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Energy consumption in air-conditioning; Improvement and Reduction

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Abstract

Anew technique to reduce latent heat to improve energy consumption in air-conditioning is by using Desiccant . The aim of dehumidification process is to remove the water vapor from the processed air to liquid desiccants. Dehumidification is considered as a key feature of HVAC systems for thermal comfort. Chemical dehumidification is remove the water vapour from the air by transferring it towards a desiccant material (adsorption or absorption). Results illustrate that the application of liquid desiccant in air conditioning can improve indoor air quality, reduce energy consumption and bring environmentally friendly products, also. Lewis number increased rapidly with the increase of solution concentration Therefore liquid desiccant air conditioning systems are drawing more and more attention in recent years.

Keywords: HVAC systems; Dehumidification; Chemical desiccants; desiccants

Introduction

Energy consumption due to conventional air-conditioning is very high, especially in hot, humid areas. The total air-conditioning cooling load can be divided into sensible and latent parts.

Two types of space loads affect building humidity and temperature:

Sensible load this is the addition of heat to the building space and comes from a variety of sources (e.g., sunlight, envelope, people, lights, and equipment). Latent load this is the addition of moisture to the building space and comes from multiple sources (e.g., infiltration, mechanical ventilation, and occupant activities).

Cooling loads can be reduced by reducing a building's sensible cooling loads by improving the envelope, integrating properly sized daylighting systems, reducing unwanted solar heat gains, reducing internal heat gains, and specifying cooling equipment with high nominal efficiencies.

Shaded by trees play a major role in sequestering CO_2 and delay global warming also; improving air quality by reducing smog.

An inverter can be used in an air conditioning system to reduce energy consumption by controlling the speed of the compressor motor to drive variable refrigerant flow in an air conditioning system to regulate the conditioned-space temperature.

Electrically driven vapor compression systems typically dehumidify by first overcooling air below the dew-point temperature and then reheating it to an appropriate supply temperature, which requires additional energy.

Another dehumidification strategy incorporates solid desiccant rotors figure(1)[1] that remove water from air more efficiently than vapor compression; however, these systems are large and increase fan energy consumption due to the increased airside pressure drop of solid desiccant rotors.

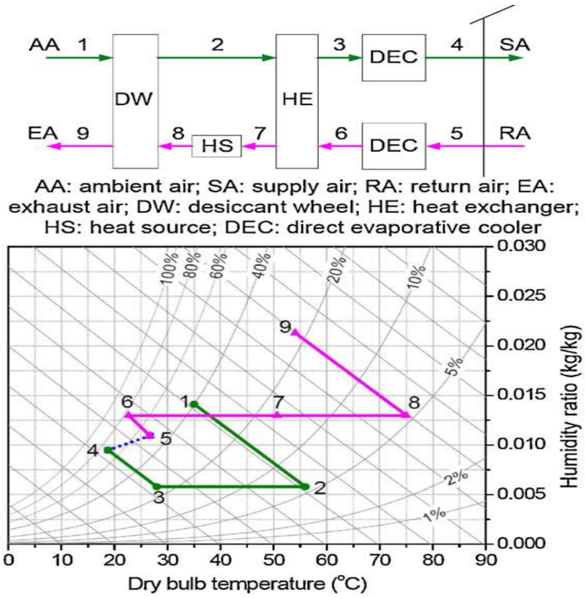

Fig (1) solid desiccant rotors

A third dehumidification strategy involves high-flow liquid desiccant systems. These systems require high-maintenance mist eliminators to protect the air distribution system from corrosive desiccant droplet carryover[2]. These are commonly used in industrial applications but rarely in commercial buildings because of the high maintenance cost.

