TECHNICAL NOTE ON EVAPORATIVE COOLING

Renato Lazzarin, President of the IIR's Commission E1

Principles

The air has a variable water content from 0 (dry air) to a maximum value (saturated air) that strongly depends on its temperature. Relative humidity is an index of how far is air at a given temperature from saturation (0% dry air, 100% saturated air). Specific humidity is the mass of water contained by a unit mass of dry air. Relative humidity can be increased introducing water in the form of numerous minute droplets into the air, using a process known as *nebulisation, pulverisation or atomisation.* A second method is based on the use of a suitable solid media that, both due to its extensive geometric configuration and its highly-porous microscopic structure, exposes the air to a very large area that, if kept wet, acts as a vast *water-air interface surface*.

If the temperature of water is not far from the temperature of the air to be humidified, the evaporation of water reduces the air temperature till the so called wet bulb temperature. Wet bulb temperature coincides with the dry bulb temperature only when the air is saturated, otherwise it is lower. The cooling of the air is due to the increase of the latent portion of the internal energy of the air while the sensible portion decreases.

The cooling effect produced by the evaporation of water from containers with permeable walls, such as the wineskins or unglazed terracotta vases, has always been exploited: the small quantity of water that perspires through the porous barrier when evaporating maintains the rest of the container at a temperature that when stable is near the wet bulb temperature of the outside air.

How lower is the wet bulb temperature depends on the initial temperature and relative humidity of the air. The reduction in temperature is only slight if the starting point is a relatively low temperature, as the moisture content that can be absorbed is limited. Take the example of air at a temperature of 7 °C and with a relative humidity of 40%: the lower limit temperature is around 2 °C, a significant decrease from the starting value, but only small in absolute terms. The cooling capacity of an adiabatic humidification system is higher in the event of relatively high starting temperatures and low moisture contents. Looking at the wet bulb temperature of relatively dry air, at a temperature of 25-30 °C, it can be seen how the temperature difference may exceed 10 °C.

Consider in fig. 1 specific cooling energy (q) and lowering of the temperature (final temperature t_2 – initial temperature t_1) obtainable by humidifying air, with a saturation efficiency η = 100%, according to the initial temperature (t_1) and the relative humidity ($\varphi 1$).

Direct cooling

The evaporative cooling of the fresh air intake may be useful if the wet bulb temperature of the outside air is lower than the value required in the air-conditioned environment and, at the same time, the specific humidity is sufficiently lower than that of the air-conditioned environment, so as to be able to easily satisfy the indoor latent loads.

Freecooling systems are used in environments where the indoor thermal load is such as to require cooling even when the outside temperature is lower than the desired indoor temperature. These systems exploit the possibility to reduce the energy required from the refrigeration system by letting in a suitable quantity of outside air, varying from a minimum value, equal to the required renewal flow-rate, to a maximum value equal to the total flow-rate the plant can deliver. Humidifying the air can extend the outside air free cooling condition, as it is only necessary that wet bulb outside temperature is lower than inside dry temperature to allow free cooling, even if outside dry bulb temperature is higher than inside. The more outside air is introduced, the greater the benefits, provided that the inside humidity is not increased too much. This usually happens in a hot dry climate. The contribution of free cooling to the load by humidification is then constrained by the maximum inside acceptable relative humidity. The extent of humidification of the air can be finely controlled with the new generation atomisers and the left part of the load can be satisfied with a traditional cooling coil. See a possible scheme in fig. 2 where a suitable mixture of renewal (outside) and recirculated air is first humidified to a set value (the required specific humidity) and it is finally cooled to the required inlet temperature[1].

