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Solar assisted air conditioning of buildings – an overview

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Abstract

Goal of this contribution is to draw a picture about some general issues for using solar thermal energy for air conditioning of buildings. The following topics are covered:

- A basic analysis of the thermodynamic limits for the use of heat cooling in combination with solar thermal energy is drawn; thereby fundamental insights about control needs for solar thermal driven cooling are obtained.
- A short overview about the state-of-the-art of available technologies, such as closed thermal driven cooling cycles (e.g., absorption, adsorption) and open cooling cycles (e.g., desiccant employing either solid or liquid sorbents) is given and needs and perspectives for future developments are described.
- The state-of-the-art of application of solar assisted air-conditioning in Europe is given and some example installations are presented.
- An overview about new developments of open and closed heat driven cooling cycles for application in combination with solar thermal collectors is given and some of these new systems are outlined more in detail.

Keywords: Solar cooling; Building air-conditioning; Technology; Example installation

1. Introduction

Summer air conditioning represents a growing market in building services world-wide in both commercial and residential buildings. Main reasons for the increasing energy demand for summer air-conditioning are the increased thermal loads, increased living standards and occupant comfort demands as well as building architectural characteristics and trends, like an increasing ratio of transparent to opaque surfaces in the building envelope to even the popular glass buildings. Air conditioning includes both temperature and humidity control of indoor air.

Particularly for large systems in the range of about 50 kW and above, different heat driven cooling technologies are available in the market, which can be used in combination with solar thermal collectors. The main obstacles for large scale application, beside the high first cost, are the lack of practical knowledge on design, control and operation of these systems. For small scale systems, many years no appropriate technology was available on the market. However, recently several companies started development of water chillers in the power range below 50 kW down to 5 kW and first commercial systems are now available. But still the further development of small capacity cooling and air conditioning systems remains of high interest.

In the 80s of the last century many activities on the development of solar energy systems for air conditioning application have been carried out, particularly in the United States and Japan. Important steps have been achieved in the development of components and systems, but finally the activities stopped mainly because of economic reasons. Recently, several new activities in this field have started and both research and demonstration projects are carried out in many countries and also in international co-operative projects for instance in the framework of the Solar Heating

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and Cooling Programme of the International Energy Agency (IEA). Particularly the development of the market of high efficient solar thermal collectors, which are nowadays produced on an semi-industrial or industrial level, provides a good starting point for new attempts.

2. Thermodynamic limits

From a thermodynamic point of view there are many processes conceivable for the transformation of solar radiation in cooling. An overview is given in Fig. 1. Although the conversion of electricity by photovoltaics and the subsequent use of this electricity in a classical motor driven vapour compression chiller is a technically feasible concept, it is not further considered here. Reason is, that in industrialised countries, which have a well-developed electricity grid, the maximum use of photovoltaics is achieved by feeding the produced electricity into the public grid. From an economic point of view this is even more valid if the price for electricity generated by solar energy is higher than that of electricity from conventional sources (e.g., feed-in-laws in Germany or Spain).

From the thermally driven technologies, which may use a solar thermal collector to provide heat to drive a cooling process, the technologies based on heat transformation are best developed. Therefore only these technologies are considered further.

A basic figure to describe the quality of the conversion of heat into cold is the thermal coefficient of performance, COP, defined as the useful cold, Q_{cold}, per unit of invested driving heat, Q_{heat}:

$$\mathrm{COP} = \frac{Q_{\text{cold}}}{Q_{\text{heat}}} \tag{1}$$

The first and second law of thermodynamics applied to the basic process of a thermally driven chiller according to a scheme shown in Fig. 2, lead to an expression for the maximum possible coefficient of performance, $\mathrm{COP}_{\text{ideal}}$:

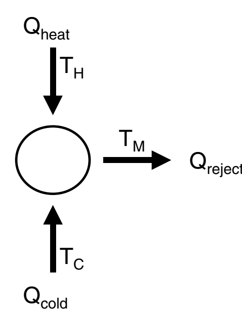

Fig. 2. Basic thermodynamic scheme of a heat driven heat pump or chiller, respectively.

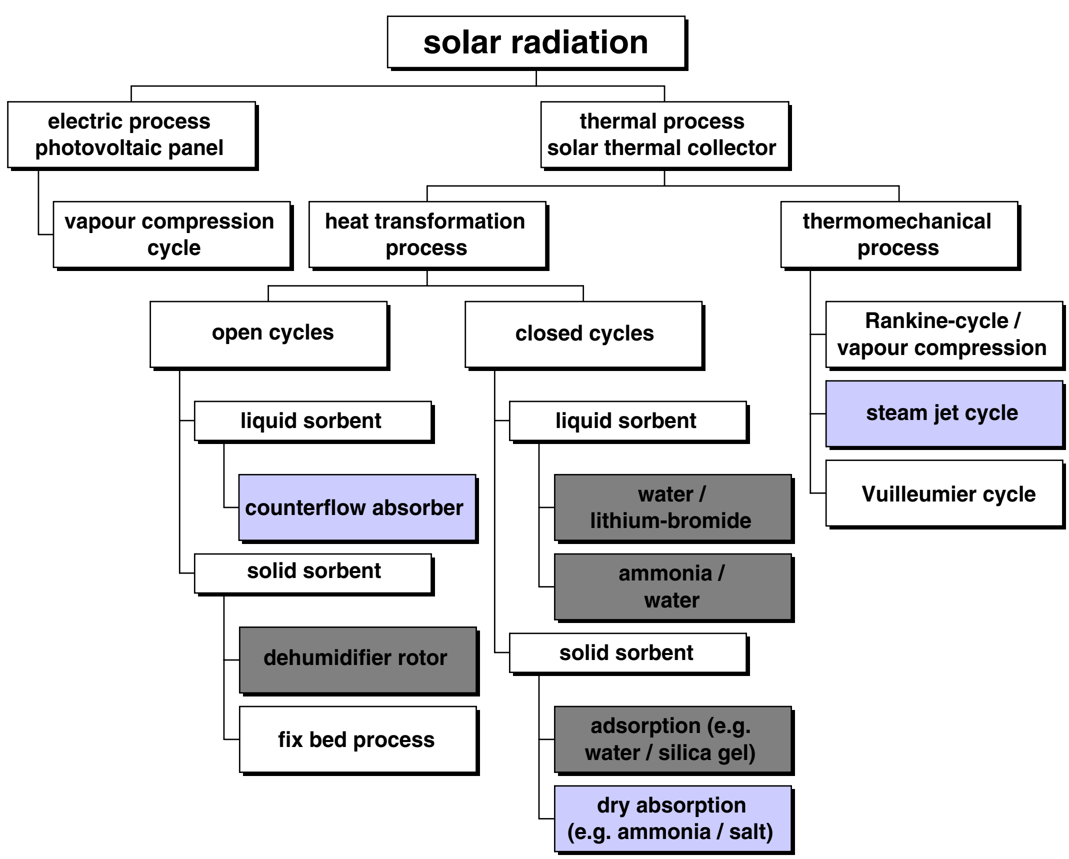

Fig. 1. Overview on physical ways to convert solar radiation into cooling or air-conditioning. Processes marked in dark grey: market available technologies which are used for solar assisted air-conditioning. Processes marked in light grey: technologies in status of pilot projects or system testing.

