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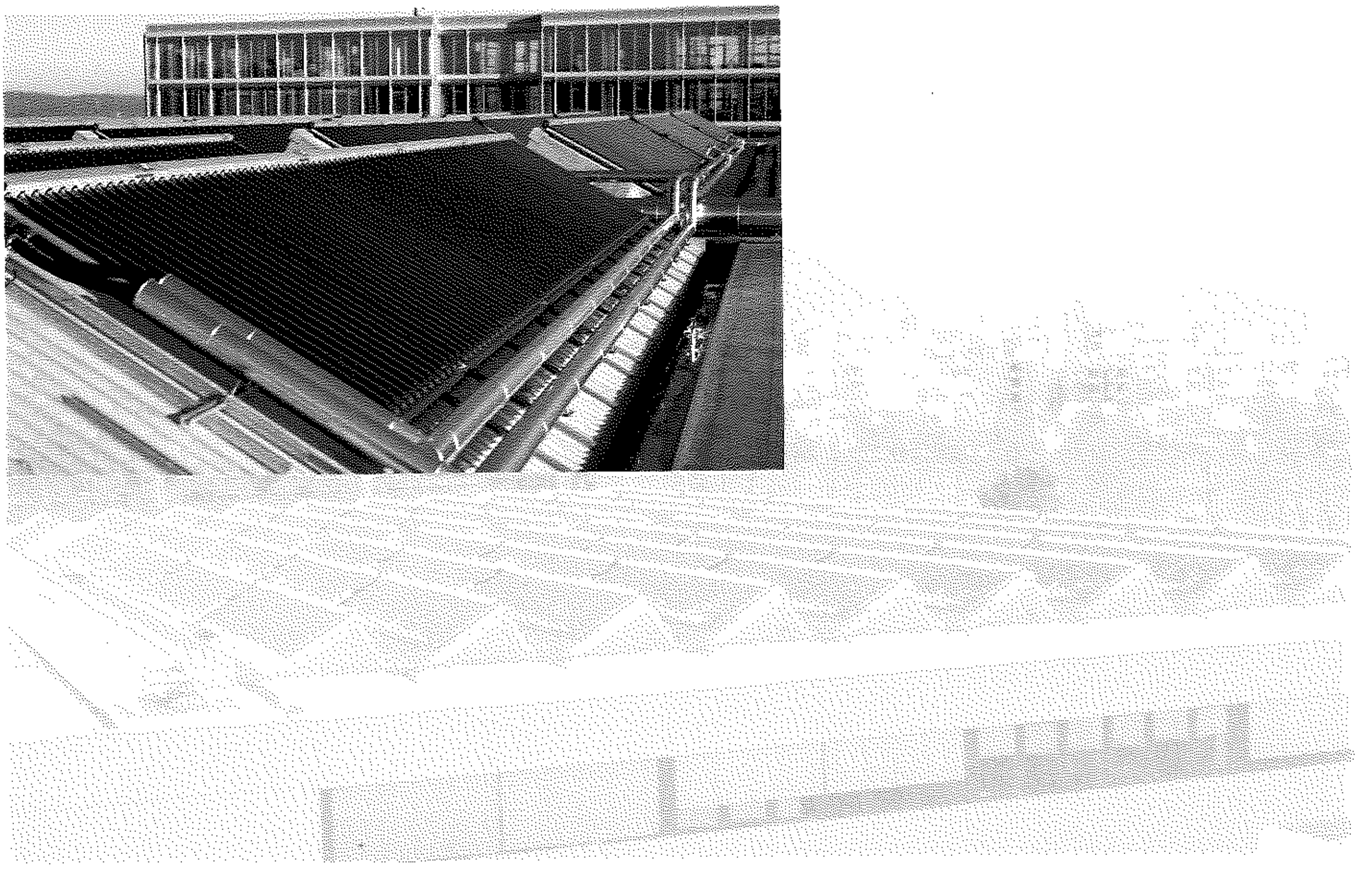
Solar Cooling Handbook

A Guide to Solar Assisted Cooling and Dehumidification Processes

3rd Completely Revised Edition



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SOLAR HEATING & COOLING PROGRAMME
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Energy consumption related to residential, commercial and industrial buildings constitutes a significant part of the overall primary energy consumption worldwide. Up to 40% of the final energy consumed in industrialized countries is attributed to buildings. Energy is mainly used for applications such as heating, hot-water, air-conditioning, cooling and lighting. Especially during the last decades, the amount of energy used for air-conditioning and cooling has increased dramatically.

There is no doubt that drastic reduction of greenhouse gases is needed to limit global warming. The majority of greenhouse gas emissions are caused by burning fossil fuels to produce energy. Energy efficiency measures and the use of renewable energy in buildings are two important ways to minimize combustion of fossil fuels in regard to buildings.

Solar thermal heating and cooling systems represent one major technical solution. Beside application in buildings, this technology can also be applied in industrial refrigeration, for instance in the food industry.

This handbook aims to provide comprehensive information about solar thermal energy systems used for air-conditioning of buildings and also for applications in industrial refrigeration. The main focus lies on technologies and equipment which are state-of-the-art and ready to use. Building planners, constructors, building owners, and manufacturers of solar and HVAC equipment will be supported in designing and selecting solar energy technologies and systems. A properly designed and carefully operated installation will give a high degree of satisfaction by providing a high level of indoor comfort to the users while using environmentally friendly technologies.

ISBN 978-3-99043-438-3
9 783990 434383
ambra-verlag.at

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AMBRA |V is part of Medecco Holding GmbH, Vienna
Printed in Austria

Cover Design: WMXDesign GmbH, Heidelberg, Germany
Layout: Martin Gaal, Vienna, Austria
Typesetting: Lena Appl, Vienna, Austria
Printing and binding: Holzhausen Druck GmbH, Wolkersdorf, Austria

Printed on acid-free and chlorine-free bleached paper

With 226 (mainly colored) figures and 40 tables

ISBN 978-3-99043-438-3 Ambra |V

ISBN 978-3-211-73095-9 2. Auflage SpringerWienNewYork
ISBN 978-3-211-00647-8 1. Auflage SpringerWienNewYork

Chapter 5

Heat driven cooling technologies: open cycle systems

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5.1 Principles and materials of desiccant cooling systems

The use of sorption air dehumidification – whether with the help of solid desiccant material or liquid desiccants – opens new possibilities in air-conditioning technology. This can offer alternatives to classic compression refrigeration equipment. Alternatively, if it is combined with standard vapour compression technology, it leads to higher efficiency by an increase of the evaporator temperature of the compression cycle. Desiccant systems are used to produce conditioned fresh air directly. They are not intended to be used as systems where a cold liquid medium such as chilled water is used for heat removal, e.g., as for thermally driven chiller based systems. Therefore, they can be employed only if the air-conditioning system includes some equipment to remove the surplus internal loads by supplying conditioned ventilation air to the building. This air-flow consists of ambient air, which needs to be cooled and dehumidified in order to meet the required supply air conditions. Desiccant cooling machines are designed to carry out these tasks.

These thermally driven air conditioning processes are known as *open cycles* because a mass transfer through the thermodynamic system boundaries occurs: the refrigerant (water) is discarded from the system after providing the cooling effect, and new refrigerant is supplied in its place in an open-ended loop.

In general sorptive *dehumidification* removes water vapour from air by transferring it to a desiccant material. Desiccant materials have a high affinity for water vapour and may be in a solid or liquid state. Sorption is a common term used for both absorption and adsorption. Absorption is the incorporation of a substance in one state into another substance of a different state (e.g., liquids being absorbed by a solid or gases being absorbed by a liquid). Adsorption is the physical adherence or bonding of ions or molecules onto the surface of a solid material.

When adsorption occurs the physical or chemical nature of the desiccant remains unchanged and the bonding of the water molecules takes place on the inner surface of a highly porous desiccant material. On the other hand, absorption entails a change, generally with liquid substances.

Generally speaking *dehumidification* based on adsorption is driven by a difference in partial vapour pressures. This occurs when the equilibrium vapour pressure of the working fluid on the surface of the sorptive material is lower than the actual partial vapour pressure in the air. In the regeneration process, when the material is heated up the equilibrium value decreases and water vapour migrates from the desiccant to air.

For materials commonly used in air-conditioning applications, the required heat for regeneration is at a relatively low temperature, in the range of 50 to 100 °C (122–212 °F), depending on the desiccant material and the degree of dehumidification. For this reason, air-conditioning systems based on sorptive dehumidification are particularly suitable for coupling with solar thermal plants.

Attractive forces between vapours and solids depend on the particular solid–vapour pair and on the physical structure of the solid. Adsorption desiccants used in solid desiccant systems are typically chemical compounds, such as synthetic polymers, silica gels, titanium silicates, natural or synthetic zeolites, activated aluminas, "silica +", etc. One of the most common is silica gel. Its structure is extremely porous and its internal surface per volume unit is significantly high, approximately 250 m^2/cm^3 (44,100 ft^2/in^3). Its pores have a diameter of a few nanometres and their volume accounts for approximately half of the total volume /5.1/.

Common absorbents used in liquid desiccant systems are various solutions of water and ethylene glycol, LiCl, LiBr, and $CaCl_2$.

As mentioned, even absorption *dehumidification* is based on the migration of water vapour from air towards the surface of the desiccant due to a difference in partial vapour pressure. Therefore, the most important property of a desiccant is its equilibrium water vapour pressure at a certain concentration and temperature. For all sorption materials, equilibrium water vapour pressure decreases with an increase in desiccant concentration and decreases in temperature. Since all currently available liquid desiccant systems allow the direct contact between air and the desiccant, low toxicity is also an important characteristic. The desiccant should also be able to contact the air without being contaminated or developing odours.

The most common absorbents for liquid desiccant processes are salt solutions, where the maximum concentration is limited by the solubility of the salt. Beyond the solubility limit, the solution would form crystals which are undesirable in the operation of the systems. Currently, the most common absorbent is Lithium Chloride. Almost all liquid desiccant machines commercially available today use this halide salt as the desiccant and LiCl has been used in industrial liquid desiccant systems for more than 50 years. Another option is Calcium Chloride ($CaCl_2$), which, at saturation, a higher water vapour pressure than LiCl, which makes it a "weaker" desiccant. However, at current prices, Calcium Chloride is at least one order of magnitude cheaper than LiCl, which is important for applications where the energy storage aspect of a liquid desiccant is significant. Mixtures of LiCl and $CaCl_2$ have also been proposed /5.2/. The major drawback of LiCl and $CaCl_2$ is the fact that they are strongly corrosive to ferrous and most non-ferrous metals. Therefore, equipment using such salts has to employ mostly polymers or fibre glass in its construction.

At least one manufacturer of industrial liquid desiccant equipment uses glycols (propylene and triethylene) as absorbents. They have low toxicity and are not as corrosive as LiCl or $CaCl_2$. However, they are volatile at conditions encountered in liquid desiccant equipment, which means some of the desiccant evaporates into the air stream, which is not compatible with HVAC applications.

In HVAC practice, desiccant materials can be utilised mainly in two ways:

- displacing a solid desiccant in honeycomb beds usually embedded in a rotating component (desiccant wheels) periodically exposed to supply and regeneration air streams
- creating a loop where the desiccant in a liquid phase circulates in two components: the conditioner (where dehumidification occurs) and the regenerator (where the desiccant is regenerated)

Sections 5.2 and 5.3 will give an extensive description of these two typologies of HVAC systems.