Low-flow liquid desiccant air-conditioning (LDAC)[3] technology provides an alternative solution with several potential advantages over previous dehumidification systems as it:

• Eliminates the need for overcooling and reheating associated with vapor compression systems.
• Avoids the increased fan energy associated with solid desiccant systems.
• Allows for more efficient ways to remove the heat of sorption than is possible in solid desiccant systems and Reduces the amount of liquid desiccant needed compared to high-flow LDAC systems.
• Is smaller and allows more flexible configurations than solid desiccant systems.
• Reduces the desiccant droplet carryover problem, thereby reducing maintenance requirements compared to high-flow LDAC systems.
• Consumes less energy per unit of water removed from the ventilation airstream compared to other systems in low-sensible heat ratio (SHR) situations where low interior humidity is required
• Can reduce peak electricity demand compared to vapor compression systems if thermal energy sources such as natural gas, solar thermal energy, and waste heat are used for regenerating the desiccant

• Can shift loads by using relatively inexpensive desiccant storage to delay regeneration until times when thermal energy is readily available and cheaper

• Reduces other energy loads through integrated design; for example:

- In grocery stores, lowering humidity levels with LDAC can also reduce loads on: (1) refrigeration system compressors; (2) defrost heaters; and (3) anti-sweat heaters (ASHs) on display case doors

- In swimming pools, using the heat of absorption to warm the pool water while using the pool water to remove the heat of absorption.

1.1 LDAC Technology

Types of LDAC technology can be most easily distinguished based on how sensible and latent loads are removed from the product airstream (or supply airstream) the two most common types of LDAC systems:

High-flow LDAC:The liquid desiccant flow rate is optimized to remove the sensible and latent energy from the process air stream. The heat and mass exchangers for this technology involve flowing two fluids: desiccant and air.

Low-flow internally cooled LDAC:The liquid desiccant flow rate is optimized to absorb moisture out of the air, and a third stream (either liquid or refrigerant) is used to remove the latent and sensible energy. The heat and mass exchangers for this technology flow three fluids: coolant, desiccant, and air.

1.2 Chemical dehumidification

Desiccants are materials with a high affinity for water vapour and may be solid or liquid. Adsorption is when the physical or chemical nature of the desiccant, generally solid, remains un-changed in the dehumidification process; absorption conversely

is when a change occurs, generally with liquid substances [4,5]. A common adsorption solid is silica gel, which behaves like a sponge. In fact, its structure is extremely porous; its internal surface per volume unit is immense, approximately 250m²/cm³. Adsorption desiccants are typically chemical compounds, such as synthetic polymers, silica gels, titanium silicates, natural or synthetic zeolites, activated aluminas,‘‘silica +’’, etc. [6,7–11].
Common absorbents are various solutions of water and ethylene glycol, LiCl, LiBr,CaCl2.In the context under examination regenerative systems are being dealt with, that is those for which the mechanism of moisture removal is continuous. Air to be treated before supplying in indoor ambient is called ‘‘process air’’. Chemical dehumidification [4,6,12,13] is based on the migration of water vapour from process air towards the surface of the desiccant due to the difference in partial vapour pressure (the value of pv is greater in humid air). It may be observed that the pressure gradient is orientated in this direction because the desiccant is dry and cool; should the material become warm and moist the pressure gradient is inverted and water vapour migrates from the desiccant to humid air. The typical cycle of the desiccants made up by three steps, Fig. (2).

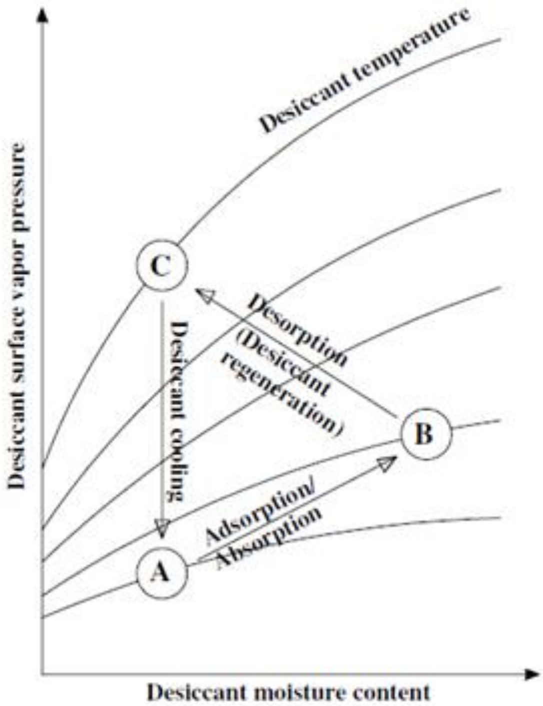

Fig. 2. Chemical dehumidification: typical desiccant cycle.