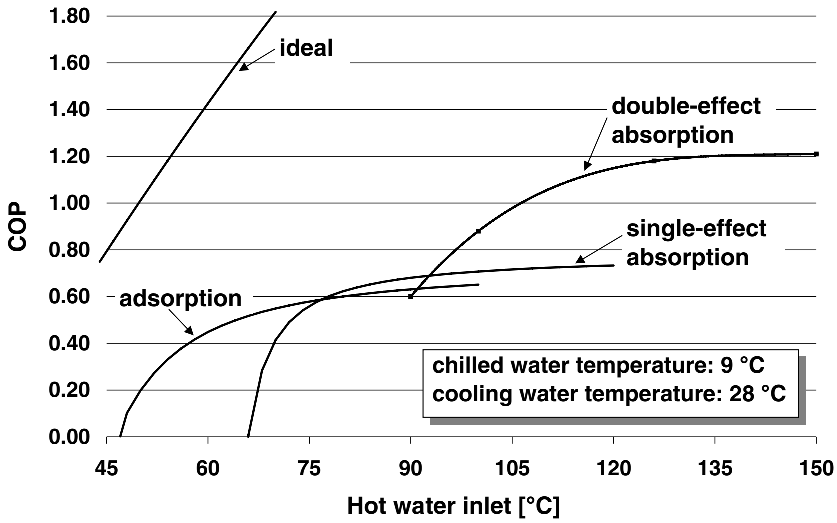

Fig. 3. COP-curves of sorption chillers and the upper thermodynamic limit (ideal) according to Eq. (2).

$$\mathrm{COP}_{\mathrm{ideal}} = \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}} \cdot \frac{T_{\mathrm{H}} - T_{\mathrm{M}}}{T_{\mathrm{M}} - T_{\mathrm{C}}} \tag{2}$$

where T_{C} is the temperature of the cold source, T_{H} is the temperature of the driving heat source and T_{M} is the intermediate temperature level at which the heat is rejected to a heat sink (in general environmental air).

The $\mathrm{COP}_{\mathrm{ideal}}$ is shown in Fig. 3 together with real COP-values of thermally driven chillers available on the market.

2.1. Basic system control

The coupling of solar thermal collectors and thermally driven chillers needs a sophisticated control since both components exhibit a reverse dependence of their efficiency from the operation temperature. This is shown in Fig. 4 on the example of an adsorption chiller and an evacuated tube collector. Beside the collector efficiency and the COP of the thermally driven chiller, also the product of the COP and the collector efficiency, indicated $\mathrm{COP}_{\mathrm{sol}}$ is shown. The latter shows a slight maximum at a temperature of about 70 °C. The position of this maximum depends on the actual conditions, i.e., the radiation on the collector and the temperatures of chilled water and cooling water of the chiller. With an advanced control the actual maximum could be detected and a 'power-point-tracking' implemented, if the cooling power of the machine is sufficient to match the actual load.

3. Techniques

Techniques which allow the use of solar thermal collectors for air-conditioning of buildings can be distinguished in two main types:

- thermally driven chillers are used to produce chilled water which can be used for any type of air-conditioning equipment;
- open cycles, also referred to as desiccant cooling systems, are used for direct treatment of air in a ventilation system.

Many details about components and systems for using solar thermal energy for air-conditioning application may be found in [1].

3.1. Thermally driven water chillers

The dominating technology of thermally driven chillers is based on absorption. The basic physical process consists of at least two chemical components, one of them serving as the refrigerant and the other as the sorbent. The operation of such systems is well documented (e.g., in [2]) and is not described here. Absorption chillers are available on the market in a wide range of capacities and designed for different applications. However, only very few systems are available in a range below 100 kW of cooling capacity. Today, also a few commercial systems for small power, e.g., below 30 kW, are available. Today absorption chillers are mainly applied if a 'cheap' heat source is available, such as waste heat, district heat or heat from co-generation plants. For air conditioning applications mainly absorption chillers using the sorption pair water–LiBr are applied. Hereby water is the refrigerant and LiBr the sorbent. The basic construction are so-called single effect machines, in which for each unit mass of refrigerant which evaporates in the evaporator one unit mass of refrigerant has to be desorbed from the refrigerant–sorbent solution in the generator. Under normal operation conditions such machines need typically temperatures of the driving heat of 80–100 °C and achieve a COP of about 0.7.

Beside single effect machines, chillers using a double-effect cycle are available. Two generators working at different temperatures are operated in series, whereby the condenser heat of the refrigerant desorbed from the first

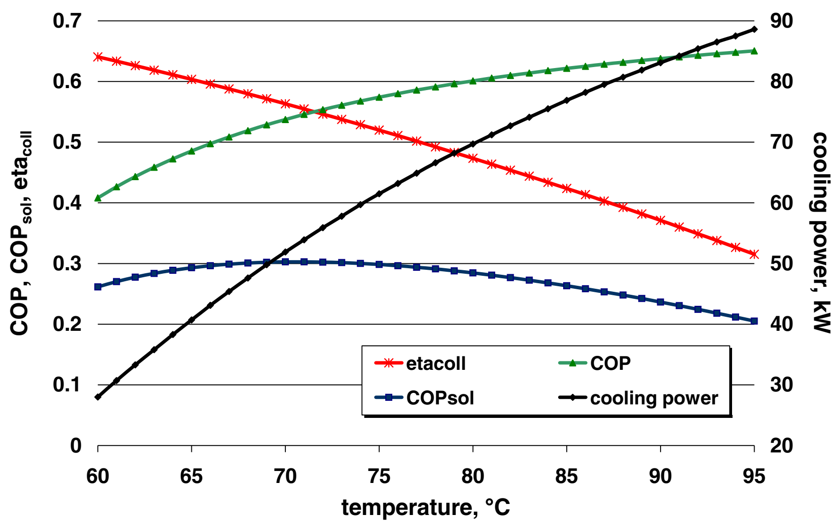

Fig. 4. COP-curves of a silica gel adsorption chiller (COP), collector efficiency (etacoll), solar COP (COP_{sol}) and cooling power as function of driving temperature.

generator is used to heat the second generator. Thereby a higher COP in the range of 1.1–1.2 is achieved. However, driving temperatures in the range of 140–160 °C are typically required to drive those chillers. This type of systems is only available in the range of large capacities of some 100 kW and above.