5.2 Solid desiccant systems

The desiccant and evaporative cooling (DEC) processes are implemented by special air-handling units and are activated according to the operation mode of the air-conditioning system. These operation modes implement different physical processes for air treatment, depending on the load and the outdoor air conditions. These systems are based on the physical principle of evaporative and desiccant cooling. Unsaturated air is able to take up water until a state of equilibrium, namely saturation has been achieved. The lower the relative humidity of the air, the higher is the potential for evaporative cooling. The evaporative cooling process uses the evaporation of liquid water to cool an air stream. The evaporation heat that is necessary to transform liquid water into vapour is partially taken from the air. When water comes into contact with a primary warm air stream it evaporates and absorbs heat from the air, thus reducing the air temperature; at the same time, the water vapour content of the air increases. In this case, the supply air is cooled directly by humidification and the process is referred to as direct evaporative cooling (Figure 5- 1).

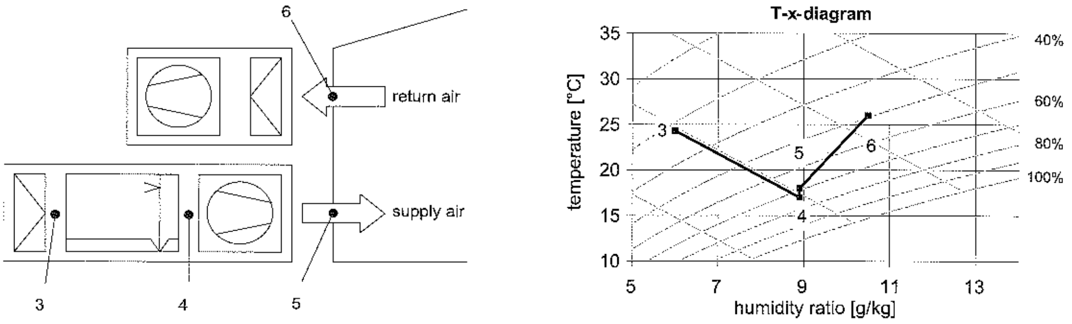

Fig. 5- 1 Schematic drawing of a direct evaporative cooling process

Indirect evaporative cooling involves heat exchange with another air stream (usually the exhaust air), which has been previously humidified and thus cooled (Figure 5- 2). In this case, the water vapour content of the primary air stream is not influenced.

These two techniques of evaporative cooling can also be combined, in a process that is known as combined evaporative cooling (Figure 5- 3).

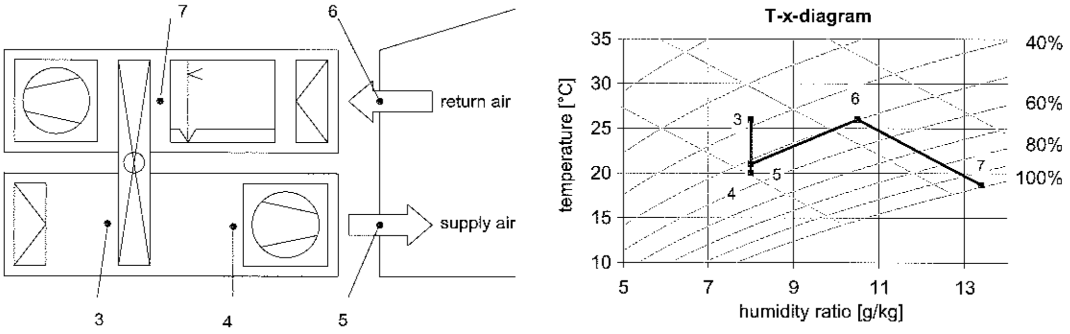

Fig. 5- 2 Schematic drawing of an indirect evaporative cooling process

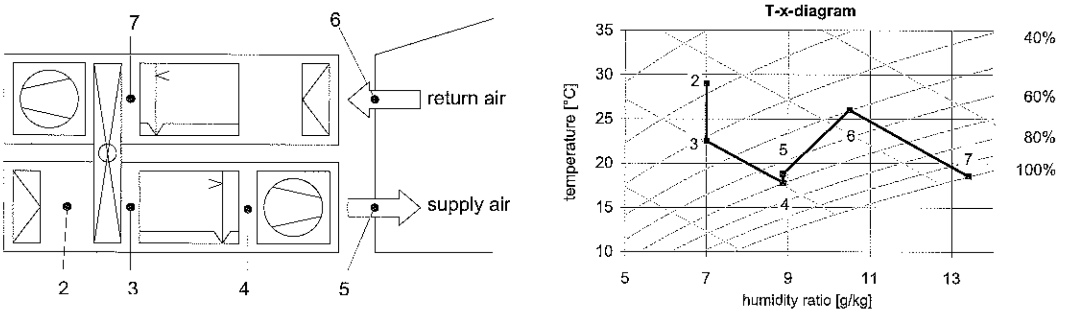

Fig. 5- 3 Schematic drawing of a combined evaporative cooling process

Complementing combined evaporative cooling with desiccant dehumidification enhances the cooling capacity of the cycle and thus it is possible to reach even lower temperatures. This combined cooling process is referred to as Desiccant Evaporative Cooling (DEC).

Using evaporative cooling, either direct, indirect or in a combined process, it is not possible to reduce the vapour content of the ventilation air. But, using a desiccant cycle, in principle lowering of the temperature and the humidity ratio of ventilation air is possible. Fresh air conditions have a considerable effect on the amount of cooling that can be achieved. If the outdoor air is properly pre-treated, the ventilation air can be cooled to lower temperatures via subsequent indirect and direct evaporative cooling. For this purpose, the involved pre-treatment is the desiccant dehumidification process to enhance the potential of evaporative cooling without obtaining a disproportionate high humidity ratio.

Regeneration heat must be supplied in order to remove the adsorbed (absorbed) water from the desiccant material. The required heat is at a relatively low temperature, in the range of 50 to 100 °C (122–212 °F), depending on the desiccant material and the degree of dehumidification. Moreover, the solar desiccant cooling systems, depending on the cooling loads and environmental conditions, will use one of the above mentioned cooling modes, i.e, direct evaporative cooling and/or indirect evaporative cooling and/or desiccant cooling, with the aim of providing comfort conditions in the building.

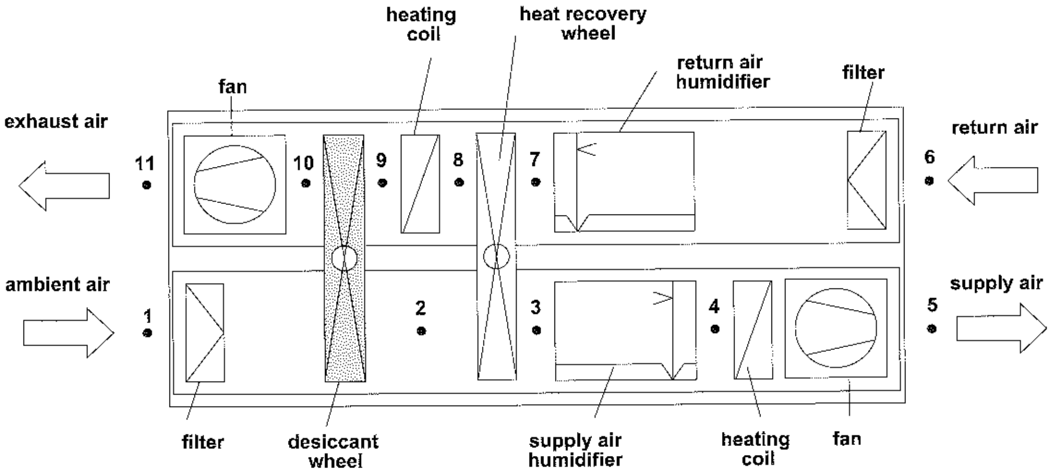

Fig. 5- 4 Schematic drawing of a desiccant cooling air-handling unit

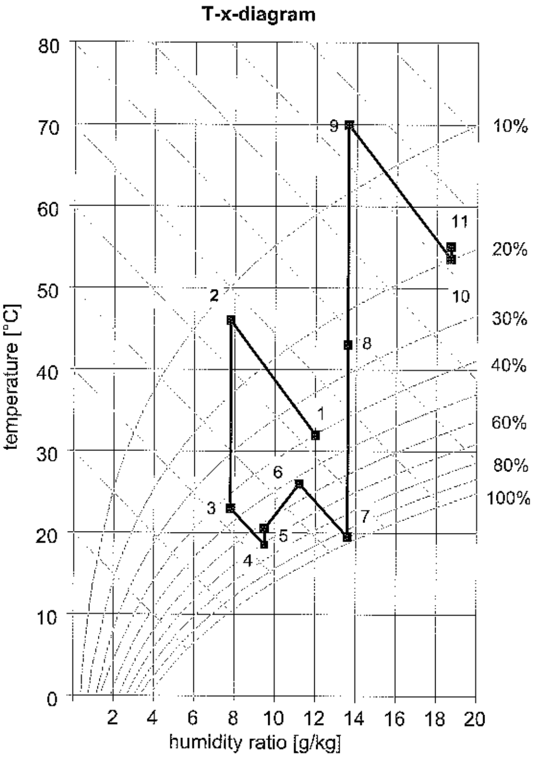

Fig. 5- 5 Typical desiccant cooling process in the T-x-diagram

The most commonly used desiccant cooling process, which is based on the use of desiccant wheels, works as follows (see Figures 5- 4 and 5- 5):

The ambient air (1) is dehumidified in a desiccant wheel, causing the air temperature to increase; the process is nearly adiabatic (2). The regenerative heat recovery leads to cooling of the air inlet to the humidifier, by means of indirect evaporative cooling (3). Depending on the air inlet temperature and humidity supplied, the temperature is reduced by direct evaporative cooling in the humidifier, with a simultaneous increase in humidity up to desired condition (4). The coil on the supply stream is in operation only for heating conditions. The fan releases heat, leading to an increase in the temperature of the supply air, which brings about the supply air condition (5). An increase in temperature of up to 1 °C (1.8 °F) is usually expected. A proper design of the fan is recommended so as to minimise the heat added to the supply air.

The return air from the room is in state (6). The air is then humidified as close as possible to saturation (7). This state is the one which guarantees the maximum potential for indirect cooling of the supply air stream through the heat exchanger for heat recovery. The heat recovery from (7) to (8) leads to an increase in the temperature of the air, which is then used as regeneration air. The air is subsequently reheated in the coil until it reaches state (9). The temperature of the latter is adjusted such as to guarantee the regeneration of the sorption wheel (9 to 10).

It is important to mention that in many desiccant systems a bypass is installed which allows that some of the air coming from the heat recovery unit bypasses the regeneration air heater and the desiccant wheel. Depending on the actual conditions up to more than 20% of the air can go through the bypass thus saving regeneration heat and also electricity because of the reduced pressure drop along the desiccant wheel.

The effectiveness of the dehumidification process is influenced by many parameters affecting the performance of the desiccant wheel such as:

- temperature and humidity ratio of the ambient and regeneration
- the air velocity
- the mass of desiccant compared to the air mass flow
- rotational speed
- process/regeneration air flows ratio

A more detailed discussion about these issues is reported in the following sections dealing with DEC air handling unit components.

Ambient conditions affect the effectiveness of the whole DEC process leading to the need to implement an appropriate control strategy and sometimes to consider different system configurations.

The cooling capacity of the DEC process, defined as the mass flow times the enthalpy drop between ambient air and supply air, can be controlled also by acting on the dehumidification efficiency of the rotor. Many options are available:

- using the by-pass of the regeneration air stream
- changing the regeneration temperature
- varying the rotational speed of the rotor
- using variable speed fans
- using additional cooling back-up devices

A focus on control strategy issues is reported in the following sections

5.2.1 System performance

As for conventional systems the performance of the DEC unit is well described by its Coefficient of Performance (COP).

