NOTE eNOTE IIR Information

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Evaporative Cooling

The IIR publishes Informatory Notes designed to meet the needs of decision-makers worldwide, on a regular basis. These notes summarize knowledge in key refrigeration-technology and refrigeration-application domains. Each note puts forward future priority developmental axes and provides IIR recommendations in this context.

Because of its low cost and its effectiveness, especially under a hot and dry climate, evaporative cooling should be used more. This informatory note gives a state-of-art of this simple and practical technology. The engineering principle and different operating system modes are explained using simplified representations. The energy saving potentials that could be made compared to conventional cooling systems and the concerns of the water consumption are highlighted. Air-conditioning, storage of perishable foodstuffs and pre-cooling which are main applications of evaporative cooling are explained. At the conclusion, the IIR provides some practical recommendations on the conditions of which this technology could be implemented.

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Introduction

The principle of evaporative cooling is based on the fact that the evaporation of a liquid absorbs significantly more heat than the amount required for its temperature to rise by a few degrees. As a simple example, one can experience it as the cold sensation felt when coming out of an open-air swimming pool in the wind even in warm weather. The water evaporates from the skin. This removes the heat required for the evaporation process and therefore cools the skin.

This process is used (in combination with others) in conventional refrigeration and air-conditioning systems. However, the term "evaporative cooling" refers to the cooling obtained solely by the evaporation of water in air.

The main evaporative cooling processes are: direct evaporative cooling, indirect evaporative cooling and a combination of both. The current note describes the applications and conditions under which these processes may offer a technical and economic advantage.

A description and further technical explanations are given in a Technical Note on Evaporative Cooling [Lazzarin, 2012] on the IIR website: www.iifiir.org

Operating Principles

Evaporative cooling is based on two important phenomena: i) at standard temperature and pressure, roughly 60 times more heat is required to evaporate a certain amount of water than to raise its temperature by 10°C; ii) air that is unsaturated with moisture can absorb a certain additional amount of water vapour, in which case the heat contained in the air is absorbed by the vaporization of the water. This liquid-to-vapour phase change causes the simultaneous cooling of the air and of the water remaining in liquid state.

Note: The amount of water vapour contained in the saturated air increases faster than the temperature. Therefore, evaporative cooling is particularly interesting in regions with hot and dry climates. Conversely, the potential for evaporative cooling decreases and tends to nil when air is close to humidity saturation levels. In humid climates, evaporative cooling may however be used at the condenser level in conventional refrigeration systems or heat exchangers for industrial processes, as described below.

Direct evaporative cooling is the simplest process: outdoor air passes through an enclosed space in which it enters in contact with water either in the form of fine droplets or saturating a porous medium. The water evaporates into the air, thereby making it cooler and moister. Because of the practical limitations of these systems, the relative humidity does not reach 100% but a few percentage points less (e.g. pathways 1 and 3 in Figures 1 and 2). Manufacturers call this process "adiabatic cooling" because the only heat exchange involved occurs between the air and the water with which it is in contact.

Indirect evaporative cooling: in this case, the air used to cool the room passes through a heat exchanger placed in an evaporatively cooled enclosed space. As the quantity of water vapour in the air remains unchanged, the relative air humidity increases to a lesser extent than in the case of direct cooling, with an equal temperature drop. The presence of the heat exchanger causes the temperature to decrease slightly less than in direct cooling systems (e.g. pathway 2 in Figures 1 and 2).

Two-stage systems: indirect and direct cooling can be used successively (e.g. pathways 2, then 3 in Figures 1 and 2), and this enables the temperature to decrease to a greater extent than when direct or indirect evaporative cooling is used alone. For example, such a system installed in an arid zone of southern California with a 38.3°C outside-air temperature and an approximately 12% relative humidity, achieves air-cooling at a temperature under 13°C (Jain, 2008). The cost of the equipment (excluding installation) to cool 1,500-sq. m premises in this context is estimated to be less than € 10,000 (approximately € 5,000 for the spray-cooling device and a little less for the heat exchanger).

