Energy Savings in Direct Evaporative Cooling: real application in the Madrid metro and simulated application for offices in Sydney

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ABSTRACT

Water evaporates spontaneously in contact with the air, absorbing around 680 W/(kg/h of evaporated water) from the air (1,053 BTU/lb).

Direct Evaporative Cooling (DEC) exploits this simple physical phenomenon to achieve high cooling capacities with low energy consumption, by evaporation of water (this is normally atomised into very fine droplets to ensure maximum evaporation).

This article describes the energy saving of a direct evaporative cooling system implemented at a Madrid metro station. Following this is an analysis of the annual energy savings achievable from a hypothetical DEC system in an AHU for offices in Sydney.

1. INTRODUCTION

Air can be cooled in several ways. This article examines the traditional method of chiller + cooling coil, free cooling + DEC and combinations of these.

As regards DEC, water, when in contact with non-saturated air, evaporates spontaneously, removing the latent heat of vaporisation from the air; the air is consequently cooled and humidified at the same time. Assuming that this exchange of energy is limited to the system made up of air and water, the cooling process is referred to as *direct adiabatic cooling* or *direct evaporative cooling* (DEC): *cooling* because the air temperature decreases; *adiabatic* because the exchange of energy occurs completely within the air + water system[1]; *direct* because the water evaporates in the air stream being cooled[2].

The heat removed from the air is equal to the latent heat of vaporisation, which can be assumed to be around 680 W/(kg/h of evaporated water) (1,053 BTU/lb). The reduction in air temperature increases as the mass of evaporated water per unit of time increases: in essence, to cool the air more, on one hand the mass of water in contact with the air must be increased (by simply increasing the flow-rate); on the other, the evaporation rate needs to be faster. To increase the evaporation rate, the air/water contact surface needs to be larger: one simple and energetically efficient method involves atomising the water into very fine droplets (as an example, considering that if 1 litre of water is atomised into droplets with an average diameter of 10 μm, the total surface area[3] of the droplets is 600 m² - 6,458 ft²).

The following chapter describes the atomiser used in the DEC application at a Madrid metro station. This is followed by the description of the metro installation and the estimate of savings achievable for offices in Sydney.

2. PRESSURISED WATER ATOMISER

The high-pressure atomiser used at the Madrid metro station, is an adiabatic humidifier/atomiser fitted with volumetric pump that delivers demineralised water (1-50 μS/cm, 0–25 ppm $CaCO_3$) at high pressure (20-80 bars, 290-1,160 PSI) to special stainless steel nozzles, which atomise the water without using compressed air. There are various models of such a system, for ducts/AHUs or rooms, with flow-rates from 60 l/h to 5,000 l/h (317 GPD to 26,400 GPD), continuous modulation or stepped control based on the external signal, so as to

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[1] In reality, the process is not perfectly adiabatic, however the deviation from the ideal situation is negligible.

[2] Indirect evaporative cooling (IEC) also exists, using a cross-flow heat exchanger on the flow of air being cooled without mixing: one flow is the air being cooled, the other is usually the exhaust air, saturated and adiabatically cooled before entering the heat exchanger.

[3] The total surface area of the droplets with diameter D and total volume V is: $6 \times {}^{V}\!/_{D}$. If V = 1 dm³ (0.035 ft³) and D = 10 μm = 10^{-4} dm (3.28084 x 10^{-5} ft), the total surface area is equal to 600 m² (6,458 ft²).

avoid wasting water; all models feature low energy consumption, between 5 and 10 W/(l/h) of atomised water, including the external reverse osmosis installation.

Figure 1 represents the structure of the high-pressure atomiser for ducts/AHUs, made up of:

- Cabinet with volumetric pump that delivers the pressurised water to the nozzles, controller and various electromechanical and water circuit components.
- Rack with atomisation nozzles arranged on vertical manifolds, capacity control and drain valves, and other plumbing components.

