactured aiming to simplify the construction configuration of the one made of ceramic pipes. This material is also ceramic, and thus can behave as a filter for the water that evaporates into the air that we want to cool. Its porosity is much higher and the wall thickness is smaller than that of the pipes, so the amount of water transported through the ceramic wall is bigger. Other advantages of this material are its low cost; its facility to be acquired, lower fragility and furthermore salt incrustations can be more easily cleaned.

However, some disadvantages can be found, such as the numerous manufacturing defaults like hollows in the surface, cracks, burst, etc. that are not so common in ceramic pipes. This problem requires a previous checking and selection of the bricks that are going to be used to manufacture the experimental device.

The device has been dimensioned to enable it to operate with its hollows filled with still water that passes through the ceramic wall of the brick with a certain flow that depend on its pressure, which can be modified by varying the feeding water column.

In the case study, water fills the hollows and come from an upper tank were it is accumulated after being evaporatively cooled with the aid of the stuffed exhaust air from the conditioned room. Given that water is filling the hollows in stillness, it is not circulating through the device and that the main evaporative cooling process is produced into the outside air stream, the cooling capacity only depends on the conditions of the air that has to be cooled [15].

The experimental device is made of 12 hollow bricks arranged in groups of 4. Each brick has a water-feeding system and an air outlet, ensuring that the hollows of the bricks are completely filled with water. Outdoor air circulates outside the bricks, in three shell passes.

Figures 24 and 25 show the operation configuration of the experimental device as well as some photographs of the manufacturing process, respectively.