The $COP_{thermal}$ of a desiccant cooling system is defined as the ratio between the enthalpy change from ambient air to supply air, multiplied by the mass air-flow, and the external heat delivered to the regeneration heater, Q'_{reg}.

$$COP_{thermal} = \frac{\dot{m}_{supply}(h_{amb} - h_{supply})}{\dot{Q}_{reg}} = \frac{\dot{m}_{supply}(h_1 - h_5)}{\dot{Q}_{reg}}$$

Eq. 5- 1

The value of $COP_{thermal}$ of a desiccant cooling system depends strongly on the conditions of ambient air, supply air and return air. Related to ambient air, the COP, defined above, usually ranges from 1.0 to 0.5, reducing its values the higher the regeneration temperature and the dehumidification required. Under normal design conditions the cooling power lies in the range of about 5–6 kW per 1000 m^3/h (2.4– 2.9 ton per 1000 cfm) of handled air.

An important performance figure is its electric COP which is calculated as the previous one but dividing by the electricity consumption of the AHU. Typical values of COP_{el}s for solar driven DEC units range from 2 to 5. Obviously these figures must be compared with EERs[1] of electrical systems which also take into account the consumption of auxiliary devices.

The solar-assisted systems must employ a back-up, either on the cold (i.e., often vapour compression chiller) or on the hot side (i.e., heat source). In many cases where low-temperature heat is available (cogeneration plants, industrial process waste heat, etc.), a heating back-up system is employed.

5.2.2 Solar desiccant cooling systems (SDEC): examples, control and operation

The desiccant cooling process can be combined with solar thermal systems in order to use heat produced by solar thermal collectors for the desiccant regeneration. The desiccant cooling systems allow the use of solar thermal energy for both cooling and heating purposes.

According to the climate and the load typologies, many configurations and combinations are possible through the choice of solar collectors typology and size of the solar collectors, the sequence of air treatments, the typology and the goal of the conventional back-up equipment and the energy sources feeding them.

The use of "standard" (i.e., with an AHU of the same type as the one depicted in Figures 5- 4 and 5- 5) solar desiccant systems (SDEC) presents some technical limitations in particular in hot and humid climates, mainly due to the high latent loads to be handled by the wheel and to the reduced potential of using evaporative cooling. Specific sequences of air treatments can be implemented in order to adapt to these conditions.

[1] These performance figures are widely discussed in chapter 7

In fact, when the humidity ratio and ambient temperature reach high values, or when indoor vapour production is relevant, the standard cycle would not be able to meet the load.

An overview of the different options for solar desiccant cooling systems is given in Table 5- 1. Three groups of systems are listed: solar-thermally autonomous, solar-assisted with back-up heating devices and solar-assisted in combination with a cold back-up (typically a vapor compression chiller). The configurations described in the table are the most common desiccant based solutions for air-conditioning applications with ventilation systems, according to the state of the art of commercially available technologies. Nevertheless, as previously stated, the system designer could find better solutions according to the specific project characteristics and constraints.

system number		liquid collector	air collector	heat storage	back-up heat	desiccant wheel	thermal chiller	back-up chiller	description	application
5.1.1	a		X			X			solar-thermally autonomous desiccant cooling systems with either solar air or liquid collector	no strict requirements for indoor conditons; 'get what you can' strategy; high correlation between solar gains and load necessary
	b	X		X		X				
5.1.2	a		X		X	X			solar-assisted desiccant cooling systems with either solar-air or liquid collector + back-up heat source	only thermally driven; convenient where low-temp. heat is available; application in temperate climates; no high dehumidification
	b	X		X	X	X				
5.1.3	a		X			X		X	solar-assisted desiccant cooling systems with either solar air or liquid collector + back-up chiller	back-up used for cooling as in common air-handling units; sufficient dehumidification even in warm-humid climates; possible to keep comfort in narrow range
	b	X		X		X		X		

Tab. 5- 1 Common typologies of solar desiccant cooling systems

The systems shown in Table 5- 1 can employ either solar air or liquid collectors. The choice between the two systems should take some technical aspects into account. In general, air systems are used for both heating and cooling purposes. In systems using air collectors as a heat source, either the air-handling unit must be appropriately modified or a duct diversion has to be added, allowing different hot air-inlet positions according to the operation mode (heating, cooling).

It is important to point out that in general no commercially available storage units are available for solar air collector's based solar systems. This implies that solar air collectors are often employed either in systems where there is a high correlation between solar radiation profiles and cooling loads or in systems where activation of building thermal masses by ventilation air is feasible, e.g., in systems using night ventilation. For air-heating purposes, they are also often applied for preheating, in order to reduce the fossil fuel consumption of a conventional burner. Water collector systems, by contrast, are generally employed in circuits where a heat storage tank is included. Furthermore the parasitic energy consumption, i.e., mainly fans, should be assessed carefully in the case of solar air collectors since it can vary more significantly according to the plant configuration, than for systems employing liquid collectors.

The following sections present some typical designs and applications, providing a system configuration and a short description of each one. Three basic examples are presented, namely:

- Solar-thermally autonomous desiccant cooling system with solar air collectors integrated as well as ambient-air designs
- Solar-assisted desiccant cooling system with solar liquid collectors, heat storage unit and back-up heat source
- Solar-assisted desiccant cooling system with solar air collectors (or liquid-based collectors) and back-up electricity driven compression machine (in the two versions: heat pump and chiller)

For each example, a general control scheme of the solar-assisted desiccant cooling unit is presented.

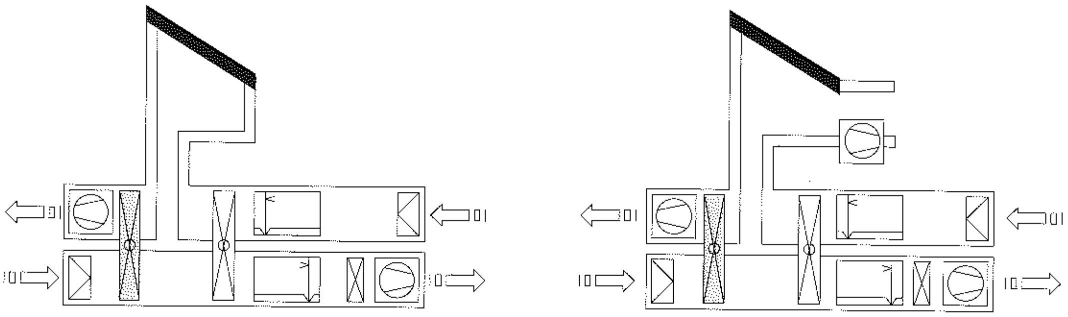

Fig. 5- 6 Solar-thermally autonomous desiccant cooling system with solar air collector, left: integrated design, right: ambient-air design

Even if solar air collectors do not represent a large market as do liquid collectors, their use for the regeneration of desiccant systems is a good option. Provided that heat storage might not be practically implementable or economically suitable (some tests are currently underway with phase changing materials) these systems present some advantages and some drawbacks:

The first advantage is the simplicity of the solar system and its lower cost. However, the absence of a heat buffer makes these HVAC systems very dependent on the climate and the load conditions. For these reasons they are recommended when cooling loads are in phase with solar radiation availability or at least when some inertia can be ensured by the thermal mass of the building.

However, as described in the previous sections, such desiccant systems can also be used as evaporative coolers only, without employing sorptive dehumidification. In this case a reduction of the supply air temperature can be achieved if a potential is available, i.e., the environmental air humidity is low enough to make evaporative cooling feasible. Therefore, such a system may be appropriate in temperate climates.

A typical application might be the all-air air-conditioning system of a seminar room with large glazed surfaces and with a lightweight structure. Such a building has load characteristics which fit well to the considered plant, since both loads and energy availability are in phase and because high ventilation air rates are required due to human occupancy /5.3/.

An important decision during the design process concerns the integration of the solar air collectors in the plant configuration. There are two possible options (Figure 5- 6) with the following specific advantages and disadvantages:

Option 1 (left side) – integrated design: the return air from the building is used for regeneration. This means that the relatively high temperature of the return air at the outlet of the heat-recovery unit serves to preheat the regeneration air. However, due to evaporative cooling of the return air before the heat-recovery component, this air also has a higher humidity ratio than the external ambient air, which is less favourable for the regeneration (i.e., requires higher regeneration temperature). An advantage of this design is that only one fan serves for both return and regeneration air.

Option 2 (right side) – design with ambient air for regeneration: ambient air is used for regeneration. In this concept the temperature increase that can be achieved by the solar collector is normally higher (since the external air temperature is significantly higher than the return air temperature after the heat-recovery component). However, the temperature level needed for the same regeneration is lower, if the humidity ratio of the ambient air is lower than that at the inlet of the solar collector in the "integrated design"; in general, this is the case in temperate climates. The lower temperature leads to increased solar collector efficiency. A disadvantage is that it is necessary to use another fan for the regeneration air, which results in higher capital and operating costs.

In both cases, as for solar-thermally autonomous systems in general, plant design and configuration choices must be based on annual simulations using climatic data and load analysis.

In general, such a system should be equipped with variable-speed fans since in some cases the supply air conditions will not be adequate to cover the entire cooling loads. The fan speed should be controlled by the indoor air temperature/ humidity levels, using the required air-flow for hygienic needs as a minimum. In addition variable air-flow on the regeneration side will allow regeneration temperature control.

The operation modes of the considered air-conditioning system implement the physical processes needed to treat the ventilation air according to the building loads. In this way, the system operation is characterised by the active components in the mode, keeping temperature and humidity control together. During the operation modes which implement the heating/cooling and humidification/ dehumidification functions, the physical processes shown in Section 5.1 take place in the air-handling unit.

The system operates in following modes:

- Free ventilation mode: none of the thermal components is active; no driving heat is required
- Indirect evaporative cooling mode: The return air stream humidifier is active as well as the heat recovery unit. The return air is brought close to saturation and then enters the heat exchanger. Only sensible cooling of the supply air stream is provided. No driving heat is required. Main control parameters: efficiency of return air humidifier (0–100%)
- Combined evaporative cooling mode: the supply air and the return air humidifiers are active. The heat recovery unit is in operation. Combined evaporative cooling, i.e., direct and indirect, is employed. No driving heat is required. Main control parameters: efficiency of supply air humidifier (0–100%)
- Desiccant cooling mode: the dehumidifier wheel, the humidifiers, the heat recovery unit and the solar air collector are active; all heat available from the solar system is used for regeneration. Main control parameters: regeneration air temperature by means of control of the fan rotational speed, supply air humidifier (0–100%)

Table 5- 2 describes the operation scheme. The bypass column included in the table is valid only in the integrated design, since no bypass is needed if there is a decoupling of the streams coming from the air collector through the regeneration part of the wheel and the air coming from the building. In this case, the air flow rate of the two streams can be controlled by the two different fans. In the case of ambient air used for regeneration, it could make sense from a technical point of view to use a bypass instead, and divert part of the stream, which would go through the collector, directly towards the desiccant wheel. This would allow control of the regeneration temperature, and a reduction of the fan electricity consumption due to the decreased pressure drop.