Figure 1. humiFog atomiser for AHU: main components

High-Pressure Atomiser: Electricity Consumption

The atomizer increases the moisture in the air by the evaporation of atomised water. Where:

- ΔW is the increase in humidity ratio in g_v/kg_{da}
- G_E is the flow-rate, in m^3/h, of the air whose humidity is increased
- 1.2 kg/m^3 is the average density of the air (0.07 lbs/ft^3)
- 10 W/(L/h) the specific power consumption of the system referred to in this paper, including the external reverse osmosis system

The power input in kW of the atomizer to generate the increase ΔW is:

$$P_{humiFog} = \text{specific power} \times \text{sprayed water flow} = \text{specific power} \times \left(\text{air flow} \times \text{density} \times \Delta\text{W in } \text{kg}_\text{v}/\text{kg}_\text{da}\right) =$$

$$= \frac{10\frac{W}{L/h}}{1{,}000} \times \left(G_E \times 1.2 \times \frac{\Delta W}{1{,}000}\right) = \frac{3}{250{,}000} G_E \times \Delta W \text{ in kW} \qquad (1)$$

High-Pressure Atomiser In Ducts/AHUs: Hygiene And Maintenance Aspects

The system used at the metro station in Madrid is compliant with the hygiene standards for atomisation in ducts/AHUs in accordance with VDI 6022 page 1 (04/06), VDI 3803 (10/02), SWKI VA 104-01 (04/06), ÖNORM H 6021 (09/03) and EN 13779 (09/07); humiFog is also compliant with the standard for humidification in ducts/AHUs for hospitals DIN 1946 part 4 (01/94), ÖNORM H 6020 (02/07) and SWKI 99-3 (03/04).

Hygiene conformity is guaranteed because the atomiser is designed and built to minimise hygiene risks in ducts without having to add any biocides to the atomised water:

- The atomisation manifolds (Figure 1) are vertical and the drain valves are opened as soon as the pump stops, so as to empty as much water as possible.
- A further drain valve is installed at the lowest point of the connection pipe between the cabinet and the rack to drain the latter when the pump stops.
- All the pipes downstream of the pump are washed with once-through water.
- The droplet separator is made up of AISI304 steel modules, sized to simplify installation and maintenance.

The use of demineralised water drastically reduces the quantity of mineral dust introduced into the air and, consequently, the risks deriving from the biofilm that this may create (biofilm is the ideal habitat for the existence and proliferation of bacteria, including Legionella). Despite this, the local and international hygiene guidelines/standards must always be observed (see VDI 6022, "Guidelines for the prevention and control of Legionella" and other references in the bibliography).

The routine maintenance of the high-pressure atomizer has a minimal effect on running costs: pump oil change around every 2,000-3,000 hours, valves and gaskets every 4,000-5,000 hours.

3. DEC IN MADRID METRO (PEÑAGRANDE STATION)

The Peñagrande station, located in Camino de Ganapanes, Madrid, has two platforms, each of which featuring an AHU with 100% outside air and a design flow-rate of 90,000 m³/h (53,000 cfm).

The AHUs are used for cooling in summer, with 100% fresh air; they are not used, on the other hand, for heating in winter, considered unnecessary due to the sensible loads generated by the travellers, the electrical and lighting systems and the metro trains. Consequently, the AHUs developed based on the original design do not have heating or cooling coils:

Figure 2. AHU at the Peñagrande station, Madrid, without DEC

In summer, the absence of cooling coils in the AHU amplifies the discomfort caused by sensible loads in the metro due to quite extreme outside temperature-humidity conditions. For example, in Madrid in August, the outside air reaches around 35° C, 40 %rH (95 °F, 40 %rH), and therefore the use of 100% outside air cannot satisfy the inside loads.

The following solutions were considered to resolve this problem:

1. add a cooling coil to each AHU
2. exploit DEC

The first solution, that is, the addition of a cooling coil in each AHU, was discarded being more costly both as regards the initial investment (purchase of a chiller and coils, systems, installation) and running costs, essentially the electricity required for the operation of the chiller.

The second solution was chosen as it is more economical in terms of purchase costs and systems and has lower running costs. The DEC solution is described below, highlighting the advantages over the chiller solution solely in terms of running costs; as regards the initial investment, we can simply underline that the DEC installation was evaluated as being less costly than the chiller and cooling coil.