In practice, the full cooling potential cannot be achieved: the physical limitations of the systems and corrosion-related problems encountered because of excessive relative humidity levels, added to constraints related to how the cooled premises are to be used, can have an impact. We will further discuss this later. Traditional cooling or dehumidification systems may therefore be required for fine temperature and humidity control.

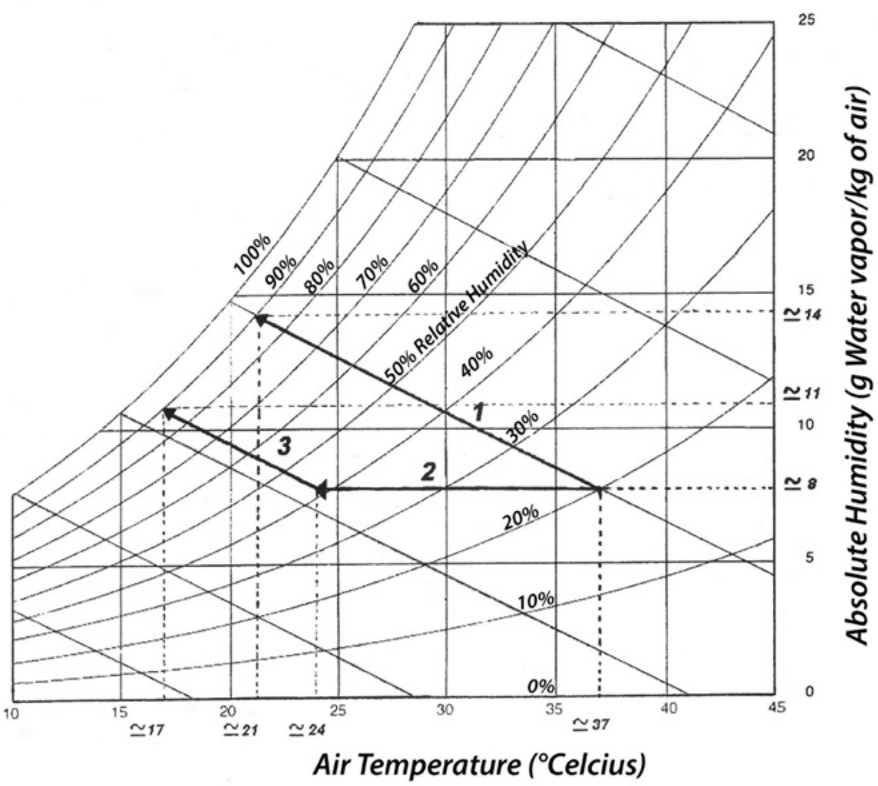

Figure 1 *: Pathways 1, 2 and 3 on a simplified psychrometric chart of the moist air at normal pressure (Carrier type chart)*

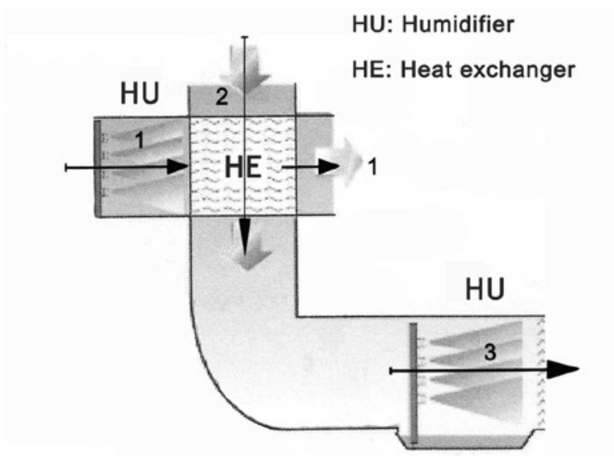

Figure 2 *: Pathways 1, 2 and 3 in a simplified diagram of a device using evaporative cooling (fans, pumps, filters and regulation devices are not shown.)*

Pathway 1/direct evaporative cooling: the air entering the system is at a temperature of 37°C and a relative humidity (RH) of 20%, based on an absolute humidity (AH) figure with approximately 8 g of water vapour per kg of air. The air leaving the system is at a temperature of 21°C, AH = 14 g/kg; the air has thus been cooled and humidified, and this explains the shift in the right oblique segment in the figure 1 (adiabatic cooling). The relative humidity of the air is 90% (the air contains 90% of the water vapour it would contain if it were saturated in terms of humidity, at the same temperature of 21°C).