Indirect cooling

If it is not acceptable to add moisture to the inlet air, when the climate is not so dry or the latent loads are high, indirect evaporative cooling may be a suitable solution. The humidification regards a secondary air stream that cools with a heat exchanger the inlet air. The secondary stream may be outside air as long as it is not saturated. In many cases, this operation is even more effective and predictable if the stream of cooling air is the air being discharged. In fact when the inside condition are controlled, temperature and humidity of the exhausted air are really very favourable to evaporative cooling. Consider a possible scheme in fig. 3. The ambient air, before being expelled, is humidified: its temperature decreases, and therefore it can be used for heat exchange with the fresh air, which is cooled without its moisture content changing. In this way, a certain level of *freecooling* is possible even if the wet bulb temperature of the outside air is higher than the ambient one. The important thing is that the wet bulb temperature of the air after the indirect heat exchange is less than the wet bulb ambient temperature. Of course the penalty of this indirect heat exchange must be taken into account.
Different types of air to air heat exchangers can be used. The most cost effective is probably the cross flow plate. The most energy effective are heat pipe and heat wheel exchangers, whereas runaround coils may be used where supply and return air ducts are far one from another[2].
Of course these heat exchangers offer a useful service even in winter for preheating the renew air by the exhaust. However the introduced pressure drop must be considered and a bypass to exclude the heat exchanger when it is not useful should be evaluated.
The effectiveness of indirect evaporative cooling is sometimes so high as not only to satisfy the air renew load but even the sensible part of the building load (for the latent part dehumidification is necessary).

Indirect/Direct Evaporative Cooling

If the climatic conditions allow, both evaporative cooling techniques can be used to maximise the *freecooling* effect. The outside air can be first cooled indirectly by the suitably humidified discharged air, and then subsequently humidified. If this is not sufficient on its own to reach a suitable delivery temperature and/or humidity, cooling and/or dehumidification coils can be used, supplied by refrigeration units. Rather than describe this in generic terms, we will look at an existing installation, the data from which have been reported in literature and can be used for a series of useful evaluations[3].
The building served by the installation described is designed for office use, with a floor area of 1,553 m^2. It is located in a rather arid area of southern California, featuring an ideal climate for evaporative cooling applications. In fact, the design dry bulb temperature is 38.3 °C, with a wet bulb temperature of just 18.3 °C and therefore a specific humidity of 0.005 kg_v/kg_a (≡ 5 g_v/kg_a) and a relative humidity of just under 12%.
The installation, shown schematically in Fig. 4, envisages first the indirect evaporative cooling of the renewal air, followed by a series of transformations that lead to a delivery temperature of 12.7

[1] Lazzarin, R., Nalini, L., *Air humidification: technical, health and energy aspects*, Cap. XI, Cooling by humidification, Carel, Brugine, 2004
[2] ASHRAE HVAC Applications Handbook, Chapter 52, *Evaporative cooling*, 2011
[3] Sukhdev S. Mathandhu, *Evaporative cooling in California*, ASHRAE J., 81-84, October 2000

°C (11.7 °C wet bulb). The co-ordinates of the air before and after every process (heat exchange, humidification, the cooling coil) take into account real performance of the equipment.
The energy demand of the system is very low compared to a conventional mechanical refrigeration cooling. This could require, say, 0.3-0.4 kW electricity per kW cooling, whereas considering the energy requested by fan and pumps, an indirect evaporative cooling might require less than 1/10 of that. As far as water consumption is concerned, even considering the inefficiency of the atomiser, it should not exceed 3 kg/h per kW cooling. Concerning the cost, a pressurised water atomiser whose rated capacity is 100 kg/h might have a market price of 5,000 €. This can be at the service of a plant with a cooling capacity up to 50 kW. The correspondent heat exchanger can have a market price of say 3000 to 5000 €. The installation cost according to labor costs and lay out can even double the final costs.

Applications

The first possible application is to realise a cooling system for comfort cooling in buildings in arid areas for direct evaporative cooling, otherwise with indirect or indirect/direct evaporative cooling. The system should be equipped also with conventional refrigeration machinery to integrate the free cooling effect particularly when a fine control of temperature and humidity is requested.
Other applications are possible to produce acceptable conditions in particular ambients where air conditioning is seldom provided.
In summer the industrial ambient can be extremely uncomfortable with the only mitigation of ventilation. Evaporative cooling usually allows to reach lower effective temperatures.
A similar, yet quite different application, has been experimented on metro stations where summer cooling is often obtained by fresh air ventilation[4]. However when outside air is very hot, no comfort can be produced by simple ventilation. Instead evaporative cooling of the inlet air gives rise to a temperature lowering of some degrees (even 7-8 °C less than outside temperature) and even if the relative humidity increases, an acceptable comfort is assured at least for the short waiting period of the trains. The running cost of the system has been documented as more than 20 times less with respect a mechanical refrigerating system.
In livestock sheds, solar radiation and the production of heat due to the metabolism of the animals causes an increase in temperature above the threshold of supportability, especially during the summer. The problem arises particularly in poultry farms where, due to the fact that the birds do not perspire, an excessive ambient temperature may have fatal results, with potentially very significant economic consequences.
Mammals can tolerate higher temperatures, but with harmful effects on metabolism, on weight growth and on reproduction; in the case of dairy cattle, the production of milk is affected.
In addition to the ventilation system required for the correct renewal of air, in all these cases evaporative cooling is a suitable method for maintaining the correct range of temperature-humidity conditions.
There is not enough room to deal with applications in greenhouses, produce storage cooling, cooling the intake air in gas turbines, process cooling and many others where evaporative cooling allows to obtain favourable conditions at negligible costs in terms of investment and operation.