Each of the two AHUs was fitted with DEC, adding the humiFog adiabatic atomiser and a droplet separator:

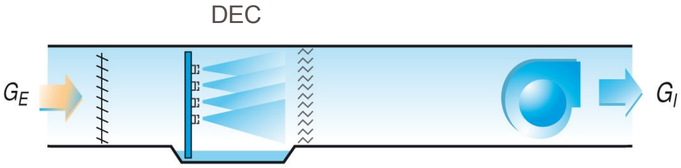

Figure 3. AHU at Peñagrande station, Madrid, with DEC (diagram)

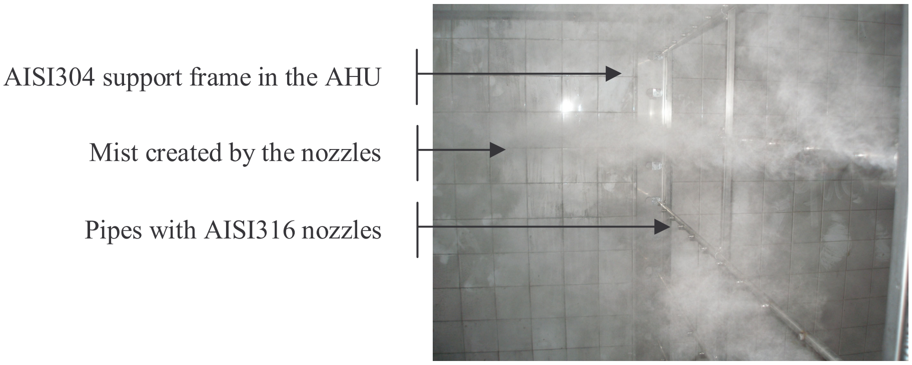

Figure 4. AHU at Peñagrande station, Madrid, with DEC: water atomisation

The droplet separator causes a pressure drop of around 140 Pa (0.020 PSI), which, in turn, reduces the air flow-rate of the fan to the measured value[4] of 71,818 m^3/h (42,270 cfm).

Each of the two high-pressure atomisers was sized to reduce the temperature from 35 °C, 40 %rH (95 °F, 40 %rH) to around 27 °C, 70 %rH (81 °F, 70 %rH; this slightly high humidity is reduced during mixing in the environment and is, in any case, bearable given the short waiting time for the trains and the comfort ensured by the lower temperature):

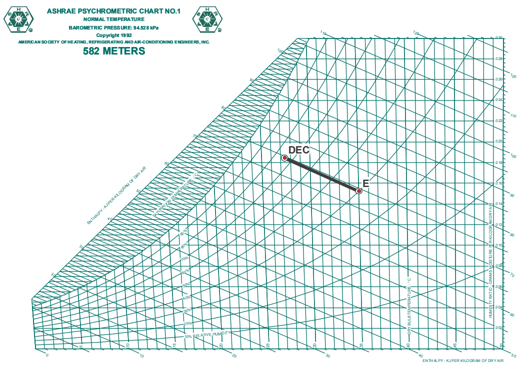

Figure 5. AHU at Peñagrande station, Madrid, with DEC: psychrometric transformation

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[4] The significant difference from the design value of 90,000 m^3/h (53,000 cfm) is due both to the fact that the fan operates at fixed speed, and therefore cannot make up for the resistance of the separator, and the fact that probably without the separator the actual flow-rate is less than 90,000 m^3/h (53,000 cfm).