	Mode	Components active (+), not active (-)									Condition
		Desiccant rotor	**Heat recovery unit**	**Humidifier supply air**	**Fan supply air**	**Humidifier return air**	**Bypass regeneration air heater**	**Regeneration air heater**	**Fan return air**	**Fan regeneration air (only ambient-air design)**	
increasing cooling load	Free ventilation	-	-	-	+	-	open	-	+	-	supply air temperature and humidity o.k.
	Indirect evaporative cooling	-	+	-	+	+	open	-	+	-	supply air temperature exceeds set value
	Combined evaporative cooling	-	+	+	+	+	open	-	+	-	supply air temperature exceeds set value; supply air humidity below set-point
	Desiccant cooling	+	+	+	+	+	<20%	+	+	+	supply air temperature and/or humidity exceeds set value; solar heat available

Tab. 5- 2 Operation scheme of a desiccant cooling unit driven by heat coming from a solar air collector

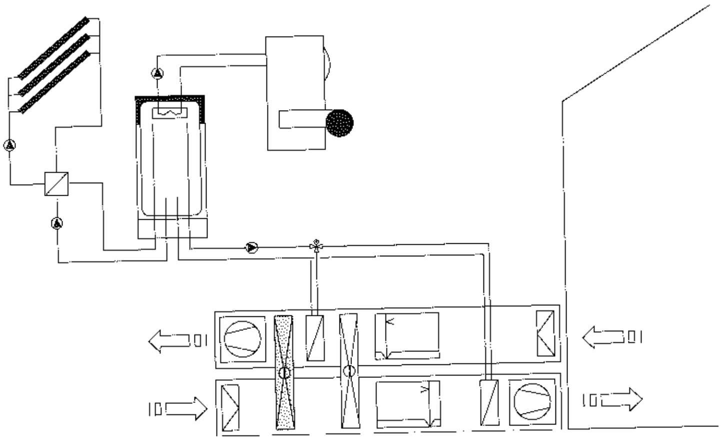

Fig. 5- 7 Solar-assisted desiccant cooling system including collectors with liquid heat-transfer medium, storage tank and back-up heat source

This is a very common design for a solar-assisted air-conditioning system using the desiccant cooling technique. Solar heat is supplied either to the heat storage tank or directly to the load, depending on its integration in the plant scheme. If the solar heat available is not sufficient, the back-up heat source is used. In the case that the back-up heat source is also connected to the storage tank, the top storage temperature is the parameter used for control purposes, i.e., as soon as this temperature falls below the set value, the back-up heater turns on. If the back-up heater is directly integrated into the water cycle which provides heat to the regeneration air heater, it is switched on as soon as the desired regeneration temperature is higher than the one of the hot water stored. In this design, the full tank volume is available to store solar heat. But the operation conditions of the back up heater are not optimal.

The general structure of the control scheme is the same as the one described in the previous example; the modes described in the previous section are valid also in this case, as can be seen in Table 5- 3.

When the configuration discussed above, i.e., back-up heater integrated into the plant scheme, works in the desiccant cooling mode, it is recommended to adjust the applicable regeneration temperature. In this way the water temperature enters the regeneration air heater according to the actual indoor cooling needs. Using a variable regeneration temperature complicates the control procedure but allows a higher plant efficiency under part load conditions. Moreover, the latter has two positive effects: the storage tank volume is used in a more efficient way and the solar collectors operate with higher efficiency.

In general, such a system should be equipped with variable-speed fans since in some cases the minimum air-flow, i.e., the required flow of fresh air, could not cover the cooling loads. Nevertheless, if the system is designed to cover only part of the loads (i.e., other air-conditioning systems are installed), the air-handling unit could be equipped with fixed-speed fans. If variable-speed fans are installed, their speed should be controlled by the indoor temperature/humidity unless hygienic needs make a higher volume flow necessary. This means that the control strategy would be based on the one shown in the previous section, but if comfort conditions were not achieved, the air flow rate in the "desiccant cooling mode" would be increased.

increasing cooling load

Mode	Desiccant rotor	Heat recovery unit	Humidifier supply air	Fan supply air (*)	Humidifier return air	Bypass regeneration air heater and desiccant wheel	Regeneration air heater	Fan return air(*)	Condition
Free ventilation	-	-	-	+	-	open	-	+	supply air temperature and humidity o.k.
Indirect evaporative cooling	-	+	-	+	+	open	-	+	supply air temperature exceeds set value
Combined evaporative cooling	-	+	+	+	+	open	-	+	supply air temperature exceeds set value; supply air humidity below set-point
Desiccant cooling	+	+	+	+	+	≤20%	+	+	supply air temperature and/or humidity exceed set value
Desiccant cooling increased air-flow	+	+	+	++	+	≤20%	+	++	supply air temperature and/or humidity exceed set value

(*) the sign ++ applies for increased air-flow according to control strategy

Tab. 5- 3 Operation scheme of a solar-assisted desiccant cooling system including collectors with liquid heat-transfer medium, storage tank and back-up heat source

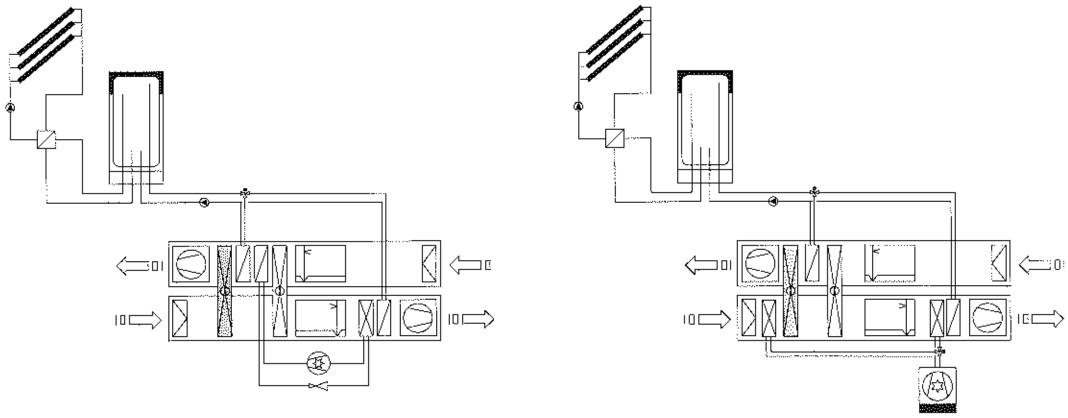

Fig. 5- 8 Solar-assisted desiccant cooling system including collectors with liquid heat-transfer medium and back-up chiller. Twi configurations are shown: left: chiller as an integrated heat pump; right: chiller cooled by ambient air

The two systems described here use conventional compression chiller technology as the back-up. In the first case (see Figure 5- 8 left), the compression machine is used as a heat pump between the supply and the return air streams. It operates by lowering the temperature of the supply air and delivering the condensation heat to the regeneration air. The psychometric states of the moist air process are described in Figure 5- 9.

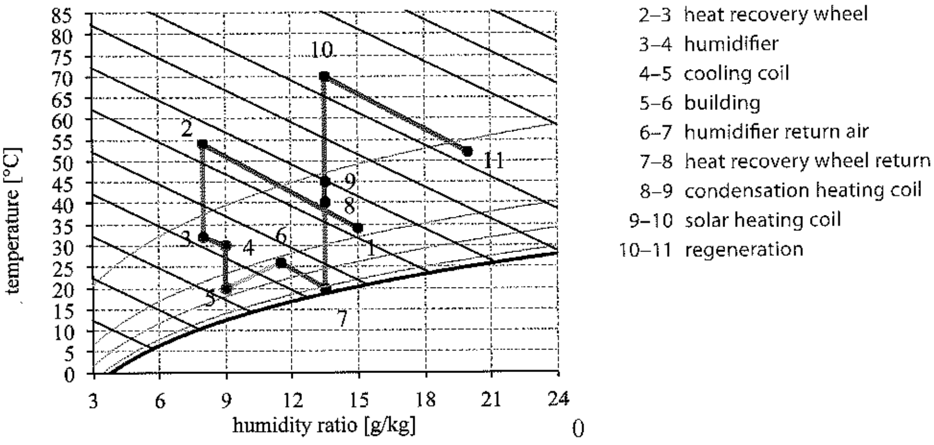

Fig. 5- 9 Desiccant cooling process with integrated heat pump and additional cooling coil in the T-x-diagram 1–2 desiccant wheel

Therefore a direct evaporator and direct condenser without additional water circuits are used. The advantage of this system is the high heat recovery rate that can be achieved since the heat pump provides both cooling of the supply air and heating of the regeneration air. The heat pump has to work at a higher compression rate due to the higher temperature difference compared to a machine using ambient air for condensation. Although the supply-air cooler can always provide cooling, it is necessary also to install a humidifier on the supply air side; if enough solar radiation is available the latter allows the plant to be operated as a conventional solar desiccant cooling system as in previous examples.

The second option (see Figure 5- 8 right) is a SDEC with two cooling coils integrated into the supply side. The cooling coils are connected to a circuit where a conventional vapour compression chiller is included. It should be noted that another configuration derived from the latter is mostly employed, if the climate conditions are not extreme. In fact, the most commonly used solar-assisted desiccant cooling systems with a back-up chiller include only the cooling coil after the heat recovery wheel. In this configuration, the desiccant component is intended to carry out all of the dehumidification. The chiller will then cover only a part of the sensible load, i.e., the part not covered by combined evaporative cooling.

The configuration with two cooling coils is designed for humid climates as in tropical areas. Under these kinds of weather conditions, with high humidity ratios of the ambient air (e.g., greater than 20 g/kg (140 gr/lb)), the sorption process, in standard DEC systems, is not able to reduce the air humidity sufficiently to achieve comfortable supply-air conditions (at regeneration temperatures compatible with common solar thermal systems). Therefore, another DEC configuration has to be used. The system shown here has the advantage that the first cooling coil (coil 1), which is installed before the dehumidifier and which can be used for cooling and dehumidification, works at a higher temperature level compared to the case where all the dehumidification is achieved by the chiller. The pre-dehumidified air is further dehumidified in the sorption wheel to the desired level for the supply-air humidity. In this configuration the humidifier for the supply air is not operated when the two cooling coils are used. Moreover even in cases where in the first cooling coil the air dehumidification does not take place, the relative humidity of the air entering the desiccant wheel is higher. And as consequence the dehumidification process, given the same boundary conditions, would result in a larger amount of water vapour taken away from the supply air stream (compared with a standard DEC configuration). Since the second cooling coil (coil 2) is only used to cover sensible loads, it can also work at a higher temperature level.

Figure 5- 10 shows the effects of the two coils operation.

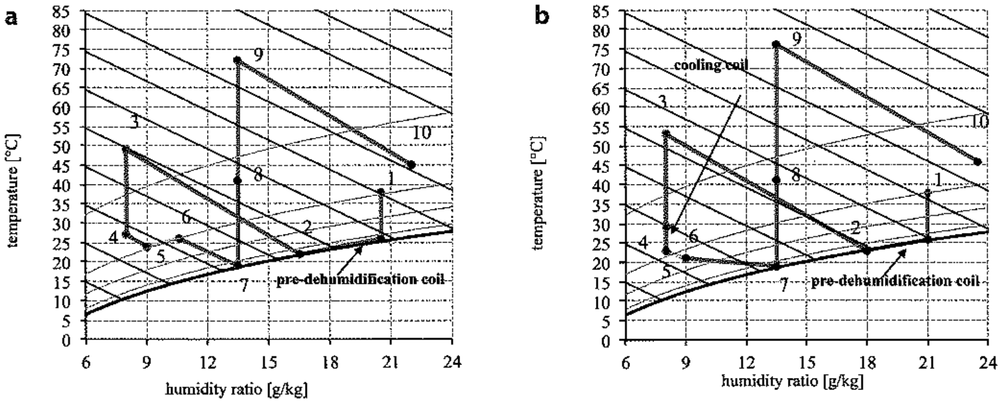

Fig. 5- 10 Two coil desiccant cooling process in the T-x-diagramm with only the first cooling coil in operation (a) and with both cooling coils in operation (b)

Another advantage of this system is that the EER of the chiller, which serves both cooling coils, can be higher than in a case where the air-conditioning load is covered entirely by the chiller. Therefore, this kind of system offers more than just desiccant cooling. It is a highly efficient concept in warm and humid climates, to combine solar-driven dehumidification with a conventional vapour-compression chiller.