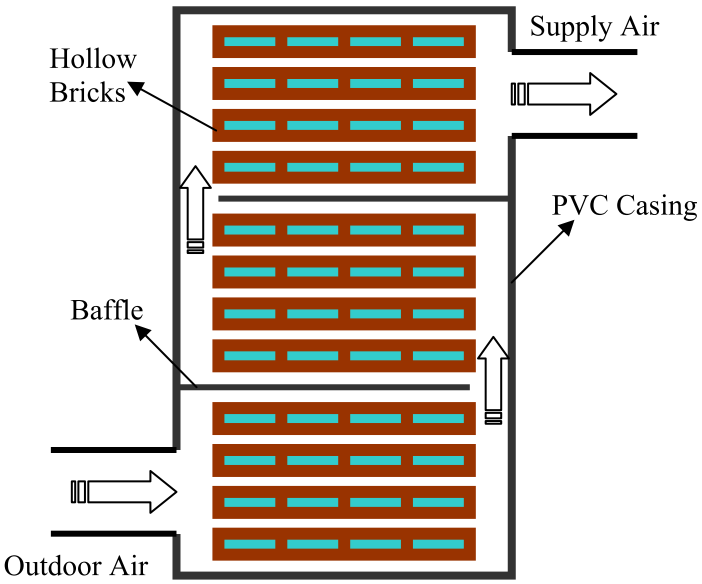


Figure 24. (a) Outdoor air circulation scheme

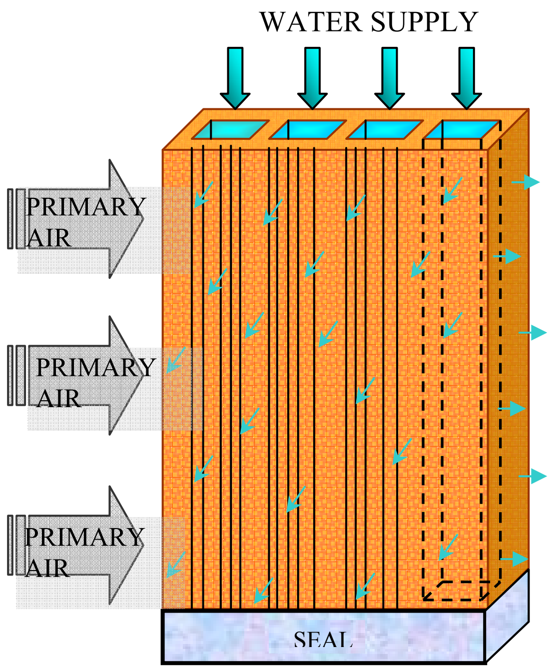


Figure 24. (b) Operation configuration of the bricks

Figure 25. Photographs of the manufacturing process

The system works as a direct evaporative cooler, where the primary air stream is cooled by the water evaporation from the outerwall of the bricks into that air. The cooling capacity of the device depends on the amount of evaporated water from the humid surface into the air. Thus, the mechanisms of mass-transfer are consequence of the mass-diffusion through the ceramic material (water capillary transported) and the convective diffusion due to the vapour pressure of water gradient between the surface and the air.
Figure 26 shows the system behaviour in similar conditions to the ones established for the semi-indirect evaporative recover made of ceramic pipes introduced before. This test has been performed for outside air temperature of 40 C, 18 % of relative humidity and 540 m^3/h.
The graph shows how air can be cooled from 40 C to 32 C just taking advantage of the cooling capacity of the evaporative system, being able to provide differences of temperature between inlet and outlet air close to those of the recovering system made of ceramic pipes. Moreover, the cooling capacity in this case is also associated to the increase of outside air relative humidity.
Thus, the system's cooling capacity is similar to the one obtained for the ceramic pipes, while this new device has more advantages.

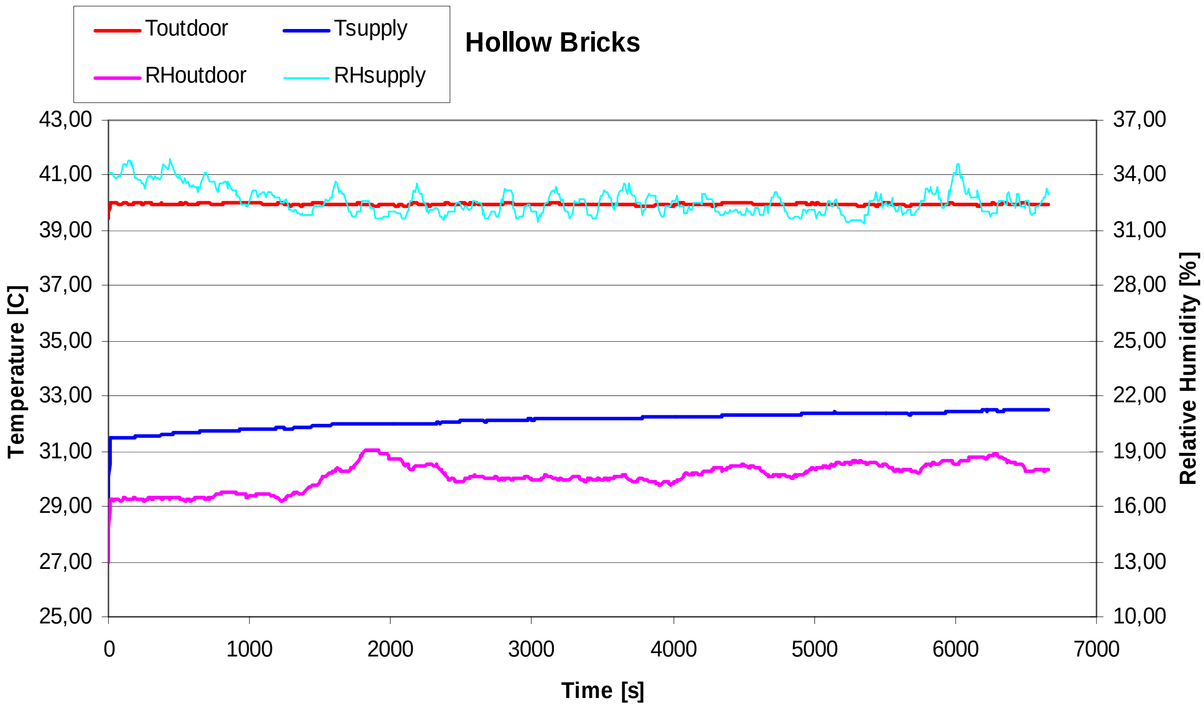


Figure 26. Characteristic test for the device operating with dry outdoor air

6.3 Textile evaporative cooler

It has been traditionally and widely used to cool air in dry and hot climates to dispose humid clothes in the room that has to be conditioned.

With the aim to reduce the size and weight of the systems introduced before, which are made of ceramic material, another device mainly made of wet textile band has been designed, manufactured and characterised. It is basically a cotton band of 25 cm width and 1600 cm length, disposed in a plasticized wire matrix. The cloth is humidified with the aid of an upper water distributor, which is fed by pumping water from a lower tank.