Beside systems using a liquid sorbent also machines with solid sorption materials are available. In these cycles a quasi continuous operation requires that at least two compartments which contain the sorption material are operated in parallel. Market available systems use water as refrigerant and silica gel as sorbent. They consist basically of the two sorbent compartments, the evaporator and the condenser. While the sorbent in the first compartment is regenerated using hot water from the external heat source, e.g., the solar collector, the sorbent in the second compartment (adsorber) adsorbs the water vapour coming from the evaporator; this compartment has to be cooled in order to enable a continuous adsorption. The water in the evaporator is transferred into the gas phase being heated from the external water cycle; here actually the useful cooling is produced. If the cooling capacity reduces to a certain value due to the loading of the sorbent in the adsorber, the chambers are switched over in their function. To date, only two Japanese manufacturer produce adsorption chillers. Under typical operation conditions with a temperature of the driving heat of about 80 °C, the systems achieve a COP of about 0.6.

3.2. Open cycles – desiccant cooling systems

While thermally driven chillers produce chilled water, which can be supplied to any type of air-conditioning equipment, open cooling cycles produce directly conditioned air. Any type of thermally driven open cooling cycle is based on a combination of evaporative cooling with air dehumidification by a desiccant, i.e., a hygroscopic material. Again, either liquid or solid materials can be employed for this purpose. The standard cycle which is mostly applied today uses rotating desiccant wheels, equipped either with silica gel or lithium-chloride as sorption material. All required components are standard components and have been used in air-conditioning applications for buildings or factories since many years.

The standard cycle using a desiccant wheel and the corresponding states of the air in the cycle are shown in Fig. 5. Systems according to this scheme are typically employed in temperate climates. The air follows the following processes during the system:

- 1 ⇒ 2 sorptive dehumidification of supply air; the process is almost adiabatic and the air is heated by the adsorption heat and the hot matrix of the wheel coming from the regeneration side;
- 2 ⇒ 3 pre-cooling of the supply air in counter-flow to the return air from the building;
- 3 ⇒ 4 evaporative cooling of the supply air to the desired supply air humidity by means of a humidifier;
- 4 ⇒ 5 the heating coil is used only in the heating season for pre-heating of air;
- 5 ⇒ 6 a small temperature increase is caused by the fan;
- 6 ⇒ 7 supply air temperature and humidity are increased by means of internal loads;
- 7 ⇒ 8 return air from the building is cooled using evaporative cooling close to the saturation line;
- 8 ⇒ 9 the return air is pre-heated in counter-flow to the supply air by means of a high efficient air-to-air heat exchanger, e.g., a heat recovery wheel;
- 9 ⇒ 10 regeneration heat is provided for instance by means of a solar thermal collector system;
- 10 ⇒ 11 the water bound in the pores of the desiccant material of the dehumidifer wheel is desorbed by means of the hot air;
- 11 ⇒ 12 exhaust air is blown to the environment by means of the return air fan.

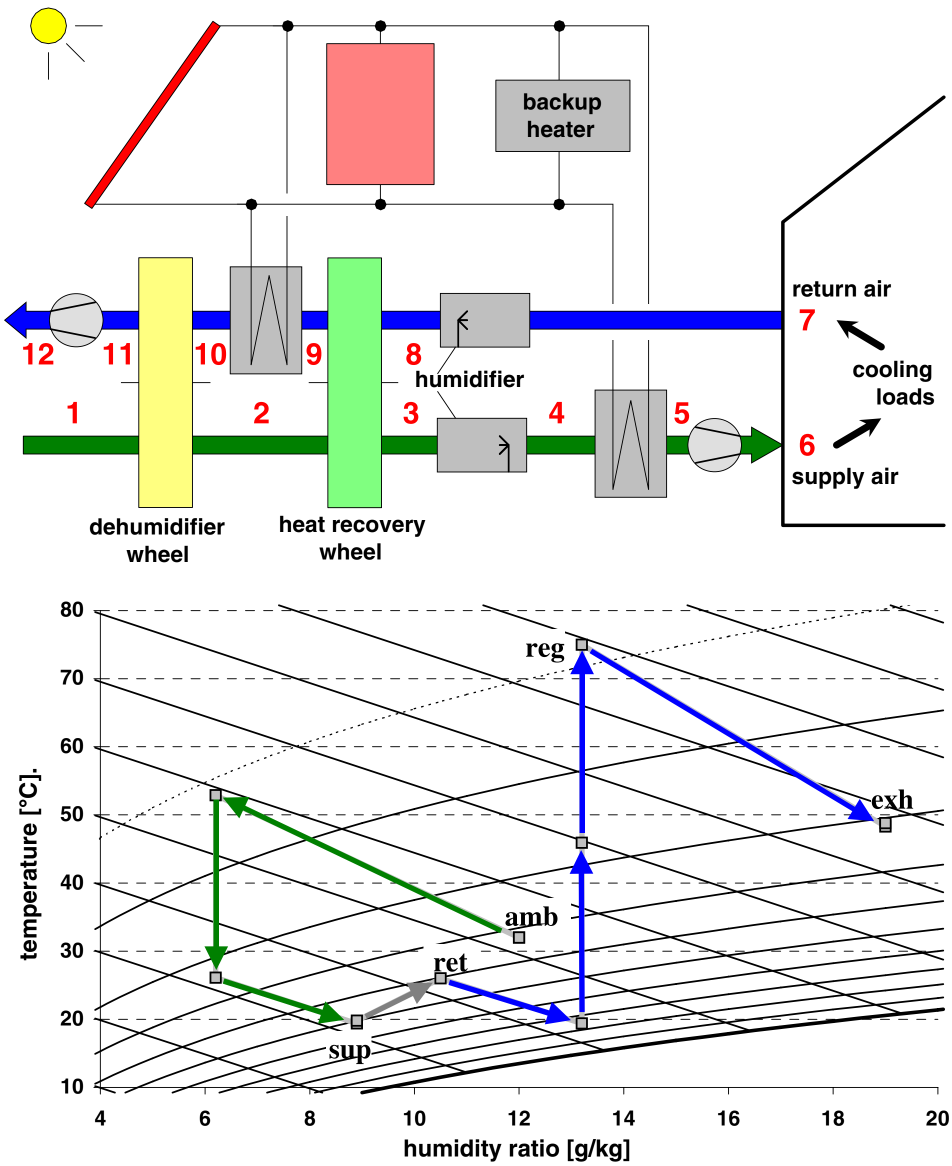

Fig. 5. Standard desiccant cooling cycle using a dehumidifier wheel with solar thermal energy as driving heat input (top) and the change of the air states during the process in the *T*–*x* diagram of humid air (bottom).