	Mode	Components active (+), not active (-)											Condition
		Cooling coil 1 (cooling + dehumidification)	Desiccant rotor	Heat recovery unit	cooling coil 2 (only sensible cooling)	Humidifier supply air	Ventilator supply air	Humidifier return air	Bypass regeneration air heater and desicant wheel	Regeneration air heater	Ventilator return air	Back-up chiller	
	Free ventilation	-	-	-	-	-	+	-	open	-	+	-	supply air temperature and humidity o.k.
increasing cooling load	Indirect evaporative cooling	-	-	+	-	-	+	+	open	-	+	-	supply air temperature exceeds set value
	Combined evaporative cooling	-	-	+	-	+	+	+	open	-	+	-	supply air temperature exceeds set value; supply air humidity below set-point
	Desiccant cooling without chiller	-	+	+	-	+	+	+	≤20%	+	+	-	supply air temperature and/or humidity exceed set value
	Desiccant cooling with coil 1 active	+	+	+	-	-	+	+	≤20%	+	+	+	supply air humidity exceeds set value
	Desiccant cooling with coil 2 active	-	+	+	+	+	+	+	≤20%	+	+	+	supply air temperature exceeds set value
	Desiccant cooling with coil 1 and 2 active	+	+	+	+	-	+	+	≤20%	+	+	+	supply air temperature and humidity exceed set value

Tab. 5- 4 Operation scheme of a desiccant cooling unit dirven by heat coming from solar collectors with liquid heat transfer medium and a compression chiller that provides chilled water fort wo cooling coils (according tot he system in 5-10 b)

The general structure of the operation strategy of these systems is the same as for the previous SDEC example. However, the humidifier for the supply-air stream must be controlled in a different way. The control sequence works with increasing loads up to the desiccant cooling mode. Table 5- 4 describes the operation scheme of a system employing two cooling coils. Figure 5- 11 shows a desiccant air-handling unit with a configuration which is a merge of the two previously described: two additional coils are fed by an integrated heat pump.

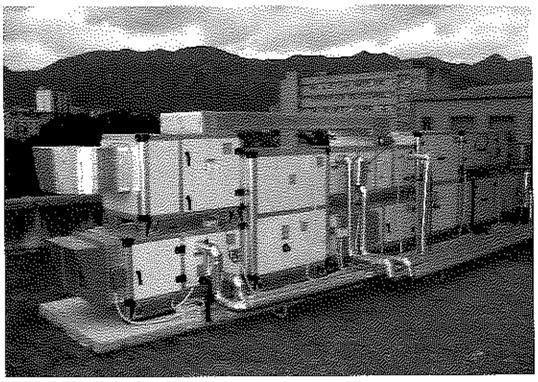

Fig. 5- 11 Example of a desiccant air-handling unit with integrated heat pump and two additional coils (nominal air-flow 1500 m^3/h – 883 cfm) *Source: Dept. Energy, University of Palermo, Italy*

Many other configurations of the AHU are possible by combining different collectors and heat exchangers typologies, humidification/free cooling processes, exhaust/re generation/process air paths or by the introduction of additional devices (i.e. enthalpy wheels).

Possible further variants of the standard DEC cycle are today focussed on the possibility of enhancing the free cooling effect, to use more efficient indirect evaporative cooling and to use the available heat regeneration processes in the smartest way.
According to design and ambient conditions these tasks can be fulfilled in many ways:

- using wetted static heat exchangers instead of rotary wheels
- using cooling tower water in a conventional cooling coil
- choosing between the exploitation of return air and ambient air on the saturation side of the indirect evaporative cooling according to their enthalpies.
- choosing between saturated exhaust air and ambient air for the regeneration of the wheel.

Moreover, significant performance improvements are achievable with smarter control strategies (e.g., demand-based control, neural networks, fuzzy logic).

In practice it has been observed that many systems fail to achieve good energy savings. The reasons for this are manifold: too complex hydraulic layouts, insufficient control systems, high parasitic electricity consumption, etc.

With regard to design and operation, some simple rules can be recommended:

- the hydraulic system and the air paths should be as simple as possible and only as complex as necessary
- the design should be supported by detailed simulations of loads and system performances
- a rigorous commissioning phase with recording and analysis of operating data is essential in order to achieve the targeted energy savings

The latter item is discussed in the next paragraph.

5.2.3 Possible operational problems

Often DEC systems have been designed without properly considering the maximum humidity conditions (9.5–10 g/kg (66.5–70.0 gr/mb)) of inlet air necessary to cope with the room latent load associated with a design inlet temperature of about 20 °C (68 °F). If the heating effect of the fan operation and that related to the uninsulated air ductwork is neglected, air could be introduced into the room at 22–23 °C (71.6–73.4 °F) minimum temperature.

When DEC systems have also to meet the whole sensible load of the room, it is compulsory to consider also the room temperature distribution. If exhaust air is gathered from the higher zone in rooms with remarkable vertical temperature gradients, the potential of the indirect evaporative cooling can be reduced. The same problem can be caused by poor insulation of the exhaust air ducts.

DEC system operations are strongly reactive to short time constant internal load swings. When internal loads rise over design conditions the inlet temperature rises according to the conditions of the exhaust air. In systems without active back-up, this process can be switched only with a smoothing of the internal load or when more favourable ambient air conditions occur.

In general, pressure drops in AHU and ducts must be considered. In DEC systems, air must pass through several additional devices in comparison to what happens in a conventional unit. The main resistance is caused by the desiccant wheel. As a general figure, the pressure drop for a standard DEC AHU could be from 2 to 2.5 times higher than in a conventional unit. Also, air losses and leakage must be avoided. Depending on the position of the fans, either in the desiccant wheel or in the rotary heat exchanger, relevant infiltration between the streams (due to the difference in pressure between the two channels in the AHU) occurs. When air ducts are not properly sealed the total reduction of inlet air mass flow can reach 20% with respect to the design value. The importance of this increases the smaller the air volume flow of the AHU. For this reason, DEC air handling units employing rotors that are not generally designed for air volume flows below 2500 m^3/h (1471 cfm).

Even if the flow rate is not reduced, improper mixing with return air can reduce the process effectiveness. The latter could arise from poor maintenance and cleaning of the rotors: dust deposits can cause humidity transport.

Control systems can fail if control system sensors are not correctly located. Temperatures and humidity in the AHU channel's section can vary significantly, due to the heat and mass exchange process (inhomogeneous in the positions after the wheel) and rapid air movements. It is a good practice to check the reliability of the measurements by periodical calculation of enthalpy and mass balances in the AHU sections. Good quality sensors must be also chosen.

5.2.4 Main components of solid DEC air handling units

The key components of desiccant cooling systems, namely the desiccant wheel, the rotatory heat exchanger and the humidifiers, are described in the following sections.

5.2.4.1 Dehumidifiers

Different technologies can be used to dehumidify moist air using solid desiccant material /5.4/: cyclic heat and mass exchangers and desiccant wheels.

Desiccant wheels

Rotary dehumidifiers, known as desiccant wheels are the most well-known and commercially available devices, employing solid desiccant for air dehumidification. The desiccant material is coated, impregnated or formed in place on a supporting rotor structure, similar to that of a common rotary heat exchanger. Typically, the basic material which forms the supporting structure is a mix of different fibres, including glass, ceramic binders and heat resistant plastics. A desiccant wheel functions as a heat and mass exchanger between two air streams, i.e., supply and return, and can be operated either as a dehumidifier or as an enthalpy recovery component in desiccant cooling and heating modes, respectively. Depending on the chosen operating mode (dehumidifying or enthalpy recovery), the rotational speed of the wheel varies commonly within the ranges of 6–12 rotations per hour for dehumidification and 8–14 rotations per minute for the enthalpy recovery mode, respectively. The physical process taking place across the wheel is further described only for the dehumidifier mode; the process for the enthalpy recovery mode is similar to that of usual enthalpy recovery wheels.

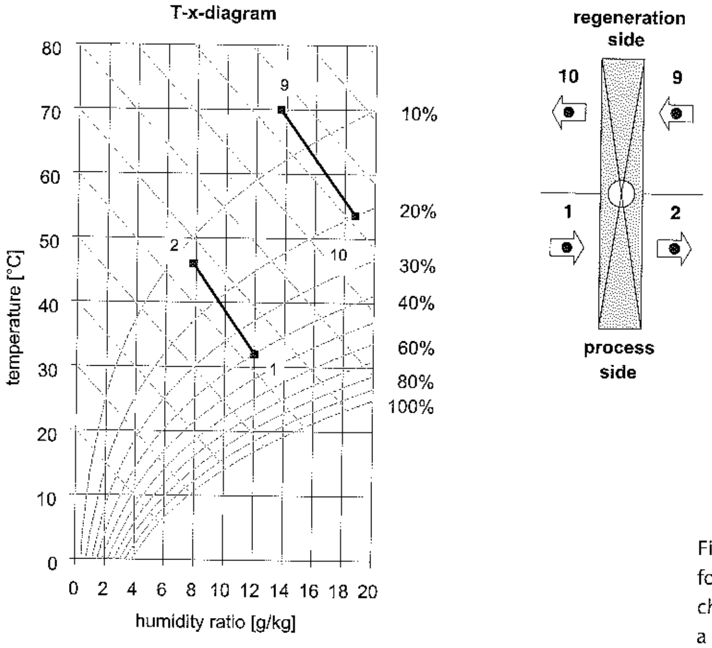

Fig. 5- 12 Psychometric chart for moist air showing the state changes for dehumidification in a desiccant wheel

The wheel is divided into two sectors, of which the first one is used for dehumidification of moist air while the second one is used for the regeneration. The ratio between the area of these two sections can vary according to the design power and the temperature of the regeneration air stream. In general, the reduction of the regeneration air mass flow to the minimum amount required is a good practice to reduce the energy consumption of the fans.

Figure 5- 12 is a schematic illustration of the psychometric state changes occurring during the dehumidification of air in a desiccant wheel. The state numbers refer to those in Figure 5.4. The supply air is dehumidified (state change 1–2) on the process side of the rotor. The return air, after being heated, flows through the regeneration side of the rotor (state change 9–10) causing desorption of the water that was bound in the desiccant on the process side. For a given desiccant wheel operating under conditions of given air-flow rates and a given speed of rotation, the state of the out going process air (2) depends primarily on the incoming air states 1 and 9.

The desiccant is regenerated by supplying heat to the regeneration air, which is sufficient to raise the temperature of the desiccant to a value at which the vapour pressure of the water bound in it exceeds the partial pressure of the water vapour in the warm regeneration air stream. The energy associated with the sorption and desorption processes is equal to the latent heat of condensation plus a differential heat of sorption. Therefore the change in the state of the air on the process side occurs with an increase in enthalpy. It is beneficial to have a low total heat of sorption. In addition, the state change is also affected by the heat stored in the rotor matrix on the regeneration side. As mentioned above, the two previous operation modes are a function of the rotational speed of the wheel. With rotational speeds above a certain value (e.g., 20 rotations per hour), the activated sorption capacity of the wheel is reduced. The process can be represented on the psychometric chart along a line which connects both inlet air points for the two streams; this corresponds to an enthalpy recovery behaviour which is favourable for winter applications, i.e., heat and moisture recovery from the return stream.

Desiccant materials usually used in the honeycomb structure of the desiccant wheel are: silica gel, lithium chloride or new composite materials.

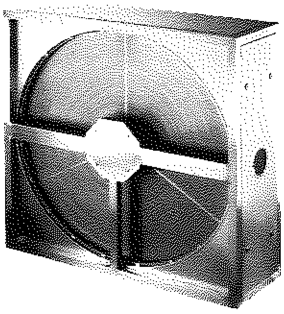

Fig. 5- 13 Example of a sorption desiccant wheel integrated into a cassette
Source: Klingenburg GmbH, Germany

The structure of the wheel is normally similar to honeycombs, creating parallel micro-channels where the air stream goes through. The physical shape of the micro-channels affects the relationship between the air mass transfer and the pressure drop. It can be of manifold type: staggered parallel strips, parallel plate, circle, square, triangle and packed bed.