(A–B) in A the desiccant is cold and dry; removing water from the process air, the surface pvgrows reaching the pv value of the surrounding air; the equality is reached in B state: the migration of the vapor stops.
(B–C) the desiccant is removed from the process air, heated and exposed to a different air flow(regeneration air, which is then discharged in atmosphere) the gradient changes its direction and the migration of the water vapour occurs from the desiccant towards the air current. Instate C the humidity content has the starting value (A), but the pv is much greater because of the high temperature reached by the material.
(C–A) the material is cooled until the starting temperature. The values of humidity content andpv are restored. The cycle can be repeated.

Liquid desiccant systems have also been suggested as a way to shift latent loads to times when energy is cheaper and/or renewable or waste energy is abundant. Latent load shifting can be accomplished with liquid desiccant, which is a relatively inexpensive form of storage. Liquid desiccants can also be used for removing biological and chemical pollutants from process airstreams thereby improving indoor air quality.
The desiccant can be used either in a stand-alone system or coupled judiciously with a vapour compression system to achieve high performance over a wide range of operating conditions. LDAC technology may provide additional energy savings by allowing the main cooling system’s evaporator temperature to be set higher, which lowers the cooling load and associated energy consumption. It

should be possible to downsize the sensible cooling system for new buildings and major HVAC retrofits. As an example, reducing the indoor relative humidity (RH) from 55% to 35% was shown in one study to reduce the latent load and compressor power demand of open vertical dairy cases by 74% and 19.6%, respectively; the RH reduction also reduced defrost duration by 40% (Faramarzi et al. 2000). Another benefit is that store managers may be more willing to install refrigerated case doors because product view will remain unobscured by fog or frost. Case doors reduce the load on the food refrigeration systems.

Fig.(3) shows three of the main components of the LDAC system: the conditioner, the regenerator, both are shown in the top portion of the fig. (3). And the economizers shown in the bottom portion of the fig. (3).