Application of the cycle described above is limited to temperate climates, since the possible dehumidification is not high enough to enable evaporative cooling of the supply air at conditions with far higher values of the humidity of ambient air. For climates like those in the Mediterranean countries therefore other configurations of desiccant processes have to be used. Two possible configurations are shown in Fig. 6 and Fig. 7.

In addition to the components shown in Fig. 5 the configuration in Fig. 6 uses an enthalpy exchanger, a rotor which enables total heat exchange, i.e., exchange of sensible heat and humidity. Using this component ambient air is pre-cooled and pre-dehumidified using the return air from the building. Behind the enthalpy exchanger the air states air such that the conventional desiccant cycle can be employed; however, higher regeneration temperatures are necessary in order to enable sufficient regeneration of the desiccant wheel.

The configuration in Fig. 7 shows a system which consists of a desiccant cycle combined with two cooling coils in the return air stream supplied with cold water, e.g., from a conventional chiller or other cold sources like a well or a river as appropriate.

The advantage of this combination of sorption wheel and cooling coils is that relatively high supply temperatures of the cooling water to the coils are sufficient. Ambient air is pre-cooled and pre-dehumidified before it enters the desiccant wheel. Since the pre-dehumidification takes place on a high humidity level, high cold water temperatures are sufficient to cool the air below the dew-point. Sorptive dehumidification takes place to adjust the supply air according to the desired supply air humidity. Since the temperature of the air behind the heat recovery unit will still be to high to enter the room directly another cooling coil is employed which has to cool down the air. In the example shown in

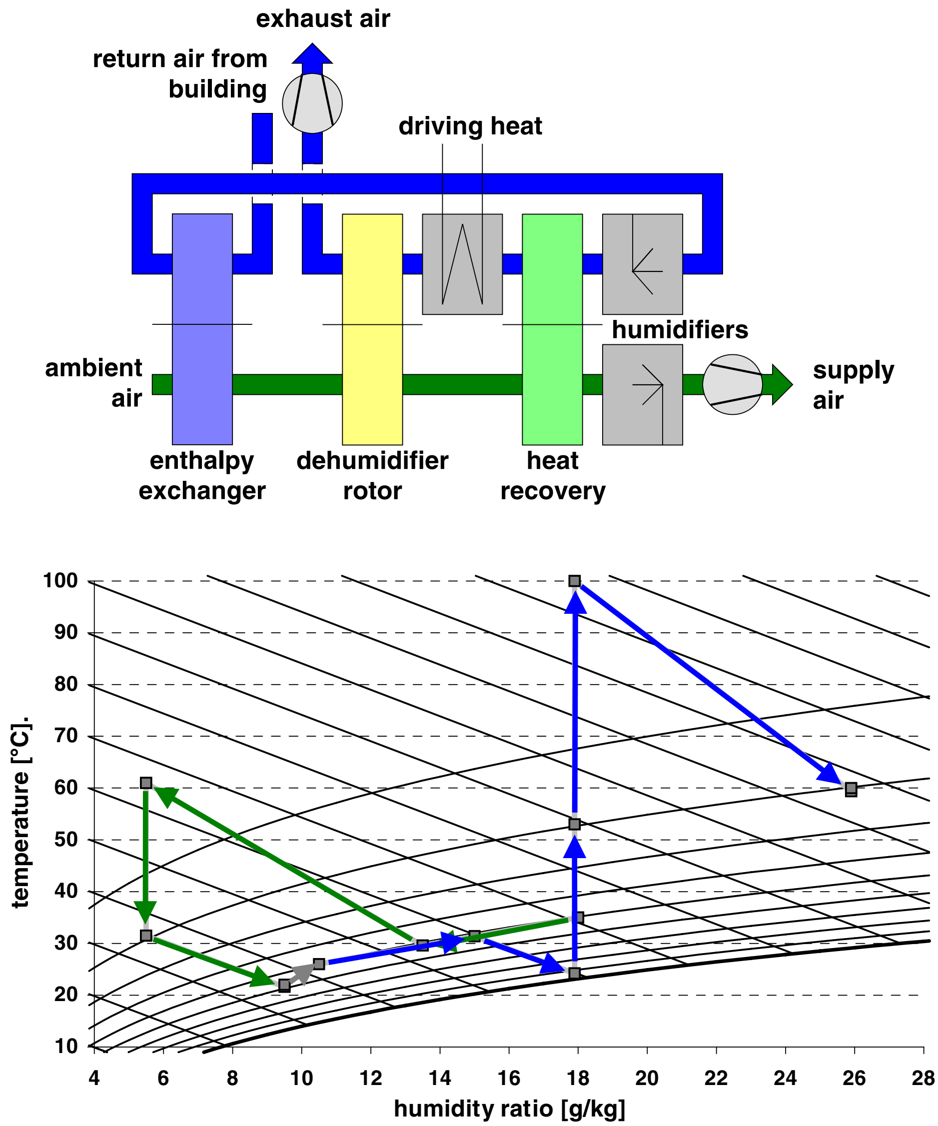

Fig. 6. Desiccant cooling cycle for climatic conditions with high ambient air humidity values; an enthalpy exchanger pre-cools and pre-dehumidifies air before it enters the standard desiccant cycle according to Fig. 5.

Fig. 7 the air has to be cooled down from about 25 °C to about 18.5 °C; therefore again a relatively high temperature of the cold water is sufficient. If a compression chiller is used for providing cold water it can be operated at high evaporator temperatures and thereby with a high COP. Such a system is recently being installed in a building of the gas utility in Palermo (AMG) in combination with a co-generation plant which provides the heat to regenerate the desiccant material. The project is supported by the European Commission (MITES – Micro Tri-generation System for Indoor Air Conditioning in the Mediterranean Climate) [3].

Systems employing liquid sorption materials which have several advantages like higher air dehumidification at the same driving temperature and the possibility of high energy storage by means of concentrated hygroscopic solutions are note yet market available but they are close to market introduction; several demonstration projects are carried out in order to test applicability of this technology for solar assisted air conditioning.

In general, desiccant cooling systems are an interesting option if centralized ventilation systems are used and ongoing developments on advanced cycles promise to increase their applicability in combination with solar thermal energy.

4. Installations in Europe

Today about 70 systems are installed in Europe that use solar thermal collectors for air conditioning. Most of the systems were realized in either Germany or Spain, see Fig. 8.