Rotors are available with many depths ranging from 50 to 400 mm (2 to 16 in), even if in HVAC applications the values rarely exceed 200 mm (8 in).

Parasitic energy inputs include: the electric drive motor used to rotate the wheel (with negligible consumption) and fan power required to overcome the pressure drops through the process and regeneration sides of the wheel.

Typical values of pressure drop for average air velocities (3 m/s (10ft/s)) range from 100 to 300 Pa (0.4 to 1.2 in H_2O – 60 °F). Figure 5- 14 shows indicative values of pressure drops for different air velocities and wheel depths.

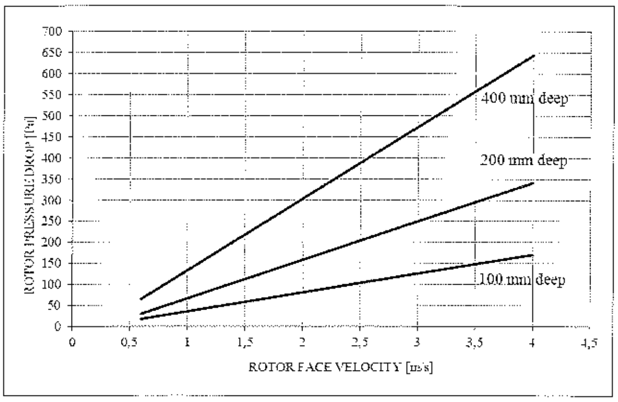

Fig. 5- 14 Example of pressure drop abacus for desiccant wheels as a function of air velocity and depth

Performance of the dehumidification wheel can be defined in many ways.
One possibility is to assess the effectiveness for the humidity ratio, defined as follows:

$$\varepsilon = \frac{\Delta x_{real}}{\Delta x_{ideal}} = \frac{x_{in} - x_{out}}{x_{in} - x_{out,ideal}}$$

Eq. 5- 2

where Δx_{real} and Δx_{ideal} are respectively the actual and the maximum attainable, differences of humidity ratio the dehumidifier carries out. Δx_{ideal} is the difference that would be achieved if the process air stream were in thermodynamic equilibrium with the regeneration air, i.e. when the relative humidity in 1 (see Figure 5- 15) equals the one in the regeneration stream (9).

The wheel behavior can be described through several physical and empirical models available in literature. These models are generally used in detailed dynamic simulations of the systems.

As an example, a simplified model based on empirical data gives the following linear relationships between relative humidity and specific enthalpies of supply and regeneration air, valid for supply and regeneration air flow rate ratio equal to one:

$$RH_{in} - RH_{out} = a(RH_{in} - RH_{reg}) + b$$

Eq. 5- 3

$$h_{out} - h_{in} = c(h_{reg} - h_{in}) + d$$

Eq. 5- 4

The four coefficients a,b,c,d can be calculated starting from the little empirical data on different operating conditions /5.5/.

In practice, it is often useful to refer directly to the amount of water removed for given operating conditions. This data is generally available in test certified manufacturer data sheets. Figure 5- 15 shows an example of performance diagram which can be used.

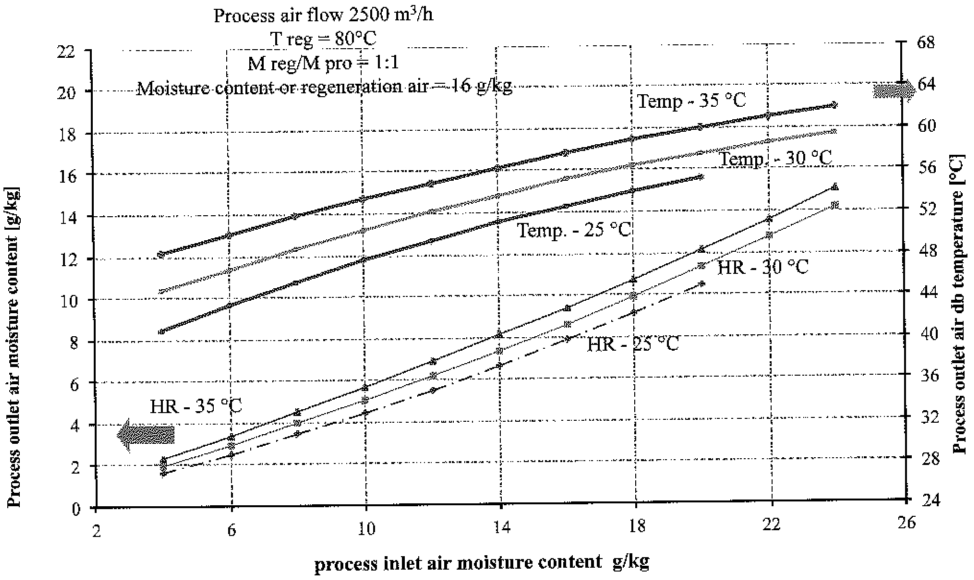

Fig. 5- 15 Example of performance chart for desiccant wheels for given process/regeneration air flow ratio, regeneration temperature and humidity ratio, air velocity and rotational speed (1 °C = 33.8 °F)

Table 5- 5 gives a list of desiccant wheel manufacturers, along with a short description of the available products. It is difficult to provide market prices for sorption regenerators since they are not an independent market product but are purchased by manufacturers of air-handling units. The actual price depends strongly on the size of the air-handling unit.

Company	Country of Origin	Desiccant	Wheel Size
Munters USA	US	SiGel, AlTi, Silicates, New Proprietary	0.25 - 4.5 m
Munters AB	Sweden	SiGel, AlTi, Silicates, New Proprietary	0.25 - 4.5 m
Seibu Giken	Japan	SiGel, Am, Silicates, New Proprietary	0.1 - 6 m
Nichias	Japan	SiGel, Mol. Sieves	0.1 - 4 m
DRI	India	SiGel, Mol. Sieves	0.3 - 4 m
Klingenburg	Germany	Al oxide, LiCl	0.6 - 5 m
ProFlute	Sweden	SiGel, Mol. Sieves	0.5 - 3 m
Rotor Source	US	SiGel, Mol. Sieves	0.5 - 3 m
NovelAire	US	SiGel, Mol. Sieves	0.5 - 3 m

Tab. 5- 5 Manufacturers and product description of sorption dehumidifiers /5.6/ (no claim for completeness)

Cyclic heat and mass exchangers

Such a system consists of two desiccant beds (A and B in Figure 5- 16, usually vertical [5.4]) where air passes periodically. In order to ensure the continuity of the dehumidification process, desiccant beds work complementarily: when the first one is dehumidifying moist air the second is being regenerated by a hot air stream. In the first period outside moist air is dehumidified in the desiccant packed bed A until a certain degree of saturation of the desiccant with moisture has been achieved, while the second bed (B) is being regenerated with a hot air stream. In the second period, moist air passes through a desiccant bed B (now dry) while hot air regenerates the saturated desiccant bed A. The most common desiccant material used for the cyclic heat and mass heat exchangers are silica gel or zeolite. There is no information about commercially available devices of this sort.

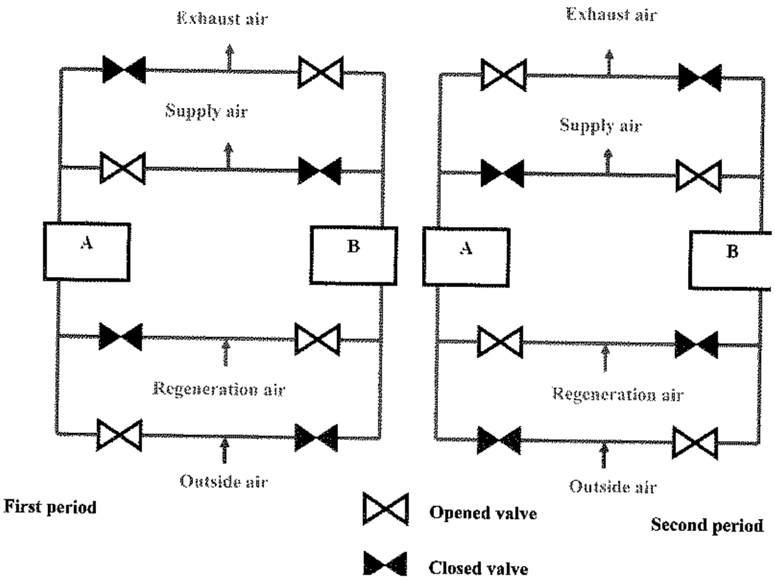

Fig. 5- 16 Cyclic heat exchangers

Cooled desiccant dehumidification: ECOS system concept

A new development of a system concept called ECOS (Evaporatively COoled Sorptive heat exchanger) is currently developed at the Fraunhofer Institute for Solare Energy Systems ISE and at the Department of Energy of the Politecnico di Milano. The ECOS system concept is based on an alternating batch-process consisting of two cooled sorptive-coated heat exchangers. This allows for providing a semi-continuous air-flow to the conditioned space (see Figure 5- 17).

ECOS is a sorptively cooled heat exchanger employed for building air-conditioning. The novel system is the implementation of an original desiccant and evaporative cooling process. The process is based on simultaneous sorptive dehumidification and indirect evaporative cooling of the supply air stream. The design of the process results in a higher dehumidification potential in comparison with conventional DEC systems /5.7/. The system implementing the process is based on a counter-flow air-to-air heat exchanger technology. The heat exchanger is divided in supply (sorptive) and return (cooling) channels, which are physically separated but in thermal contact. The sorptive material is fixed on the heat exchanger sorptive channels. In the sorptive channels the supply air is dehumidified. A continuous humidification of the cooling stream takes place in the cooling channels. The latter, used for indirect evaporative cooling of the supply air stream, is always kept in over saturated conditions during the process.

The complete system consists of two sorptive heat exchangers, operated periodically. While one component is used in air-conditioning operation mode the other one is regenerated and pre-cooled before the next air-conditioning operation mode. The regeneration consists in releasing the water vapor load of the sorbent material to the environment by means of a hot air stream (60–90 °C (140–194 °F)). The pre-cooling phase is intended to lower the temperature of the heat exchanger after the regeneration, taking up the heat stored in the heat exchanger thermal mass. Moreover a complete air-conditioning system will include at least a humidifier at the entrance of the cooling channel which brings the air to almost saturated conditions before entering the channel.

In the ECOS process the sorptive process is cooled and it results in an enhancement of its sorption capacity. The main advantages of the ECOS cooled sorptive heat exchanger concept are the enhanced dehumidification, the simultaneous cooling of the supply air and the strict separation of the supply and the return air flow, avoiding carry-over effects which are common in rotary DEC systems. Moreover it can also be designed for low capacities (200 m^3/h (118 cfm)).

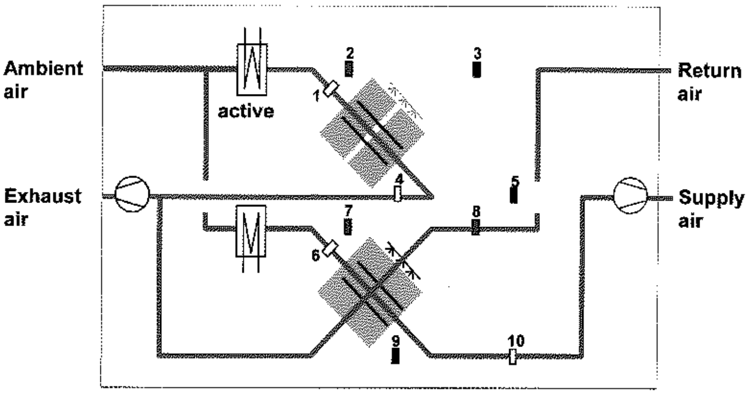

Fig. 5- 17 ECOS system concept: regeneration of the upper heat exchanger and ambient air dehumidification and cooling in the lower heat exchanger

5.2.3.2 Humidifiers

In HVAC applications humidifiers /5.8/ can be used for two different applications, raising the humidity in winter for heating applications (by injecting water vapour), or decreasing the temperature by evaporative cooling for summer application. The second case concerns the desiccant air handling unit. For cooling applications two basic processes can be used: contact humidifiers or spray humidifiers.