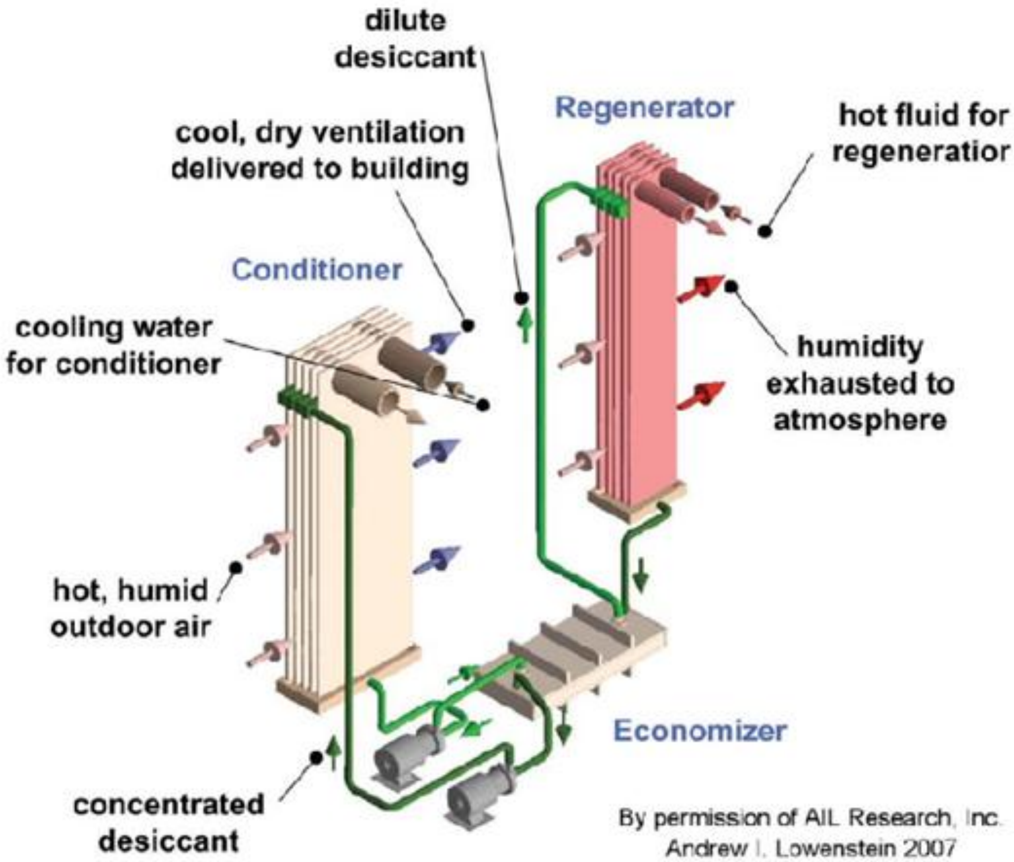

Figure 3 show a 3-D schematic diagram of low flow LDAC

1.3The system cools the air via the following steps:

1. Hot-humid outdoor air (OA) (process air) enters the conditioner and flows past the film of liquid desiccant flowing down the flocked external surfaces of each plate. The plates of the system are configured as a water-cooled (internal to each plate) parallel-plate heat exchanger.
2. The air is dried as water vapor from the air is absorbed into the desiccant. The diluted desiccant is then pumped to the regenerator. Now the dry air is further cooled by a standard vapor-compression evaporator coil or chilled water coil if needed and then supplied to the space.
3. Scavenging air (usually OA) enters the regenerator and contacts the diluted desiccant flowing down the plates (much like the conditioner working in reverse). The plates and the desiccant are heated by hot fluid (water or glycol) flowing in the plates to help the water desorb from the desiccant.
4. The scavenging air picks up the desorbed moisture and is exhausted to ambient.

The thermal energy required for regeneration can be provided by fossil fuel boilers; solar thermal collectors; or heat recovered from reciprocating engine generators, micro turbines, turbines, fuel cells, or other processes with recoverable heat at (150°–210°F)[14]. The desiccant used in LDAC systems is most often lithium chloride (LiCl). In some cases calcium chloride ($CaCl_2$) is used because it is significantly cheaper, which is especially advantageous in applications where more than about

(60) minutes of desiccant storage is needed; however, $CaCl_2$ cannot dry air as deeply as LiCl.

1.4 Energy, cost breakdown, and comfort benefits

• Heating, cooling, and fan energy savings: Heating energy savings were negligible. Some small benefit may be gained by adding complex control strategies, which take advantage of the latent heat of vaporization generated in the LDAC conditioner during the heating season; however, this was not modeled in this work and thus heating savings are minimal. Cooling energy is reduced because the need for overcooling with the vapor compression system is eliminated by removing the latent load from the ventilation air upstream of the cooling coils. Fan energy savings are realized from fewer cooling runtime hours.

• Lower average RH:Table(1)shows the annual average RH in the zones treated by the LDAC for the case with electric reheat coils. This example shows that the RH levels are lower in the LDAC models because the LDAC was controlled to provide the driest air possible so that the refrigeration system does not waste energy dehumidifying the zone air. Although a control strategy could be devised to maintain similar RH levels for the two models, we elected to use realistic and different control strategies for the baseline and the LDAC. This resulted in conservative savings estimates because the baseline systems were not forced to produce the low humidity levels achieved with the LDAC. Lower RH levels lead to better product preservation by avoiding frost buildup on frozen foods and moisture collection in packaged baked good

wafra		Kuwait city		abdali	
Baseline	**LDAC**	**Baseline**	**LDAC**	**Baseline**	**LDAC**
60%	51%	58%	47%	62%	52%

Table 1

1.5 Effects of air humidity ratio on mass transfer coefficient and Lewis number

Liquid desiccant dehumidification is a nonlinear process because of two reasons: one is coupled heat and mass transfer during the process and the other is that the important properties of the air and desiccant solution – hC, hDare changing because of different parameters of inlet air and solution. Two sets of experiments were carried out with different air humidity ratio, shown in Table (2).Fig. (4a) represents the effects of the air humidity ratio on the mass transfer coefficient and Lewis number. The mass transfer coefficients are greatly dependent on the air humidity ratio.