[4] Simonetti, R., *Energy saving in direct evaporative cooling: real application in the Madrid metro and simulated applications in Sidney offices*, Proc. 10th Int. Conf. for Enhanced Building Operations, Kuwait, 2010

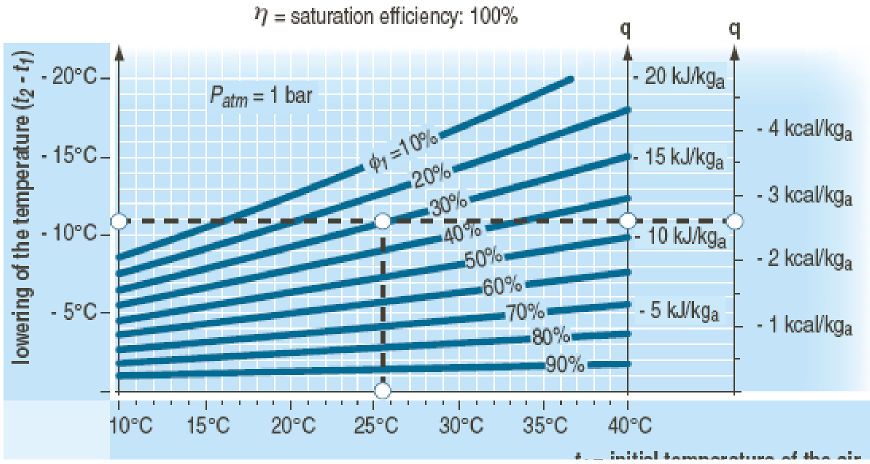
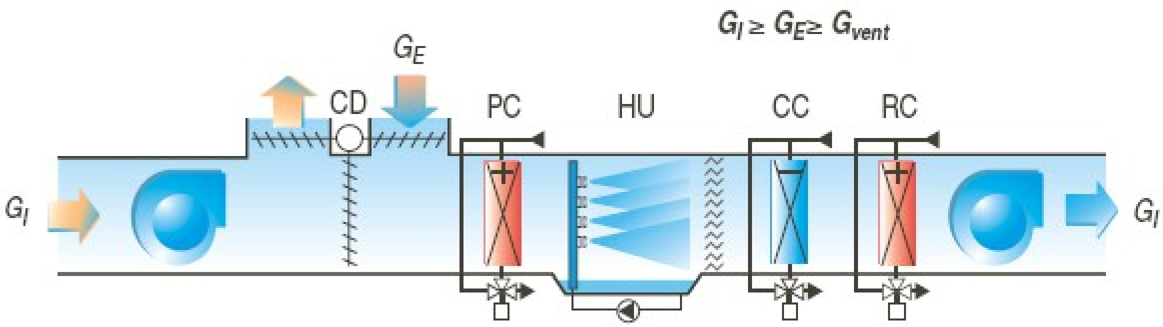
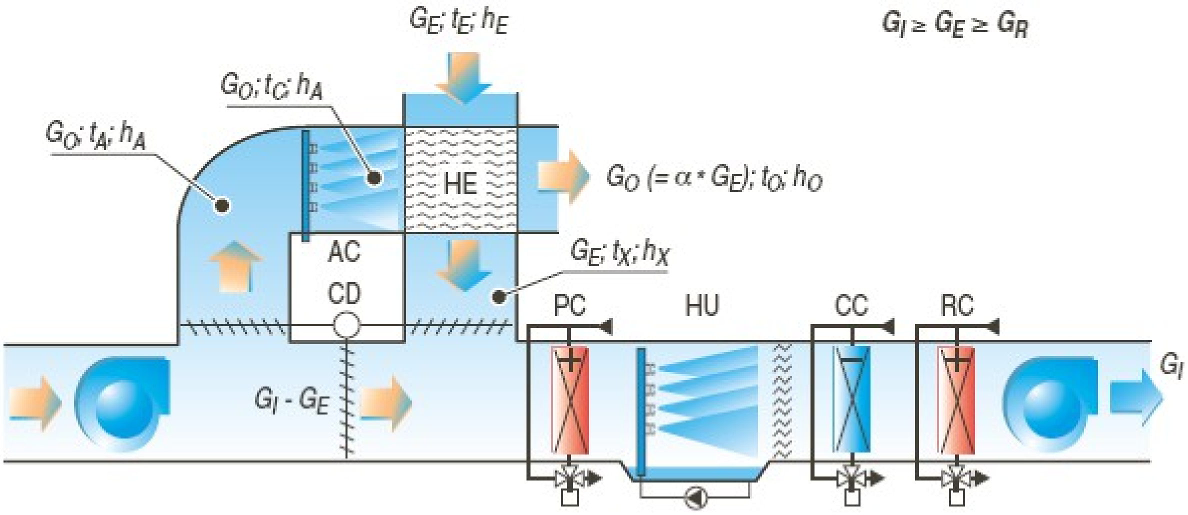