The advantages of this new system are: its easy manufacture; simple maintenance, limited to the periodic cleaning of the textile material; and its low consumption. On the other hand, contrary to ceramic-based devices it does not present the advantage of filtering the water that is evaporated into the primary air stream. Moreover, given that the mass-exchange through convective processes is produced in both sides of the cloth, the surface from which the water evaporates to evaporatively cooling the air is much bigger. In the experimental prototype the real effective area is estimated to be about 7 m^2, for part of the surface is not effective due to the edge effects characteristics in the design.

The main disadvantage is the risk of legionnaire’s disease. In fact, water used in the process must be previously treated with a biocide. However, water temperature is close to the wet bulb air temperature, being in most cases below the necessary value to permit the spread of the bacteria. On the other hand, humidification is produced from a humid surface, thus not appearing aerosols by dragging drops from it if air velocity is not very high.

In Figures 27 and 28 some photographs of the experimental device manufacturing steps are shown. It can be noticed that extruded polystyrene separators are needed to ensure that the air paths are open between the clothes. The upper distributor and lower water tank provided with a pump are also shown.

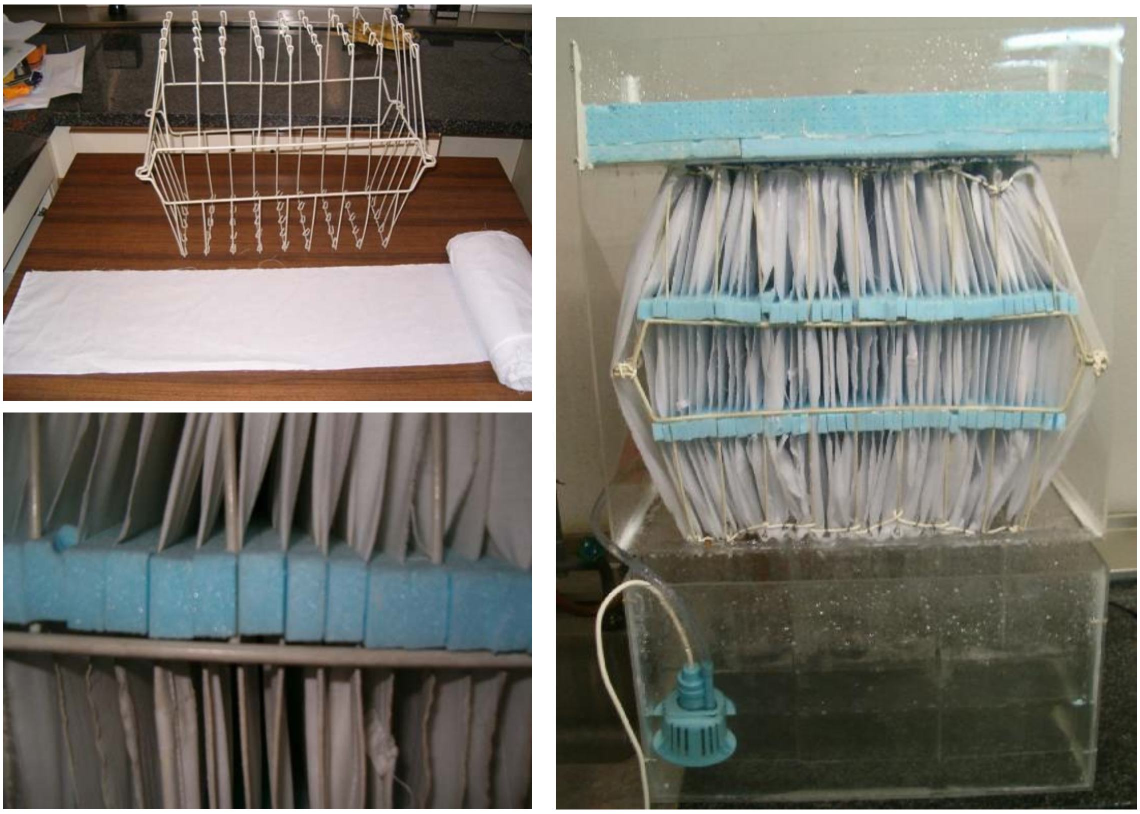


Figure 27. Photographs of the manufacturing process of the textile evaporative cooler

Figure 28. Final image of the textile evaporative cooler

The whole device has been connected to an Air Treatment Unit to permit reproducing different conditions of outdoor air that could experimentally characterize the cooling capacity and humidity variation of the system. The maximum air volume flow provided by this system is 480 m^3/h, which is slightly below the values established in previous tests for the other experimental evaporative devices.
This experimental configuration does not permit controlling the temperature at the outlet, so outdoor air temperature is not constant though it allows studying the behaviour of the system when it varies.
Similar to the other systems introduced, in Figure 29 gathers the experimental results obtained with this new prototype for similar outdoor air conditions already studied with the other two, characteristic of continental climates during summer season (about 37-42 C and RH: 15 %).