Group	T_a (°C)	ω (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
(a)	25.5	7.3–11	0.255	0.08475	30	35.7
(b)	24.7	10–16	0.118	0.08475	30	36.5

Table2 Experimental conditions

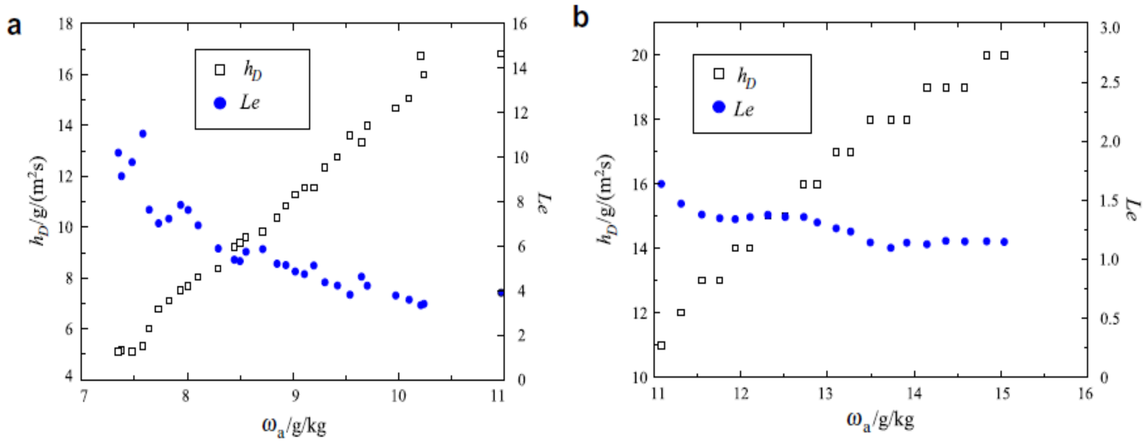

Fig.4 . Effects of air humidity ratio on mass transfer coefficient and Lewis number.

The mass transfer coefficients increased twice as faster as the increase of the humidity ratio from 7.3 to 10.97 g/kg at the air flow rate of 0.255 m^3/s. The Lewis numbers reduced rapidly from 10 to 4. Fig. 4b shows the effects of the higher humidity ratio on the mass transfer coefficients with the humidity ratio from 10 to 16 g/kg and an air flow rate of 0.118 m^3/s. Whereas, the Lewis number was nearly constant and kept around (1.3). From the results of Fig. (8), it is concluded that the mass transfer coefficients increase rapidly with the increase of the air humidity ratio, but the Lewis number reduce at different rates.

1.6Effects of desiccant concentration on mass transfer coefficient and Lewis number

The experiment conditions were shown in Table (3). In this set of experiment, the thick solution with the solution concentration Xs= 40.2% was confected by 30 kg LiCl dissolved into 44.6 kg pure water. The solution absorbed the water from the air and became diluted, and the diluted solution was pumped into the dehumidifier again till the solution concentration was less than 35%. Therefore, the solution with some different concentrations could be tested

T_a (°C)	ω_a (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
24.9	8.3	0.254	0.0861	29.5	34.0–40.2

Table 3 Experimental conditions

Fig. (5)presents the effects of the desiccant concentration on the mass transfer coefficient and Lewis number. The figure indicates that the mass transfer coefficients increased obviously by increasing the mass concentration of the solution. The mass transfer coefficient was about only 2g/(m^2 s) at the solution concentration of 34.7%, whereas the h_D was about 21g/(m^2 s) at the solution concentration of 40.2%, which was more than 10 times of the former. This is just the reason of desiccant solution with high concentration yielding good dehumidification performance. Also, the results showed the Lewis number increased rapidly with the increase of solution concentration. When the concentration of desiccant solution was nearly 40%, the Lewis number was about 1.7.