Pathway 2/indirect evaporative cooling: under the same initial conditions, the air is cooled in a heat exchanger and the latter is cooled using direct cooling. The air is not in contact with water, its absolute humidity (8 g/kg) remains unchanged during this process. Because of the limitations of the exchanger, the temperature at the outlet is slightly higher than in the previous case (e.g. 24°C instead of 21°C).

Pathways 2+3/two-stage system: the air leaving the compartment in which indirect cooling is applied (T = 24°C, AH = 8 g/kg) undergoes direct cooling (pathway 3) which lowers its temperature to 17°C and raises its absolute humidity to 11 g/kg (RH = 90%).

Note: it is possible to send part of the cooled air coming from the exchanger into the first humidifier and also to re-circulate the fraction of non-evaporated water. Therefore, the air coming out of the heat exchanger can be cooled (pathway 2) to a temperature even lower than in the figure 1, and this without increasing its absolute humidity (in which case the horizontal arrow 2 on the figure 1 is extended to the left). The part of the air that is not recycled to the humidifier is directed towards the room to cool. If necessary (for the comfort of the occupants in very dry climates, for instance), the air passes through a second humidifier before entering the room [Jain, 2008; Bruno, 2010].

Energy savings and water consumption

On average, the energy consumption can be 4 times lower [Energy.gov, 2012] than that of a conventional device with the same cooling power, but can go down to 10 times lower in a hot and dry climate [Herman, 2009 ; Jaber, 2011]. The overall operation cost is approximately 20 times lower than that of a standard vapour compression system [Lazzarin, 2012).

Water consumption can be a concern, particularly in arid regions, where evaporative cooling is the most beneficial. The evaporation of 1 cubic meter water can produce a cooling effect of about 2.5 x10^6 kJ (700 kWh), i.e. as much as 230 kWh required by a classic air-conditioning system with a coefficient of performance (COP) of 3. In practice, a fraction (around 20%) of the water is utilized, not to cool the air, but to avoid the deposit of minerals that may result from excessive concentration due to the evaporation.

The quality of the water must be monitored and the water treated if necessary, by disinfection, filtration or demineralization:

- **for sanitary reasons**: particularly in water recirculation systems, the risk of Legionnaire's disease must be taken into account. On the other hand, in the case of direct air cooling for houses or workplaces, there is a risk of aerosol migration and the water should not contain pathogens;
- **for technical reasons**: the more minerals and particles in suspension in the water, the more frequent these "rinsing" operations need to be, as overloaded water may be unusable. This will increase water consumption at an equal cooling capacity.

Applications of evaporative cooling

The choice of the cooling system (direct, indirect or two-stage, or even multi-staged, with or without recirculation of air or water) is a technical and economic choice which depends on the temperature and humidity of the ambient air, on the possible requirements of the temperature and humidity for the refreshed premises and on the quality of the water. The air cooled thanks to direct cooling can be pulsed on the premises only if the quality of the water allows for it.

1. Air conditioning

The main application of evaporative cooling is the air-conditioning of premises in hot and arid regions. Humidification of excessively dry air improves comfort to an extent: when it is hot, the human body's thermal regulation depends precisely on evaporative cooling as perspiration is the evaporation of water through pores and this natural regulation process is hindered when the air is too humid. It is generally considered that human thermal comfort conditions are met when the temperature is between 20 and 27°C and relative humidity between 30 and 65-70% [Lazzarin, 2012]. However, the definition of the conditions of temperature and humidity considered "comfortable" for the human body depends at least to an extent on individual perception. The role of clothing should also be taken into consideration as regards the sensation of freshness and so should relative air humidity and velocity (air renewal rates, fans), outdoor temperature and the local climate. This is why there are several standards concerning this, for example ANSI/ASHRAE Standard 55, EN 15251 and ISO 7730.