The cooling power of all the installed systems sums up to about 6.3 MW and the total collector area to about 17,500 m^2. As shown in Fig. 9 about 59% of systems use absorption chillers. In about 11% of the installations an

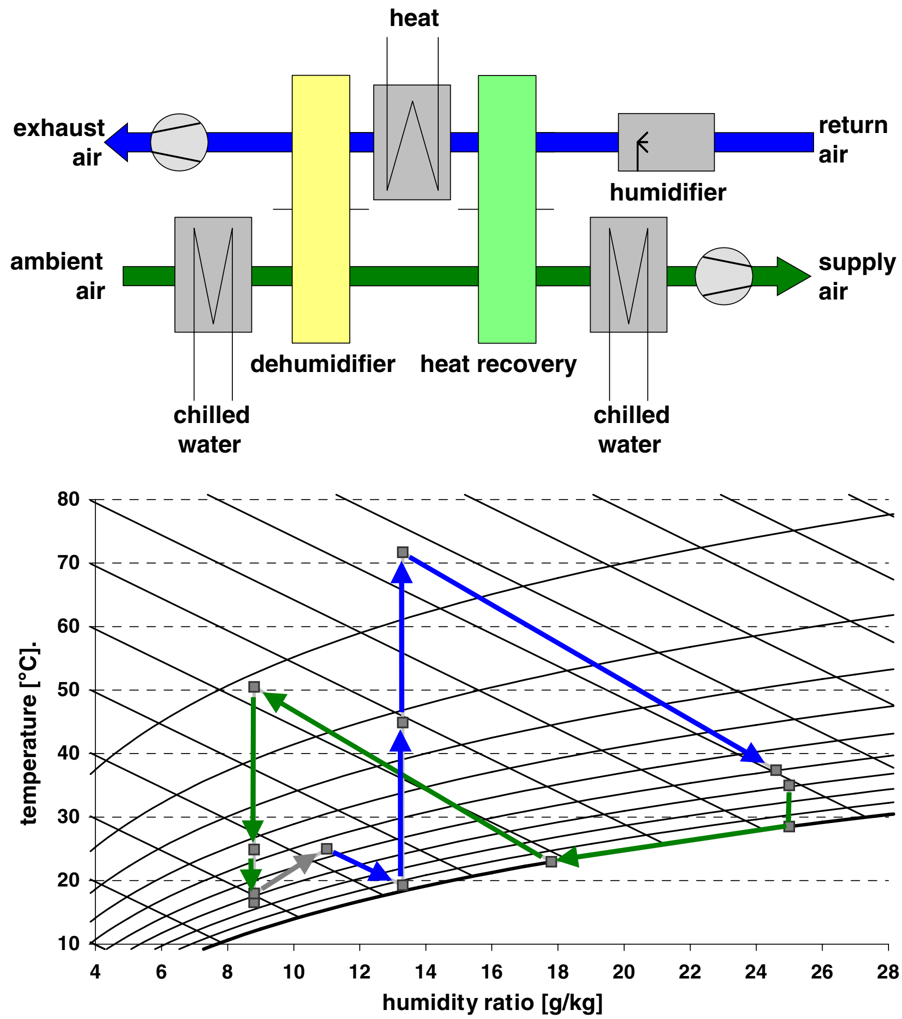

Fig. 7. Desiccant cooling cycle with cooling coils supplied by chilled water for climatic conditions with very high ambient air humidity levels; the first cooling coil pre-cools and pre-dehumidifies the air and the second cooling-coil adjusts the supply air temperature according to the desired value; no supply air humidifier is employed.

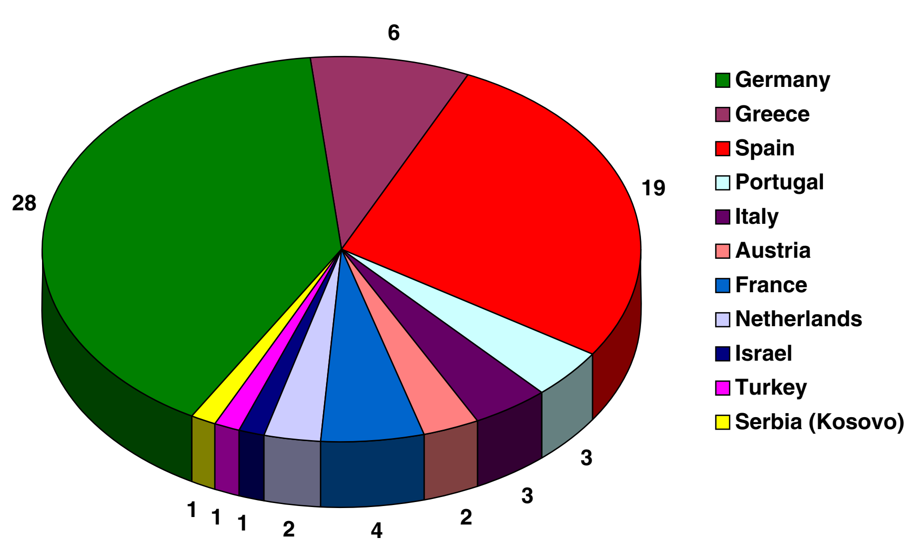

Fig. 8. Overview about systems installed in Europe (no claim to be exhaustive).

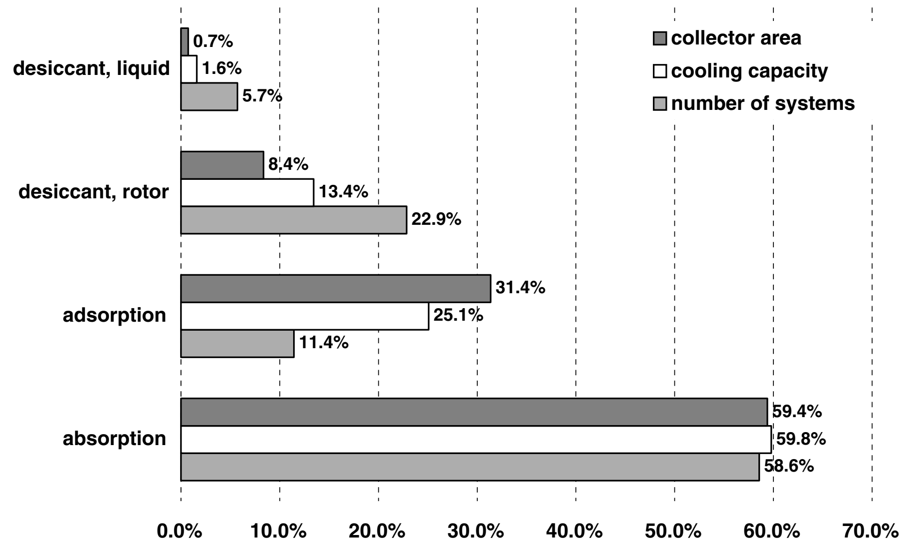

Fig. 9. Distribution of systems in terms of number of systems, cooling capacity and installed collector area.

adsorption chiller is installed and in about 23% of the installations a desiccant cooling system using a sorption wheel. Only about 6% of all installations use liquid desiccant technology which shows that this technology is still less developed on a commercial level. In terms of the cooling capacity the distribution looks somewhat different, since about 25% of the total installed cooling capacity uses adsorption chillers, i.e. installations using adsorption generally have a large cooling capacity. The two largest systems installed today use adsorption chillers with 350 kW cooling capacity; these are the Sarantis cosmetics factory in Greece and the federal office for environmental issues of Bavaria in Augsburg. Looking at the installed collector area the distribution is even more different. For instance desiccant systems using rotor technology are using only about 8.5% of the total collector area installed in all the installations, although about 23% of the installations use this technique.