The corresponding flow-rate of water that must evaporate was calculated by applying the humidification load formula:

$$\text{air flow} \times \text{density} \times \Delta\text{W in } \text{kg}_\text{v}/\text{kg}_\text{da} = G_E \times 1.2 \times \frac{W_{DEC} - W_E}{1{,}000} = 71{,}818 \times 1.2 \times \frac{18.45 - 15.24}{1{,}000} \cong 277 \text{ kg/h} \quad (1462 \text{ GPD})$$

where:

- G_E = 71,818 m^3/h (42,270 cfm) is the flow-rate of outside air
- 1.2 is the average density of air, in kg_a/m^3
- W_E = 18.45 g_v/kg_{da} (0.0142 lbs_v/lb_{da}) is the humidity ratio of the outside air at 35 °C, 40 %rH (95 °F, 40 %rH)
- W_{DEC} = 15.24 g_v/kg_{da} (0.0172 lbs_v/lb_{da}) is the humidity ratio downstream of the DEC system, at 27.4 °C, 74.3 %rH (81.3 °F, 74.3 %rH)

Considering that the distance between the atomisation nozzles and the droplet separator is a little less than 2 m (6.6 ft), some of the droplets produced do not evaporate completely and are removed by the separator. To ensure evaporation of 277 kg/h (1462 GPD) of water as estimated above, two 350-kg/h (1850-GPD) high-pressure atomizers units were installed: the higher water flow-rate makes up for the partial evaporation of the droplets, thus guaranteeing the evaporation of 277 kg/h (1462 GPD) of water as required by the design conditions.

The DEC was validated positively by the company that operates the Madrid metro, due to the economic advantages of the used atomizer compared to an equivalent chiller (only the costs of electricity and water consumption were considered, in the period from 7-25 August 2006, assuming an electricity cost of 0.15 €/kWh = 0.26 AUD/kWh and a water cost of 0.80 €/m³ = 1.37 AUD/m³ (0.003 €/gal = 0.005 AUD/gal); costs are based on 1 AUD = 0.58285 € exchange rate as of Aug 28th, 2009):

Table I - Comparison between running costs (electricity and water only) of DEC by water atomiser and an equivalent chiller –

Value	**DEC (real data)**	**Equivalent chiller** **(estimated data with EER = 2.5)**
Operating hours $h_{operation}$ (7-25 August 2006)	270	270
Power input (a)	5.54 kW (2 x 2.77 from eq. 1)	146.42 kW (see note [5])
Electricity (b = a x $h_{operation}$)	1,496 kWh	39,535 kWh
Cost of electricity (c = b x 0.15 €/kWh = b x 0.26 AUD/kWh)	€224 - AUD 389	€5,930 - AUD 10,279
Water consumption (d)	29,850 litres (7,900 gal)	not applicable
Cost of water (e = d / 1,000 x 0.80 €/m³ = d / 1,000 x 1.37 AUD/m³)	€24 - AUD 41	not applicable
Total running cost (f = c + e)	**€248 - AUD 430**	**€5,930 - AUD 10,279**
Hourly running cost (f / $h_{operation}$)	0.92 €/h - 1.59 AUD/h	21.96 €/h - 38.07 AUD/h

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[5] $$P_{chiller} = \frac{\text{Total decrement of air enthalpy}}{\text{EER}} = \frac{\text{Air flow in kg/s} \times \text{specific heat} \times \text{temperature decrement}}{\text{EER}} \cong \frac{\left[\frac{1.2 \times (2 \times G_E)}{3600} \times c_{p,air} \times (t_E - t_{DEC})\right]}{EER} \cong 146.42 \text{ kW}$$

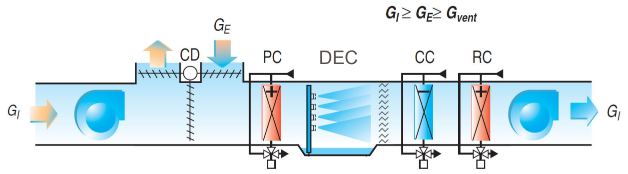
where $c_{p,air}$ = 1.006 kJ/kg_{air} the specific heat of air at constant pressure; 1.2/3600 converts G_E from m³/h to kg/s. The value of $P_{chiller}$ without sign is used here.

It is clear that DEC guarantees significant cost savings compared to an equivalent chiller installation. This conclusion would not differ even if considering the maintenance costs of the chiller and DEC with the used atomizer, the latter being much simpler and estimated to be around €1500 per year (including spare parts and working hours for the activities required by the VDI 6022 standard and by the "GUIA TÉCNICA PARA LA PREVENCIÓN Y CONTROL DE LA LEGIONELOSIS EN INSTALACIONES").