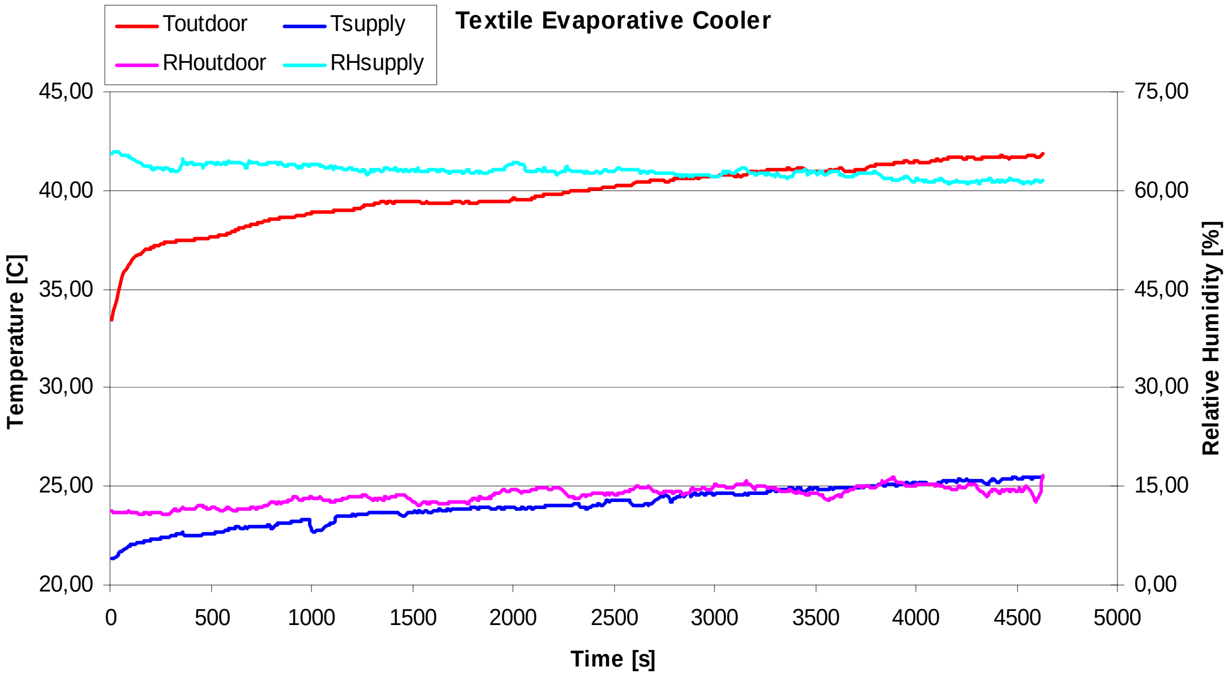


Figure 29. Experimental results obtained for the textile evaporative cooler

Regarding the experimental results obtained, it is inferred that the device can cool the air from its initial conditions of 40 C to 25 C, conditions that are included in the comfort area defined by ASHRAE (Figure 30). As well as the other two cases, cooling is performed as a consequence of an increase in the humidity level, though in this case it is more effective for not being limited by the capillary transport of water. Actually, it only depends on the convective mass-diffusion process originated by the gradient of vapour concentration between the wet cloth and the air that has to be cooled.
Nevertheless, it should be noticed that the thermal sensation for the defined conditions of outdoor air would correspond to an extremely hot environment, while the air conditions obtained after being treated by the evaporative cooling system would correspond to a slightly hot environment which could be neutralised for example by modifying the air velocity in the occupied area, in order to increase the effect of the convective cooling of the skin.
Despite the disadvantages noted and the precautions suggested for its use, this system appears to be an interesting energetic alternative for cooling ventilation air.