A distribution of the specific collector area defined as the collector area installed per kW of cooling capacity is shown in Fig. 10. The installed collector area for the water chillers (absorption, adsorption) is higher than for the desiccant systems. A typical value for water chillers lies in the range of 3 m^2 per kW while for the desiccant systems a typical value is about 1.5 m^2 per kW which corresponds to about 10 m^2 per 1000 m^3/h of nominal air flow rate.

However, the following remarks are necessary when talking about the specific collector area:

– The collector area is not defined in a similar way for all systems; for some installations only the collector

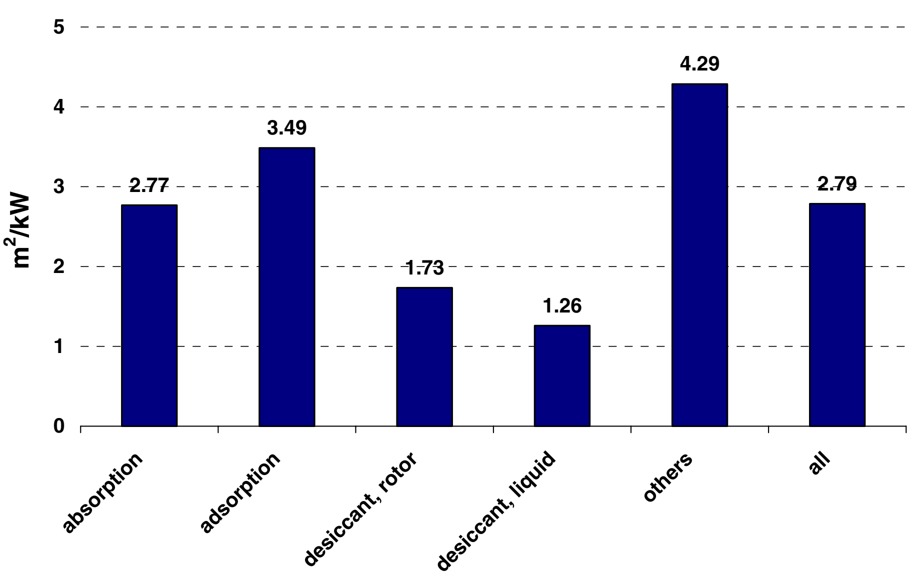

Fig. 10. Distribution of the specific collector area (collector area in m^2 of installed cooling capacity in kW) for the different technologies.

absorber area is known, for some the aperture area and for others the collector gross area.
- In some of the installations solar energy is not only used for air-conditioning but also for other purposes and therefore the area has been designed larger.
- In some other plants solar energy is only used as an additional heat source beside others like wood burners.

For this reason it is difficult to compare the installed collector area for the different systems.

4.1. Examples of installations

In Freiburg/Germany a solar cooling system is operated by the University hospital for air-conditioning of a laboratory. The system consists of an adsorption chiller with a capacity of 70 kW and a field using evacuated tube collectors with an aperture area of 170 m^2. The project was monitored over a period of 4 years with accompanying optimization of control and operation. Main results are: the solar collector works properly and the COP of the adsorption chiller seems acceptable after a series of improvements in control. But the electric consumption, mainly of the cooling tower cycle is far too high. Fig. 11 shows the adsorption chiller and Fig. 12 the collector field of the system.

Operation results of the system in Freiburg of a tpyical summer day are shown in Fig. 13. It can be seen that during the main daytime hours most of the driving heat for the chiller is delivered from the solar system.

Another system which is also installed in Freiburg/Germany is a desiccant cooling system which is used for air-conditioning of the seminar room and the cafeteria of the building of the chamber of trade and commerce.

The system consists of a desiccant air handling unit using a silica gel desiccant wheel with a nominal air flow rate of 10,200 m^3/h and 100 m^2 of solar air collector to regenerate the desiccant material. A scheme of the system is shown in Fig. 14 and a photo of the solar collector panels in Fig. 15.

Fig. 11. Adsorption chiller installed in the University hospital in Freiburg.

Fig. 12. Solar collector field (evacuated tubes) installed in system at University hospital in Freiburg.

Main results and problems encountered are: improvements of the systems performance were achieved by modification of the dehumidifier wheel rotation speed, the control of the air flow through the solar air collector and the placement of the humidity sensor. By these measures the COP increased, but was still lower than expected when the system was designed. Indoor conditions are in a proper range and the users are satisfied very satisfied about the systems operation.

4.2. General experiences with installed plants

In Task 25 "Solar Assisted Air Conditioning of Buildings", a project that has been carried out in the framework of the Solar Heating & Cooling Programme of the International Energy Agency (IEA) 11 plants in six countries were monitored. Some important experiences and hints regarding control are:

- Many plants have shortcomings in the hydraulic design and the control. The design of the collector field has to ensure a equal flow through the different collector strings and has to be stagnation proof. In general this is a higher challenge than for systems used for hot water production due to the higher temperatures needed for operation of the thermally driven cooling equipment.
- A control of the driving temperature of the thermally driven cooling equipment following the actual demand is able to increase the overall performance but it requires a sophisticated control, which in general is also more susceptible to malfunction.
- A hydraulic design which allows to bypass the heat buffer storage can also increase the overall efficiency but makes the control also complex.