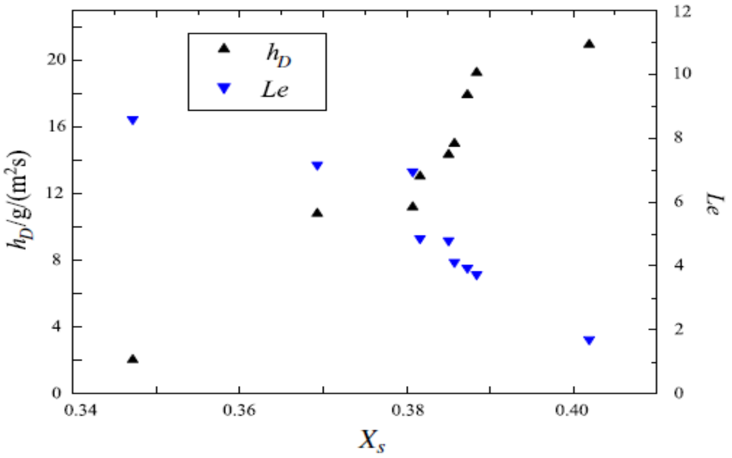

Fig. 5 . Effects of solution concentration on mass transfer coefficient and Lewis number.

The schematic diagram of the liquid desiccant dehumidification setup is shown in Fig. (6). It is made up of a dehumidifier, a pump, a concentrated solution tank, a diluted solution tank, a Rota meter, etc. Two liquid desiccant tanks(Tank 1 and Tank 2) are cylinders with the same dimensions,(70) cm in height and (55) cm in diameter. Before experiments, valve (5, 6) used for drainage were close and liquid desiccant solution with the weight concentration of about39% was confected by(59) kg of lithium chloride granular dissolved into 92 kg pure water and poured into the Tank1. After closing the valve (1, 4) and opening the valve (2, 3) dehumidification experiments started, and the liquid desiccant solution was transported from the Tank (1) to the dehumidifier by the pump and collected in the Tank(2). Until the Tank(1) was emptied out, the desiccant solution was pumped again via the dehumidifier from the (Tank 2 to the Tank 1) by opening the valve (1,4) and closing the valve(2, 3) and so repeated. The inlet temperature of the solution entering into the dehumidifier was controlled by the cooler and the electric heater which was controlled by a temperature controller. The flow rate of the solution was adjusted by the valve (3or4). An environmental chamber was used for providing the air with different temperature and humidity. The environmental chamber provided the measuring instruments for the flow rate, dry-bulb temperature and wet-bulb temperature of the air, respectively. The dry-bulb and wet-bulb temperature at outlet point were measured by(T4) and (Ts_2). Temperatures of the desiccant solution at inlet point and outlet point were measured by (T1) and (T2).

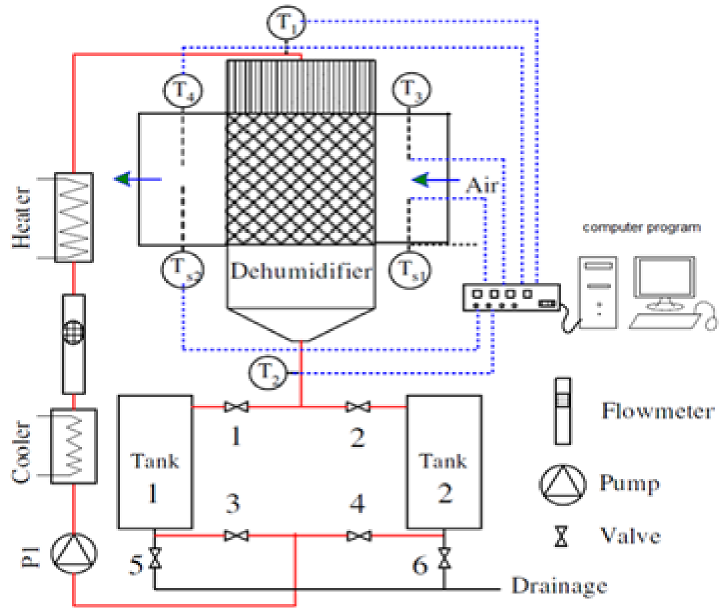

Fig.6 schematic diagram of desiccant dehumidification setup

Calculation

The latent ton-hours per scfm in a given hour are calculated as follows:

$$\text{Latent ton-hour per scfm per hour} = \frac{(\text{Outside air humidity ratio - 65 gr/lb}) \times 4.5 \times 1{,}050}{7{,}000 \times 12{,}000} \quad (1)$$