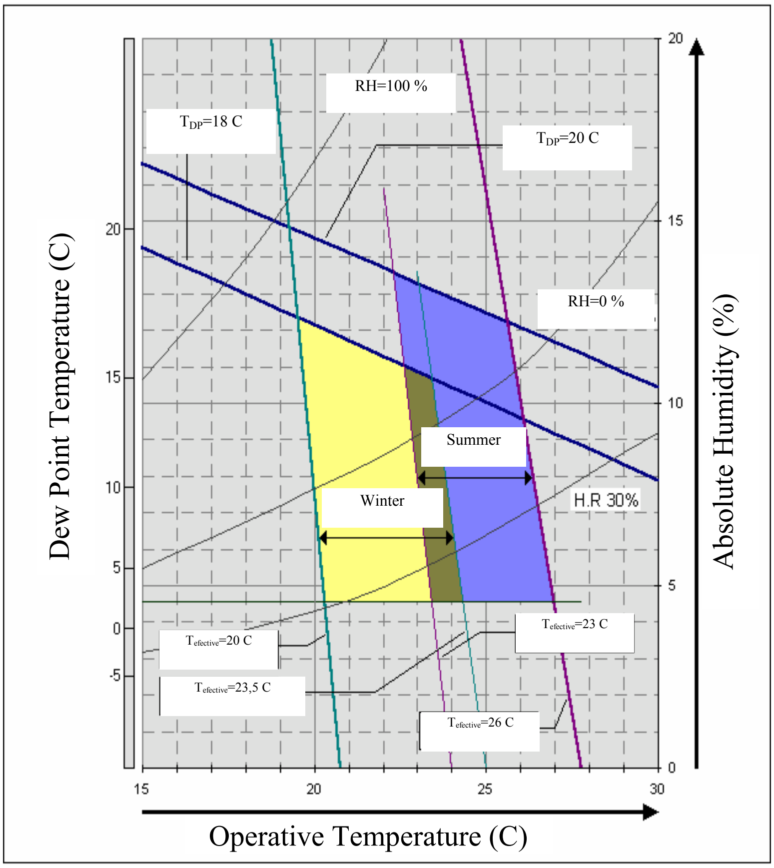


Figure 30. Zone of thermal comfort defined by ASHRAE

7. Conclusions

The phenomenon of evaporative cooling has being traditionally used to cool air; however, it is not very applied despite its high energetic efficiency currently, due to problems related to this process, such as legionnaire's disease or the device maintenance, but mainly to the strong prominence of other conventional cooling systems such as mechanic compression.

The necessity to reduce the energetic consumption in buildings to fit to the numerous international normative and protocols, ensuring an adequate comfort level inside, lead to the importance of developing alternative processes to reduce the dependence of this sector on fossil fuels. There are many interesting alternatives for heating processes, such as the ones provided by solar energy applications. On the other hand, to cool air in summer, mainly in hot and dry climates, the process of evaporative or adiabatic cooling appears as an alternative.

There are many systems that can operate as direct, indirect or mixed evaporative coolers, depending on whether to neutralise the internal loads it is adequate to adiabatically cool the air or it is required a sensible cooling with an indirect system, less effective but avoiding humidification of supply air.

Although evaporative systems consume water, also power plants require water consumption in the production of the electricity used by the conventional air-conditioning systems.

The problems associated to contamination by legionnaire's bacteria can be minimized by different proceedings such as an adequate cleaning of the systems, treatments with chemical or physical biocides, ensuring that the bacteria concentration in the evaporated water is not important, avoiding elements filled with still water, the generation of aerosols, etc. It must be considered that it is a problem to take into account, but that should not avoid the use of these really energetic effective cooling systems.

Three experimental prototypes have been introduced, which have been designed, manufactured and characterised by the Thermal Engineering Research Group of the University of Valladolid. The experimental results have been obtained for similar conditions of outdoor air typical of dry and hot summers, 40 C and low relative humidity.

The results obtained for the two systems based in ceramic materials, the one made of ceramic pipes in a recovering configuration and the direct evaporative cooler, are quite similar. Their main advantage is that the operation of the system permits the previous filtering of the water that evaporates into the air. However, their cooling capacity is limited because the amount of evaporated water depends on the mass-diffusion through the ceramic wall, being this fact the main resistance in the mass-exchange process, limiting the cooling capacity of these systems.
Finally, the direct evaporative cooler made of cloth, presents a higher efficiency than the first two ones, as it permits cooling air with low humidity content from 40 C to the comfort conditions established by ASHRAE.
The places where these systems result to be more effective are those characterised by dry and hot climates. However, evaporative cooling systems in a recovering configuration can be applied in whatever climate, as they take advantage of stuffed exhaust air from conditioned rooms, whose conditions are close to those of comfort, to cool the water used in the evaporative process.

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