For system control it is important to find the best compromise between complexity and efficiency. A general experience is that it is more important to install a robust system with less risk of malfunction than to increase the efficiency

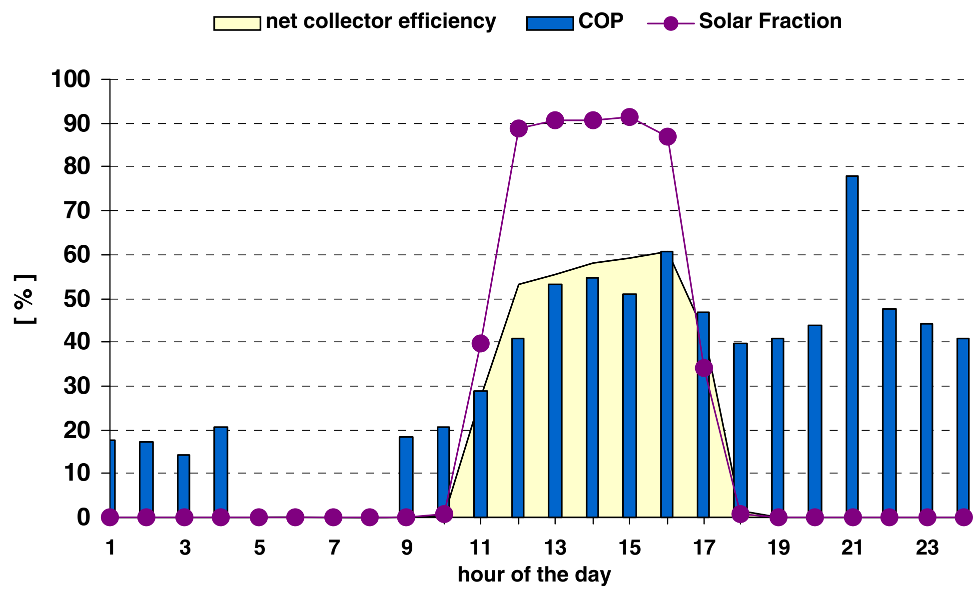

Fig. 13. Operation of the system installed at the University hospital in Freiburg during a typical summer day.

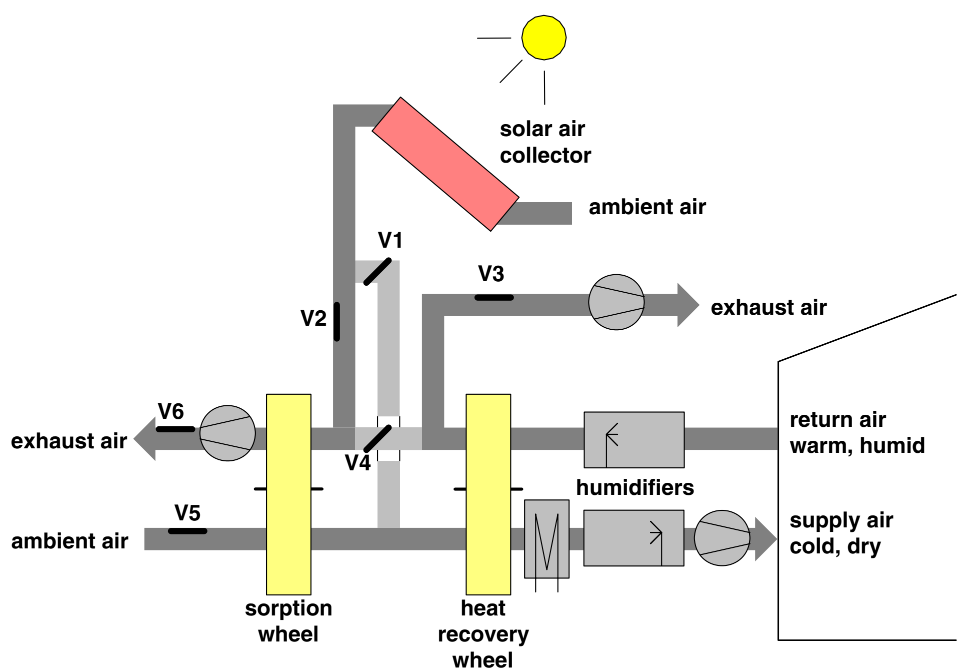

Fig. 14. Scheme of the desiccant cooling system installed at the building of the chamber of trade and commerce in Freiburg/Germany.

to the possible maximum. Further important observations from the monitoring are:

– In many cases the expected energy savings could not be realized completely in practice. In most cases the reason is a higher parasitic energy consumption of the auxiliary components such as cooling towers or ventilators in desiccant systems. However, these problems are often due to the conventional components and they only became obvious because of the monitoring program. In almost all systems the electricity consumption of the solar collector system (control, pumps) contributed only a very small fraction to the overall electricity consumption.
– In general a higher effort for system design and planning is necessary due to the higher complexity compared to conventional plants.
– A comprehensive commissioning phase is mandatory in order to test all possible operation conditions. Only then it will be possible to detect problems such as, e.g., charging the heat buffer storage by the backup heat source or a continuous full operation of the cooling tower even under no load or part load conditions.

Fig. 15. Solar air collector of the system installed at the building of the chamber of trade and commerce in Freiburg/Germany.

– Finally, a continuous automatic system monitoring, e.g., using web-based systems is recommendable in order to detect malfunctions or control problems. This is almost standard for large technical systems in buildings today and is particularly reasonable for solar assisted air-conditioning.

5. New developments of thermally driven cooling equipment

In the last years several developments were ongoing in order to develop new thermally driven cooling equipment. Here two main directions could be observed:

– Many R&D activities focus on the development of thermally driven water chillers in the range of low cooling capacities (<50 kW down to less than 5 kW). Different technologies are employed for this purpose focussing, concepts using liquid sorption materials such as lithiumbromide/water or ammonia/water as well as solids such as silica gel/water, zeolite water or solid absorption using salt/water systems. An overview about main developments is given in Table 1.
– Several R&D activities focus on the development of open cooling cycles using liquid desiccants. Liquid desiccants have some important advantages compared to systems using sorption wheels as described above. With liquid desiccants it is possible to separate the processes of absorption and regeneration in time and thereby to use the liquid sorption material as chemical storage; pre-condition to achieve high storage densities is to establish a high efficient absorption process which leads to a large difference between concentration of concentrated and diluted solution. Another advantage of using liquid desiccants is that it is more easy to cool the sorption process and thereby to realize a higher dehumidification with low regeneration temperatures compared to the usual desiccant cooling system.
– One of the recent R&D projects also deals with an advanced solid sorption process in which the sorption process is cooled in order to obtain a large dehumidification of the process air.

Information about the R&D activities of open cycles is also given in Table 1. In the following two developments recently carried out by Fraunhofer ISE are shortly described.