We have chosen to define the "space-neutral" conditions as 75°F (24°C), 50%RH (65 gr/lb[39 g/.45 kg])[3]
4.5 = lbs of air per hour per cfm.
7000 = grains of water vapor per lb.
1050 = heat of vaporization of water at standard temperature and pressure in Btu per lb.
12000 = represents the Btu's per hour of one ton of air conditioning capacity
The values for each of the 8760 hours of the year are calculated and summed to form the latent (dehumidification) load portion of the index.

For desiccant wheels, Jurinak model[15] have been selected for the performance analysis as following

$$\eta_{f1} = \frac{f_{1so} - f_{1si}}{f_{1ei} - f_{1si}} \quad (2)$$

$$\eta_{f2} = \frac{f_{2so} - f_{2si}}{f_{2ei} - f_{2si}} \quad (3)$$

$$f_{1j} = -2865 T_j^{-1.49} + 4.344 w_j^{0.8624} \quad (4)$$

$$f_{1j} = \frac{T_j^{1.49}}{6360} - 1.127 w_j^{0.07969} \quad (5)$$

Where subscripts s and e means supply and exhaust, respectively, and(i, o) inlet and outlet respectively is temperature in K and w humidity ratio in kg/kg. the desiccant wheel effectiveness mainly depend on the material, wheel structure, and rotary wheel speed based on our finite difference analysis [16] of desiccant wheels, at the optimum rotary speed, η_{F1} is 0.30 and $\eta_{F2}$is 0.85 for 2.5 kg honeycomb desiccant wheel. Other characteristics of the wheel are: duct wall thickness, 0.2 mm; duct geometry, sinusoidal; material, silica gel; effective material fraction, 0.7; wheel length, 0.2m

heat and mass transfer coefficients h_C, $h_D$were developed as following by regression method:

$$h_D = 3.0223 \times 10^{-4} U_a^{0.7407} \omega_a^{2.1505} \exp(-0.0011294 T_s) \times \exp(-0.057101 T_a) \exp(19.377 X_s) \quad (6)$$

$$h_C = 6.834 \times 10^{6} U_a^{1.3} T_a^{-3.9} T_s^{-1.2} \omega_a^{2.2} \times \exp(6.68 X_s) \exp(-5.71 \times 10^{-2} T_a) \times \exp(-1.13 \times 10^{-3} T_s) \exp(-9.28 \times 10^{-2} \omega_a) \quad (7)$$

where Ua is the velocity of the air entering the packing, m/s. In the correlations the flow rate of the solution is permitted to ignore considering that it is very little but enough to wet the packing.

If the process uses hot water or steam to achieve a latent coefficient of performance (COP) of 0.8– 0.94 depending on ultimate desiccant concentration. Latent COP is defined as:

$$COP_{Latent} = \frac{(Moisture\ Removal\ Rate) * (Heat\ of\ Vaporization)}{Heat\ Rate\ (Higher\ Heating\ Value)} \quad (8)$$

COP is maximized by maximizing the regeneration temperature and change in concentration while minimizing the ultimate desiccant concentration. Including the COP of the water heater (about 0.82), a typical combined latent COP is 0.82 × 0.85 = 0.7.