Furthermore, air conditioning concerns not only human beings, but also livestock: extreme heat has an impact on its health, breeding and growth. In addition, poultry lacks skin thermal regulation (evapotranspiration), and excessive temperature can therefore prove fatal to it.

2. Storage of perishable foodstuffs

In hot countries, evaporative cooling cannot achieve the temperatures recommended for products of animal origin or for most of the products of vegetal origin. However, in some cases, it may allow a significant slowdown of the deterioration process of tropical fruit and vegetables, thus making possible an appreciable gain in terms of shelf life and marketing periods.

The increase in relative humidity reduces the wilting and weight loss by evapotranspiration of fruit and vegetables, but an excess of relative humidity encourages the proliferation of unwanted organisms, including fungi (botrytis, penicillium...) resulting in the deterioration of the products, or even in the production of bio-toxins. For the preservation of fruit and vegetables, recommended humidity is generally 85-95%. The risk of corrosion of metal parts is also to be taken into consideration.

3. Pre-cooling

When evaporative cooling does not achieve the desired temperatures, in some cases, it can be used for pre-cooling operations, so as to reduce the energy consumption of conventional devices used to achieve the temperatures required, as well as the sizing of these devices, thus allowing for lower operation and investment costs.

Note: higher temperatures are usually observed in the dry season in continental climate areas, far from major sources of moisture. This causes strong daily thermal amplitude, with very low relative humidity in the hottest period of day. A similar situation occurs in temperate climates likely to undergo episodes of hot, dry wind coming from the desert, as on the southern shore of the Mediterranean for example. In these regions, evaporative cooling is therefore more beneficial during the warmer periods. This is important, because the performance of conventional equipment decreases when the outside temperature increases. This also applies to all systems using evaporative cooling combined with another cooling process. The potential advantage of evaporative cooling is therefore twofold: on the one hand, it allows for reducing the size of the conventional systems operating under usual conditions, and on the other hand, it allows for reducing the oversizing of the devices that would be required to cope with higher temperatures.

a. Cooling of condensers in traditional cooling systems

In conventional refrigeration and air-conditioning systems, heat is discharged into the environment at condenser level; cooling the condenser by thanks to evaporatively-cooled water can improve the performance of the device. Incidentally, this principle is widely used in condensers and adiabatic condensers, including under humid climates.

b. Cooling of liquids

The process is similar to indirect cooling described above, except that here water or another liquid passes through the exchanger (which is itself cooled by direct evaporative cooling). The cooled liquid can then be used for air conditioning or to evacuate the heat generated by an industrial process for example. In the latter case, evaporative cooling can present an economic and technical advantage even in a relatively humid climate.

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Recommendations

Because of its low cost and its effectiveness under a hot and dry climate, evaporative cooling should be used more:

- for the air conditioning of homes and work places, which is currently the most widespread use,
- for the air conditioning of rearing houses under hot and dry climates,
- for the short term storage of products that can be subjected to relatively warm temperatures for a short period but would deteriorate rapidly in the event of more severe heat.

The increasing cost of energy can also enhance the comparative advantage of evaporative cooling for the pre-cooling and cooling of condensers of conventional refrigerating systems and of some heat exchangers under moderately humid hot climates.

However, the use of evaporative cooling requires that good enough quality water is available in sufficient quantity and that health problems are controlled: Legionella may develop in certain systems and other pathogenic and undesirable agents may develop in the case of excessive humidity in the premises.

The regions where the climate is most favourable to the application of evaporative cooling are in developed countries (Australia, USA...), in emerging countries and in some of the least developed countries.

It is therefore important to promote international exchanges of knowledge and technologies relating to evaporative cooling. The IIR brings its contribution, in particular thanks to its working parties and publications.

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