***Fig. 1 -** Specific cooling energy (q) and lowering of the temperature (final temperature t_2 – initial temperature t_1) obtainable by adiabatically humidifying air, with a saturation efficiency η = 100%, according to the initial temperature (t_1) and the relative humidity (φ_1)*



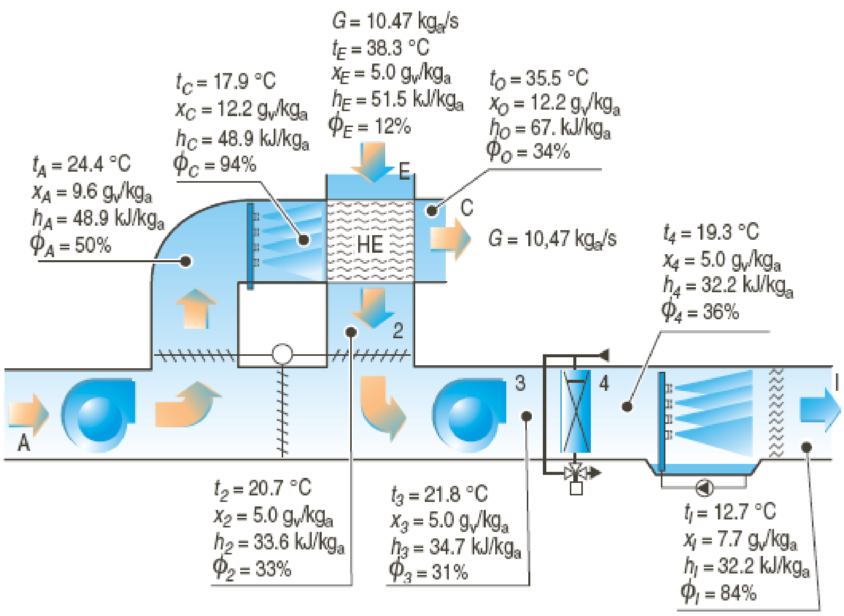
CD	Combined dampers		RC	Post-heating coil
PC	Preheating coil		G_I	Total air flow-rate
HU	Adiabatic humidifier		G_E	Outside air flow-rate
CC	Cooling coil		G_{vent}	Minimum renewal air flow-rate

Fig. 2 -System diagram for direct evaporative cooling with motor-driven dampers to adjust the recirculation of air in favour of renewal air



CD	Combined dampers	HE	Heat exchanger
PC	Preheating coil	G_I	Total air flow-rate
HU	Adiabatic humidifier	G_E	Outside air flow-rate
CC	Cooling coil	G_{vent}	Minimum renewal air flow-rate
RC	Post-heating coil	G_O	Exhaust air flow-rate
AC	Adiabatic cooler	α	Ratio between G_O and G_E

Fig. 3 Possible diagram of an installation for indirect evaporative cooling



E	Outside air	I	Air delivered into the environment
2	Renewal air after the exchanger	A	Air taken in from the environment
3	Air downstream of the fan	C	Air discharged after adiabatic cooling
4	Air after the cooling coil	O	Air discharged after the exchanger

Fig. 4 Diagram of an indirect and direct evaporative cooling installation developed in California