In summer the humidity ratio of outside air is normally higher than the indoor humidity ratio: therefor dehumidify is a demand. For example, the indoor comfort conditions are Tdb = 25Cº and ϕ = 50%, (i.e. ωr = 10gv/kga) and the outdoor air design conditions are Tdb = 32Cº and ϕ= 55%, (i.e. ωo = 16.5gv/kga), the humidity ratio of the supply air must be:
ωs<ωr =10 gv/kga<ωo =16.5 gv/kga
and the dehumidification system must be able to reduce the ω = 16.5gv/kga to ωs. In steady state, from the mass balance for water, referred to a conditioned ambient with N occupants, it is obtained:

$$\omega_s = \omega_r - \frac{N \cdot \dot{m}_{vu}}{N \cdot \dot{m}_{au}} = \omega_r - \frac{\dot{m}_{vu}}{\bar{\rho}_a \cdot \dot{V}_{au}} \quad \textbf{(9)}$$

The humidity ratio of the airflow to be supplied must be equal to indoor airflow humidity ratio minus the ratio between unitary mass flow rates (referred to each occupant) of water vapour and air. Referring to the case under examination, and assuming the following values as indicative [17]:
mvu = 60g/h _ρa = 1.17kg/m³ Vau =10dm³/s it follows that:
ωs = 10gv/kga – 1.4gv/kga=8.6gv/kga → T dp;s = 11.8C°
So, the dehumidification capacity, in terms of humidity ratio variation, must beΔω = 16.5 – 8.6 = 7.9gv/kga
It can be noted that only the 18% (1.4/7.9) of Δω is due to the indoor load, while 82% is due to the outdoor air. The dehumidification capacity (DC) usually expresses the water mass flow rate removed from the handled air flow [18]. In steady state, from the water mass balance referred to the dehumidifier, one can obtain:

DC = ṁw = ṁaΔωDE = ρavaΔωDE **(10)**

To express, as usual, DC in [kg/h] units, in Eq. (10) the following units are used: ρa [kg/m³], va[m³/h], ω [kgv/kga]. It can be observed that the unitary capacity is equal to the humidity ratio variation:

$$\mathrm{DC_u} = \frac{\dot{m}_w}{\dot{m}_a} = \Delta\omega_{DE} \quad (11)$$

Many building and furniture materials are known to be hygroscopic, thus the way in which air is supplied may give rise to condensation and would growth. It would be advisable to mix treated air with ambient air in order to increase temperature, thus preventing extremely cold air from coming into contact with surfaces, so avoiding condensation.

conclusions

In operating conditions, hybrid systems based on chemical dehumidification permit to control separately both temperature and humidity (the DW is connected to a humidity sensor, the CC to a temperature sensor). On the contrary, in traditional cooling systems only temperature is generally directly controlled (DBTCS), while humidity can vary.
Systems based on chemical dehumidification allow to reduce humidity even when required dew point temperature is very low, so allowing an easier balance of high latent loads. On the contrary, conventional systems can dehumidify air stream generally only for required dew point temperatures higher than 4Cº.
The technology based on chemical dehumidification, reducing electric power and energy requirements and the CFC and HCFC refrigerant fluids use, is characterized by a low environmental impact. Desiccant technology is a promising alternative for dehumidification.
Temperature and humidity of outdoor air have great effect on energy consumption and on COP. The energy consumption increase with the rising of the temperature and humidity of the outdoor air and COP decrease, also; more ventilation air flow rate, more energy consumption and lower COP.

Acronyms and Abbreviations

AHU	air handling unit
ASH	anti-sweat heater
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
$CaCl_2$	calcium chloride
CC	cooling coil
cfm	cubic feet per minute
CHP	combined heat and power
COP	coefficient of performance
DB	dry bulb temperature
DBTCS	control system based on dry bulb temperature
DC	Dehumidification capacity
DP	dew point temperature
DW	DW desiccant wheel
DX	direct expansion
hc	heat transfer coefficient (W/(m2 _C))
h_D	mass transfer coefficient based on air humidity
hp	horsepower
HR	humidity ratio
HVAC	heating, ventilation, and air conditioning
LDAC	liquid desiccant air-conditioning
Le	Lewis number, dimensionless
LHR	latent heat ratio
LiBr	lithium bromide
LiCl	lithium chloride
MCBD	mean coincident dry bulb temperature
MRC	moisture removal capacity
NREL	National Renewable Energy Laboratory
OA	outdoor air
RH	relative humidity
RSHI	regeneration specific heat input
SCFM	Standard cubic feet per minute
SHR	sensible heat ratio
TMY3	Typical Meteorological Year 3

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