4. VENTILATION SYSTEM FOR OFFICES IN SYDNEY WITH DEC AND FREE COOLING: ESTIMATED ANNUAL SAVINGS

In ventilation systems, energy can be saved by exploiting free cooling whenever possible, and where necessary together with DEC.

For the simulation in question, the following ventilation system was assumed:



CD	Combined dampers	RC	Post-heating coil
PC	Preheating coil	Gi	Total air flow-rate introduced
HU	Adiabatic humidifier	Ge	Outside air flow-rate
CC	Cooling coil	Gvent	Minimum air change flow-rate

Figure 6. Ventilation system with free cooling and DEC

The use of free cooling implies the possibility to vary the flow-rate of outside air from the minimum air change value (G_{vent}) to the flow-rate of air introduced into the environment (G_I). The flow-rate of outside air is modulated as described in Figure 7, so as to compensate as much as possible for the inside sensible and latent loads using the enthalpy of the outside air:

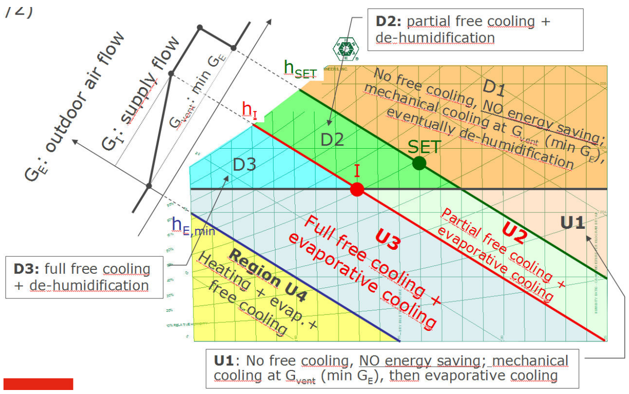


Figure 7. Sub-division of the psychrometric chart into areas by use of free cooling + DEC and modulation of the outside air flow-rate

Some basic information on Figure 7 (further information is available in chapter 11 of the book "Air humidification - Technical, health and energy aspects"):

- Point I: this is the point representing the air introduced into the environment. This can completely satisfy the inside sensible and latent loads at the flow-rate G_I. The mixture of air (return + outside) is always "brought" to point I.
- Area U2: partial free cooling is possible, because the enthalpy of the outside air is less than the inside enthalpy, but not than the inlet value h_I. The excess part of the inside sensible loads can be satisfied traditionally using a cooling coil; the remaining humidity is added by the DEC system.
- Area U3: total free cooling is possible, because the enthalpy of the outside air is less than the inlet value h_I. The sensible loads are

completely satisfied by the outside air, modulating the flow-rate; the remaining humidity is added by the DEC system.

- Area U4: partial free cooling is possible. In fact, the enthalpy of the outside air, despite being less than the inside enthalpy, is too low, therefore heating is required before adopting free cooling, the effectiveness of which is thus reduced. The remaining humidity is added by the DEC system.

Energy savings increase the more frequently outside air is introduced in areas U2, U3 and U4, as free cooling + DEC can be exploited, thus reducing the electricity required for the operation of the chiller + cooling coil.

The statistical distribution of Sydney's climate is represented by the points on the chart in Figure 8:

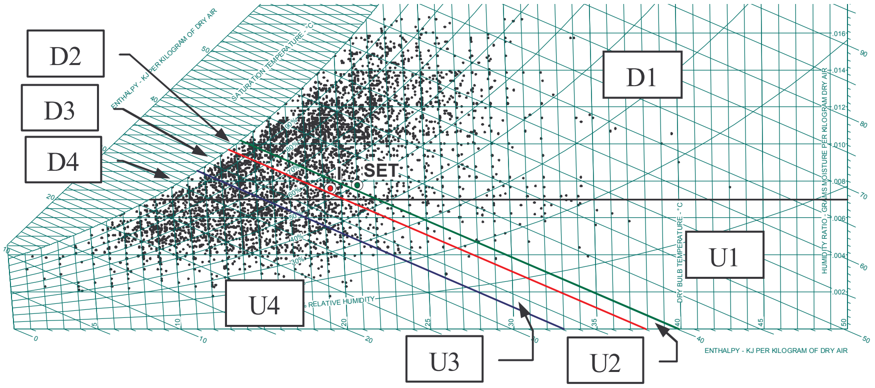


Figure 8. Sydney: distribution of climatic conditions with reference to the areas of Figure 7

The energy savings with free cooling + DEC for a hypothetical office in Sydney were estimated in relation to the following design data:

- 1 kWh electrical costs 0.12 AUD
- 1 m³ (264 gal) of mains water costs 1.87 AUD
- Office for 40 people where smoking is banned
- Ventilation from 6 a.m. to 8 p.m., every day of the year
- Set point: 21 °C, 50 %rH (70 °F, 50 %rH)
- Reference standard: EN 13779:2004
- Inside air quality: IDA1 (Table 8 of EN 13779:2004); this implies that the ventilation flow-rate G_{vent} = 800 L/s (1,695 cfm) ($= 40 \times 20 \dfrac{L}{s \times person}$ according to Table 11 of EN 13779:2004)
- Surface area: 480 m² (= 40 x 12 m²/person for landscaped office room according to Table 22 of EN 13779:2004 = 5,170 ft²)
- Air inlet temperature: 18 °C (64 °F; point I on Figure 8)
- Loads generated by the people (sedentary activity according to Table 25 of EN 13779:2004):
  - Total sensible load: 3 kW (= 40 x 75 W/person = 10,245 BTU/hr)
  - Latent load due to people: 2 kW (= 40 x 50 W/person = 6,830 BTU/hr)
- Sensible load due to lighting = 480 W (1,640 BTU/hr), deriving from:
  - Total lighting: 400 lux (Table 26 of EN 13779:2004 for offices with windows)
  - Corresponding to power consumption of 4.8 kW (= 480 m^2 x 10 W/m^2 according to Table 27 of EN 13779:2004)
  - Hypothetically, 10% is dissipated as sensible load: 480 W (1,640 BTU/hr)
- Sensible load due to computers, printers, etc.: 4 kW (= 40 x 100 W/person according to chapter 6.7.4 of EN 13779:2004 = 13,661 BTU/hr)
- DEC atomiser: efficiency $\eta_{HU} = 90\%$
- Chiller: $EER = 2.5$

- Ratio of exhaust air / inlet air: $\alpha = 0.9$ (slight overpressure on inside)

Using simulation software developed by the DEPARTMENT OF INDUSTRIAL SYSTEM TECHNIQUES AND MANAGEMENT at the University of Padova, in collaboration with CAREL SpA, the following results were calculated:

Table II - Estimated annual energy savings with free cooling and DEC for an office in Sydney –

Loads	kWh/year
Total annual load to be satisfied (inside loads + loads relating to air handling units)	54,260

Contribution of free cooling + DEC (a)	**14,467**
Energy expenditure to dehumidify the air used for free cooling (b)	0
Net free cooling + DEC (c = a - b)	14,467
Energy saved by the chiller (d = c / *EER*)	5,787
Electricity consumed by DEC (estimated) (e) Atomised water for DEC = 8,120 litres/year (2,145 gal/yr). At 10 W/(L/h), the energy consumption is equal to 8,120x10/1,000 = 81.20 kWh/year, rounded off to 90 kWh	90

Electricity saved by free cooling + DEC (f = d – e)	**5,697**
equal to around 5.7 t/year less CO_2 introduced into the atmosphere (= f / 1000, assuming that 1 kWh of electricity corresponds to 1 kg of CO_2 as shown in “LIFE-CYCLE ASSESSMENT” by Vattenfal AB)	