Contact humidifiers

In this case air enters into contact with a wet surface where water runs off by means of a circulating pump. This results in evaporation of water into the air. In this type of humidifier low efficiency is obtained and thus water is injected in large quantities into the wet pads to assure evaporation and thus a retention tank is used. These humidifiers induce a significant pressure drop due to the pads and have a major drawback which is the difficulty in controlling the humidity at the outlet of the humidifier especially when one wishes to reduce the level of humidification. In fact limiting the water flow rate of the pads is not enough because the wet pads need time to dry before reaching the desired response. On the other hand this type of humidifier often presents problems with sanitary development of germs in the retention tank. The major advantage of these humidifiers is that they do not require treatment of the upstream water and energy consumption is limited to that of the pump.

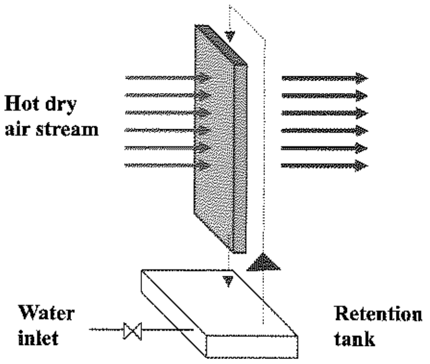

Fig. 5- 18 Wet pad humidifiers

Spray humidifiers

In spray humidifiers water is fractioned into small particles injected directly in the air stream which increases the contact surface and facilitates evaporation. The result is more effective, especially in that this process generally does not (or only slightly) induce a pressure drop. Different types can be found for spray humidifiers.

Scrubber humidifier with spraying nozzles
There are two types, the first with pressurized water the second with normal mains pressure. In the first case pressurized water is fed to the nozzle ending on a needle pointed in the middle of the nozzle hole. The water arriving at the needle breaks into easily evaporable droplets of 2 to 5 μm (0.08–0.2 thou). Although effective, this humidifier is energy demanding due to water pressure issues.

In the second case, a pump feeds sprinklers that spray water. In this case the quantity of sprayed water is much larger than that evaporated. This type is less efficient than a high pressure system, but it does not consume much energy. The humidity control is difficult.

Ultrasonic Humidifier
In this type of humidifier a water container is equipped at the bottom with a piezoelectric converter. The humidification process is as follows: The converters transform the electrical signal into a mechanical oscillation of high frequency at the bottom of the water container. The rate of evaporation is directly related to the frequency of the oscillator making the control of the humidity output very simple. On the other hand, the energy consumption of the humidifier itself is very low however the water must be treated by reverse osmosis which is energy demanding. It should be noted that this type of humidifier is not available for flow rates greater than 2000 m^3/h (1177 cfm).

Rotating centrifugal humidifier

A rotating evaporator cooler consists of a cylindrical meshed cage (Micronizer) rotating at high speed that permits water fractioning to easily evaporable 20 μm (0.8 thou) droplets.

Figure 5- 19 shows the rotating evaporative cooler. The water feeding the cage is at normal mains pressure and does not need special treatment except water softening, which is not energy demanding. Thus the consumption of this type of humidifier is similar to that of a small pump, as it is limited to the motor driving the cylindrical cage. Rotating evaporator coolers are hygienic, since the water is not recycled and losses are very limited because almost all of the water evaporates. The major advantage of this type of humidifier is the facility in controlling the humidity outlet since it is directly related to the water flow rate at the inlet of the humidifier. To control the humidification rate the water flow rate must thus be controlled.

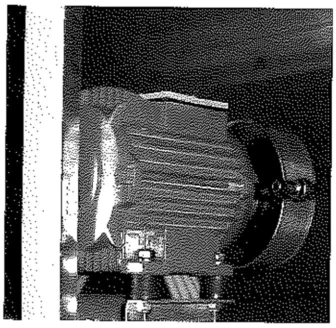

Fig. 5- 19 Centrifugal evaporative cooler

Table 5- 6 reports a summary of the main characteristics of the different types of humidifiers

Type	**Contact humidifiers**	**Spray humidifiers**			
		Pressurized scrubber humidifier	**Unpressurized scrubber humdifier**	**Ultrasonic**	**Centrifugal**
Efficiency	0.6–0.8	0,9	0,8	1	0,95
Water treatment	Not necessary softening recommended	Reverse osmosis	Not necessary softening recommended	Reverse osmosis	softening
Electrical consumption[1]	low	high	low	low	low
Excess water[2]	50%	0–10%	20%	0	0–10%
Controllability	Moderately	Very good	Moderately	Very good	Very good
Advantages	Cheap	Accuracy of control	Cheap	Accuracy of control	Accuracy of control
	Low maintenance		Low maintenance	Low maintenance	Low maintenance
Disadvantages	Hygienic problems	Energy consuming for humidification and water treatment	Hygienic problems	Expensive	Loss of water not evaporated

Tab. 5- 6 Main characteristics, advantages and disadvantages of the different types of humidifiers

5.2.3.3 Air-to-air heat exchangers

In a desiccant air handling unit, hot and fresh air is cooled down by the return air (cooled in return evaporative cooler) behind the dehumidifying section. To perform this cooling stage various sensible heat exchangers can be used: plate heat exchangers, heat pipe heat exchangers or rotating sensible heat regenerators.

The efficiency of a sensible heat exchanger is defined as follows:

$$\varepsilon = \frac{\Delta T_{realized}}{\Delta T_{\max}}$$

Eq. 5- 5

Where $\Delta T_{realized}$ is the temperature difference between the inlet and the outlet temperature achieved on the process air stream (supply air) ΔT_{max} is the maximum possible temperature difference between the hot inlet and the cold inlet.

The heat exchanger performance affects the effectiveness of the indirect evaporative cooling process in a very important way and thus the entire DEC system. In Figure 5- 20 the reference value of the effectiveness ε was set at 0.8.

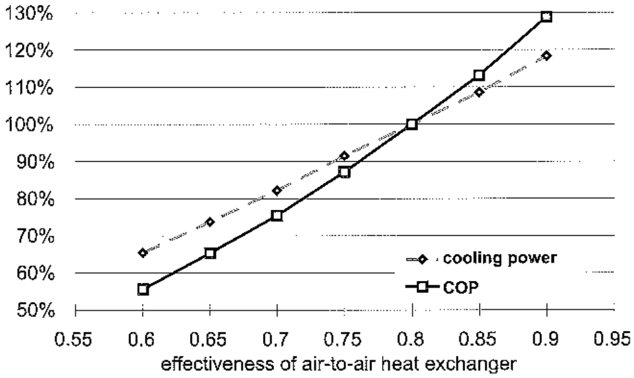

Fig. 5- 20 Influence of the air-to-air heat exchanger effectiveness on the performance of a standard desiccant cooling cycle (values for an efficiency of 0.8 were set to 100%)

For this value the cooling capacity of the desiccant cooling cycle, as well as the $COP_{thermal,}$ is set to 100%. Reducing the effectiveness to a value of 0.6 reduces the cooling power by nearly 35% and increasing the effectiveness to 0.9 increases it by about 18%. At the same time the $COP_{thermal}$ of the cycle is reduced by nearly 45% for an effectiveness of 0.6 and is increased by more than 28% for an effectiveness of 0.9, respectively. This underlines the necessity to install a highly efficient air-to-air heat exchanger in desiccant cooling units.

Plate heat exchangers

A plate heat exchanger is a cubic structure divided into two ducts separated by fin plates. The hot fluid circulates into the first duct where it heats the plates that return the heat to the cold fluid in circulation through the second duct. The efficiency of these heat exchangers varies between 52% and 68% /5.8/ for cross-flow design. Higher efficiency values can be achieved by counter-flow design; however, counter-flow plate heat exchangers for air-air-operation are only available for small capacities (up to approx. 3000 m³/h (1766 cfm)).

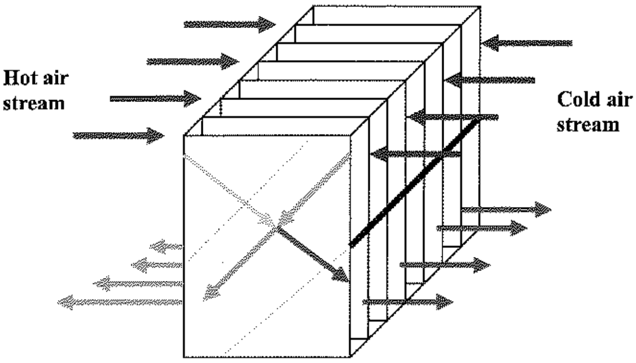

Fig. 5- 21 Figure of cross flow heat exchanger

Heat pipe heat exchangers

Heat pipe heat exchangers consist of a set of tubes closed on both sides containing a vaporizable fluid. Arranged vertically and parallel, the lower end of the tubes lies in the duct of hot fluid while the upper end in the cold duct. With the passage of the hot stream the fluid inside the tube evaporates, rises along the tube to reach the upper end, delivers the heat to the cold fluid, condenses and falls down to the lower end of the tube by gravity. To maximize efficiency, the temperature difference between the two fluids must be significant and the temperature of the hot fluid must be high enough to ensure vaporization of the fluid. These types of exchangers show a reduced efficiency from 37% to 56%.

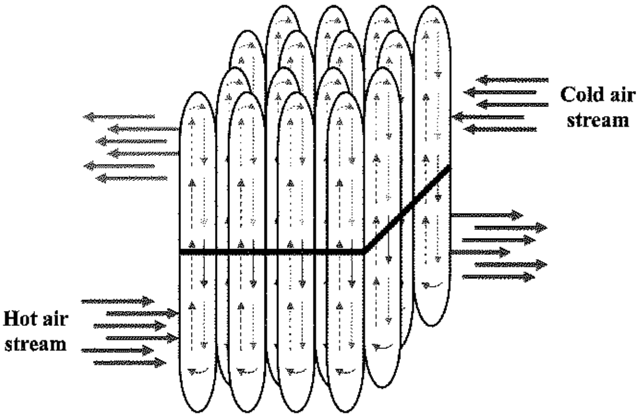

Fig. 5- 22 Heat pipe heat exchanger

Rotary (Sensible) heat regenerator

A rotary (sensible) heat regenerator is a porous matrix that passes alternately in hot and cold airstreams (Figure 5- 23). The rotation of this rotor type heat exchanger is driven by an electrical motor. The matrix stores the heat from the hot stream and releases it to the cold one. The sensible regenerators are the most commonly used ones in desiccant cooling air handling units. This type of heat exchanger reaches efficiency values of 0.6 up to 0.85 /5.8/.

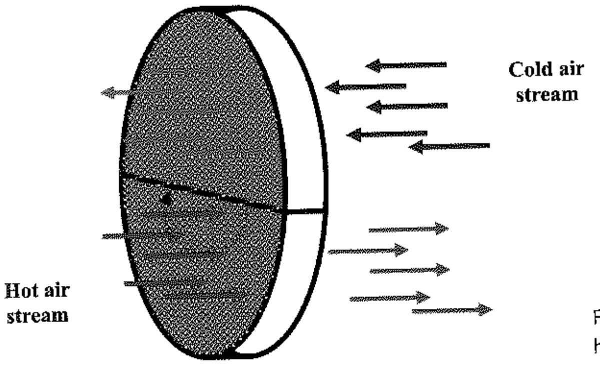

Fig. 5- 23 Sensible heat regenerator

A summary of heat exchanger characteristics is reported in Table 5- 7.