Table III - Estimated annual cost savings with free cooling and DEC –

Values	AUD/year
Cost of electricity saved using free cooling + DEC (g = f x 0.12 AUD/kWh = f x 0.26 AUD/kWh, assuming that electricity costs 0.26 AUD/kWh)	683.62
Atomised water for DEC: Volume = 8,120 litres/year (2,145 gal/yr) for a cost of [h = (Volume / 1,000) x 1.87 AUD/m^3 = (Volume / 1,000) x 1.37 AUD/m^3, assuming that water costs 1.37 AUD/m^3]	15.18
Annual saving (g - h)	**668.44**

CONCLUSIONS

Water, our most important resource, can be wisely used for reducing the electrical energy required for mechanical cooling thanks to evaporative cooling. Direct evaporative cooling (DEC) by atomisation of water is a very efficient way to reduce air temperature, as it exploits the latent heat of vaporisation that the water removes from the air when evaporating, equal to 680 W/(kg/h of evaporated water) (1,053 BTU/lb), with a very low energy consumption required to atomise the water [max. 10 W/(L/h) in the case of the atomiser examined here]. A power consumption of 10 W/(L/h of atomised water) gives 680 W/(L/h) of air cooling capacity (1,053 BTU/lb): this ratio is extremely cost effective, especially when compared to an equivalent chiller + cooling coil system, which, to generate the same cooling capacity, would draw approx. 272 W of electricity (assuming *EER* = 2.5).

The overall ratio between the power input of a DEC system using the humiFog atomiser and the power input of an equivalent chiller is calculated by combining equation (1) with the formula shown in note 5, considering that in evaporative cooling $c_{p,air} \times \left(t_E - t_{DEC}\right) \cong r \times \Delta W$ (*r* is the latent heat of vaporisation of the atomised water in kJ/kg_{water}; *ΔW* in $kg_{vapour}/kg_{dry\ air}$): ${}^{P_{humiFog}}\!\big/_{P_{chiller}} \cong \frac{36 \times EER}{r}$. For example, with water at 10 °C – 50 °F (r = 2,393 kJ/kg_{water}) and an equivalent chiller with *EER* = 2.5, the ratio would be: ${}^{P_{humiFog}}\!\big/_{P_{chiller}} \cong 0.038$. The power input of the DEC with atomiser is just 3.8% of the power required by an equivalent chiller system.

DEC becomes even more cost effective if used together with free cooling. In fact, the use of outside air that already has low enthalpy can satisfy internal loads, reducing the need to operate the chiller and the cooling coil; in addition, the free cooling effect is increased due to the cooling generated by the DEC system, which can be considered almost free, given the negligible electricity consumption.

Note that DEC increases the humidity of the air because it is based on the evaporation of water, and consequently this is cost effective when adiabatic humidification is suitable for the air-conditioned environment.

Finally, it must be stressed how DEC and free cooling, by reducing energy consumption (and corresponding costs), also contribute to reducing emissions of CO_2 and other pollutants in the atmosphere.

GLOSSARY

$c_{p,air}$	specific heat of air at constant pressure = 1.006 kJ/kg_{air}
$E_{chiller}$	electricity consumed by the chiller during operation, kWh
E_{DEC}	electricity consumed by the DEC atomiser during operation, kWh
EER	EER of the electrical chiller
G_E	flow-rate of outside air, m^3/h
G_I	flow-rate introduced into the environment (= outside air + recirculation), in m^3/h
G_{vent}	ventilation flow-rate, that is, the minimum flow-rate of outside air required in the environment, in m^3/h
$h_{operation}$	total operating hours of the DEC atomiser
m_{water}	mass of water atomised by the DEC atomiser
$P_{chiller}$	power input of the chiller, kW
P_{DEC}	power input of the DEC atomiser, kW
r	latent heat of vaporisation of the water, at its starting temperature
W_{DEC}	humidity ratio downstream of the DEC system, g_v/kg_{da}
W_E	humidity ratio of the outside air, g_v/kg_{da}
ΔW	difference in humidity ratio, g_v/kg_{da}
α	ratio between exhaust air and air introduced into the environment
η_{HU}	efficiency of the DEC atomiser

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