Type	**Regenerator**	**Plate heat exchanger**	**Heat pipe**
Efficiency	0.6–0.85	0.5–0.67	0.35–0.55
Size	Medium	Medium-Large	Small
Pressure drop	High	Medium-High	Low
Advantages	Standard component in ventilation heat recovery	Air streams are physically separated	Air streams are physically separated
	Compatible with desiccant rotor	Low maintenance	Low maintenance
Disadvantages	Maintenance is required to prevent leakage	Large if high efficiency	High temperature difference needed
	Driven by an electrical motor		Must be mounted vertically

Tab. 5- 7 Main characteristics, advantages and disadvantages of the different types of heat exchangers

5.3 Liquid dessicant systems

Liquid desiccant (LD) systems operate based on the same principles as the solid desiccant (SD) systems previously described, and most of the cycles described in sections 5.2.1 and 5.2.2 apply to liquid desiccant systems as well. However, instead of using solid desiccant materials, LD systems have separate absorbers (or conditioners), where the air is dehumidified, and regenerators (or desorbers), where the liquid desiccant is regenerated. Figure 5.25 shows a schematic diagram of a typical LD system with packed towers. An absorber (or dehumidifier) dehumidifies and cools the air and additional cooling can be used before the air is supplied to the building. In the absorber, the desiccant solution is sprayed over the tower and the air to be conditioned is blown in cross or counter flow. As the solution absorbs the water vapour from the air, it gets diluted and thus the partial vapour pressure of the water increases. The weak desiccant solution is then pumped to a regenerator so the water can be removed from the solution. The desorbing process is done by heating the solution and exposing it to a regeneration air stream. Heat can be supplied to the solution by a variety of sources, e.g. boilers, cogeneration units and, of course, solar thermal collectors.

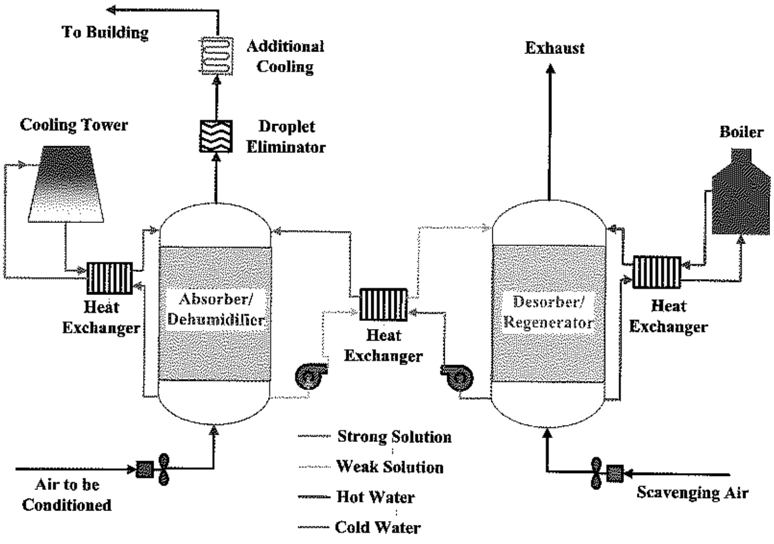

Fig. 5- 24 Typical liquid desiccant air-conditioning system

Although liquid desiccant systems share many of the positive aspects of solid desiccants, they have a few other interesting advantages: the physical separation of the absorber and desorber gives the system more flexibility and allows cooling of the absorption process and as a result liquid desiccants can be more effectively regenerated at lower temperatures, which is important for solar thermal applications. The strong desiccant solution can be stored, providing high density energy storage with little or no losses.

Figure 5- 25 shows a liquid desiccant system with desiccant storage operating in the so called ventilation cycle. This is a typical 100% outdoor air cycle where the enthalpy of the exhaust air is used to cool the dehumidification process.

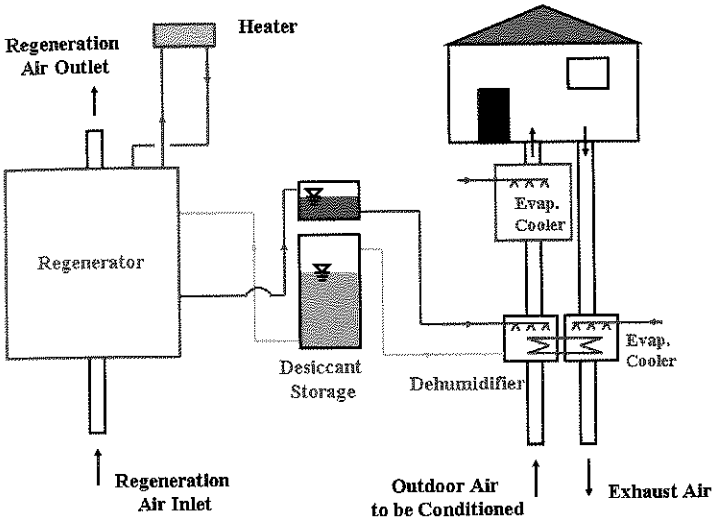

Fig. 5- 25 Liquid desiccant air-conditioning system, ventilation cycle.

Many different technologies have been investigated for the absorber and regenerator. The regenerator can be built as a packed tower, heated coil, spray chamber, falling-film parallel plates, boiler or open solar collectors. The types of absorbers that have been used in the past are packed towers, cooled coils, spray chambers and falling-film parallel plates.

The concentration of the desiccant is lower in liquid desiccant systems than in solid desiccant systems. For this reason, the desiccant must be maintained at lower temperatures so it can effectively reduce the humidity of the air, due to the fact that the driving force of the dehumidification process is the difference between the humidity ratio in the air and the humidity ratio at the air/desiccant interface. The interface humidity ratio, increases with temperature and decreases with concentration and, consequently, the driving force can be enhanced by increasing the desiccant concentration or by reducing its temperature, as shown on Figure 5- 26.

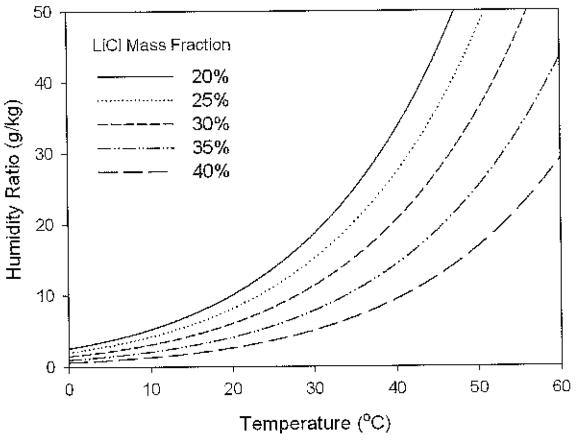

Fig. 5- 26 Equilibrium humidity ratio for LiCl-H_2O solutions at 101 kPa (14.6 PSI) total pressure

Absorber design options

Absorber with high-flow solution: lower temperatures throughout the absorber can be obtained by using a high flow rate of cooled desiccant, thereby increasing total heat capacity associated with the desiccant flow stream. This way, the desiccant drives the dehumidification process and acts as a cooling agent as well. This type of absorber is called adiabatic and it uses external heat exchangers to cool the desiccant solution as shown in Figure 5- 24.

Internally cooled absorber: another way to maintain the desiccant at a lower temperature in the absorber is to have an internally cooled absorber. This kind of absorber allows for the use of low flow for the desiccant because there is no need for a high desiccant heat capacity, since the heat does not have to be removed by the desiccant itself. Figure 5- 27 shows a schematic diagram of an internally cooled absorber where the desiccant solution trickles down the surface of a plate, in contact with the air to be dehumidified. Water flows inside a channel to remove the heat generated by the absorption process.

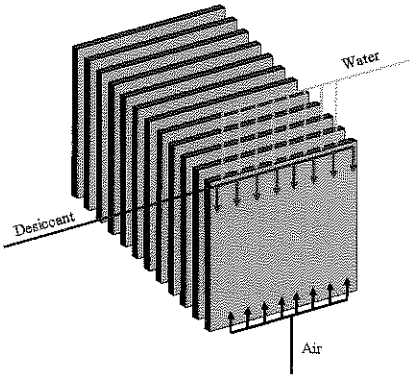

Fig. 5- 27 Internally-cooled parallel-plate absorber

The absorber operation can be characterized by the mass flow ratio (MR) between the air and the desiccant stream. An earlier review of liquid desiccant systems, /5.9/ showed that typical adiabatic systems with packed towers have MR between 0.5 and 2. On the other hand, low desiccant flow and internally cooled absorbers can use a MR above 100, as shown in /5.10/.

$$MR = \frac{\dot{m}_a}{\dot{m}_d}$$

Eq. 5- 6

As pointed out in /5.11/, low desiccant flow (or high MR) used by internally cooled systems reduces parasitic pumping power, increases the efficiency by reducing the amount of heat that is transferred from the regenerator to the absorber by the desiccant, and, depending on the design, facilitates the construction of systems with little or no carry-over of desiccant into the air stream.

On the other hand, adiabatic systems with packed towers are well known in industrial applications and are relatively cheap and easy to build.

The problem of droplet entrainment and desiccant carry-over into building air ducting is an important issue related to liquid desiccant systems, and in order to be successful any system has to address such issues through the design of the absorber and/or through the use of mist/droplet eliminators. Most eliminators require maintenance and periodic cleaning and this is an issue that has to be verified before a decision is made to install liquid desiccant equipment.

During the last few years, a number of companies have developed equipment for LD systems. Most of them, however, are still in the early stages of commercialization. Some of them are introduced here.

In 2011, Menerga, a German company, has developed a system based on packed beds. The unit, commercialized under the name Sorpsolair, has a range that goes from 2900 m^3/h to 14900 m^3/h (1707 to 8770 cfm) and integrates the desorber, absorber and indirect evaporative cooler. Figure 5- 28 shows one of the Menerga units with the flow paths for outdoor air (OA), return air (RA), supply air (SA) and exhaust air (EA). To date, a few Menerga systems have been installed in Germany with solar thermal support for desorption.

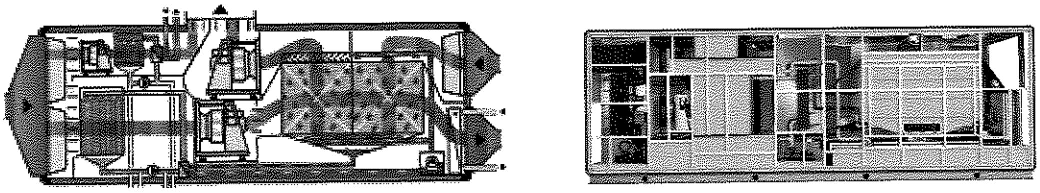

Fig. 5- 28 Menerga Sorpsolair unit with flow paths /5.12/

L-DCS is another German company offering commercial products that can be operated with heat from solar collectors. It does not have standardized equipment but the units are custom made in 10000 m^3/h (5886 cfm) increments. L-DCS technology was developed in partnership with the Bavarian Energy Research Centre (ZAE) and it uses internally heated absorbers with high MR. One of the L-DCS systems is installed in Singapore. This particular system has 540 m^2 (5812 ft^2) of flat plate collectors, a 12000 m^3/h (7063 cfm) absorber and a 7000 litres (1849 gal) LiCl storage tank.

AIL Research, an American company, also developed, in partnership with the National Renewable Energy Laboratory (NREL), internally cooled absorbers and currently has two absorber sizes available with 5100 m^3/h and 10200 m^3/h (3000 and 6000 cfm). The systems have been tested in a few pilot projects operating with natural gas and waste heat from cogeneration plants. More recently, its first solar driven project was installed in Panama City, USA, with a 5100 m^3/h (6000 cfm) absorber.

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