5.1. Advanced adsorption heat pump for a solar heating and cooling system

A prototype of a small adsorption heat pump working on the adsorption pair silica gel/water has been carried out during the last year and is result of continued work on adsorption heat transformation systems carried out at SorTech AG in co-operation with Fraunhofer ISE. At the moment the 4th prototype of this machine is characterized on a the Fraunhofer ISE test facility in Freiburg. Results of the 2nd prototype measurements can be found in ([8]). With the measured results for the coefficient of performance of the prototype different system integrations were investigated in order to find attractive areas of application. In order to obtain the performance of the machine in a real application a simulation of a whole system was carried out. Such a system is being studied in the frame of the EU supported project MODESTORE (Modular High Energy Density Sorption Storage). In the framework of this project such a system will be installed and monitored in a field test. Fig. 16 shows a scheme of the system. The system is operated with the following concept:

5.1.1. Heating

– As long as the temperature in the buffer storage is high enough to provide heat for the low temperature heating system of the building direct solar heating from the storage is provided.
– If the temperature of the buffer storage is not high enough for the heating system the adsorption heat pump is operated. It is driven by the gas boiler and the low temperature heat is extracted from the ground coupled heat exchanger. The rejected heat at the medium temperature level is provided to the heating system of the building.

5.1.2. Cooling

– Cooling is provided only if the temperature of the solar buffer storage is high enough to drive the adsorption machine. In this case the evaporator is connected to the cooling surfaces of the building and the heat is rejected to the round via the ground coupled heat exchanger. Also direct cooling via the ground coupled heat exchanger can be provided.

Table 1
Overview about recent developments in the field of thermally driven cooling equipment with relevance for solar application (the list does not claim to be exhaustive)

	Working fluid	Sorption material	Developer/s	Driving temperature (°C)	Key features characteristics, description	Reference
Closed cycles	Water	Lithium-bromide	Company Rotartica, Research center Ikerlan (both Spain)	70–95	Rotating absorber; very low temperatures on HXs	Ikerlan [4]
			Company EAW, Research center ILK Dresden (both Germany)	80–90	Market available system (cooling capacity >15 kW)	Safarik [5]
			Company Phönix Sonnenwärme; Research center ZAE Bayern; Technical University Berlin (all Germany)	70–95	Good part load bevhaviour; compact design; prototypes in operation	Kühn et al. [6]
			Polytechnic Univ. Catalunya (Spain)	75–95	Directly air cooled; still in research status	Task 25 [7]
		Silica gel	Company Sortech; Research center Fraunhofer Institute ISE (both Germany)	65–95	Compact design; no mechanical moving parts; prototypes in operation	Núñez et al. [8]
		Lithium-chloride	Company climatewell; Solar Energy Research Center (both Sweden)	70–100	High efficient storage included	Bales et al. [9]
		Sodium-sulfide	Company Sweat; research center ECN (both Netherlands)	80–90	High efficient (long term) storage; modular system, modular operation	de Boer [10]
	Ammonia	Water	Company AoSol; research center INETI (both Portugal)	100–120	Standard compenents; dry air cooling	Afonso et al. [11]
			Research institute Joanneum Research (Austria)	80–110	Prototype in operation; adjustable to different applications; low temperatures possible	Podesser [12]
			University of Applied Science Stuttgart (Germany)	70–120	No solution pump; still in research status	Task 25 [7]
Open cycles	Water	Lithium-chloride	Company Menergy (Germany)	60–90	Liquid sorption integrated in indirect evaporative cooling systems; pilot plant in operation	Röben [13]
			Technion Haifa (Israel)	60–90	Liquid desiccant system; pilot plant in operation	Gommed et al. [14]
			Research center ZAE Bayern (Germany)	60–90	Liquid desiccant system with high efficient energy storage; pilot plant in construction	Lävemann [15]
		Silica gel	Research institute Fraunhofer Institute ISE (Germany)	60–100	High efficient indirectly cooled system for air cooling and dehumidification	Motta et al. [16]

Further, the solar system is used year round in order to provide heat for the domestic hot water requirements. The system has been simulated in order to assess its annual performance. In the simulation model all components with the exception of the buffer storage are modeled with stationary characteristic curves. For the solar collector standard parameters for flat plate collectors with a selective coating were used. The building was separately simulated with

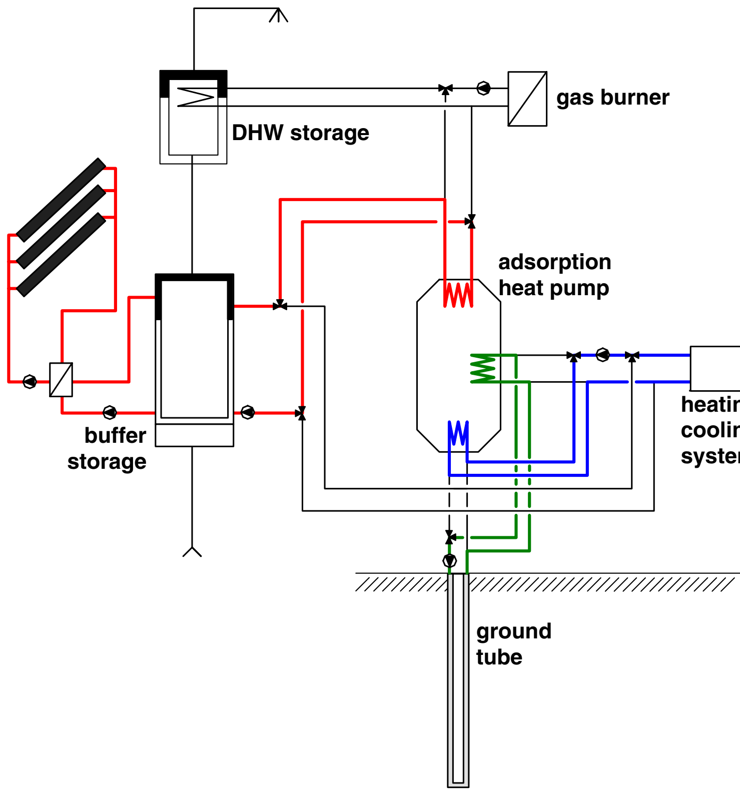

Fig. 16. Adsorption heat pump system for solar heating and cooling. A ground coupled heat exchanger is used as heat sink in summer and heat source in winter.

TRNSYS obtaining a load file for the heating and cooling demand. A 144 m^2 low energy office building with a heating demand of 30 kW h/m^2 per year (Madrid) was used as example. The results for the climatic data of Madrid/Spain are shown in Fig. 17. The results are valid for a solar flat plate collector with an area of 16 m^2 and a hot water buffer storage of 1500 l.

5.2. High efficient sorption dehumidifier

Conventional desiccant cooling systems using rotary wheels exhibit several disadvantages:

- Leakage between supply air and return air leads to reduced performance of rotor technology when applied at small capacity systems.
- The sorption process is not cooled (adiabatic process). This leads to a reduced dehumidification potential of the desiccant material compared to a cooled sorption process.
- Heat carry-over and the heat of adsorption leads to a high temperature of the process air leaving the desiccant wheel which is in contradiction to the primary goal of reducing the temperature of process air.
- The indirect evaporative cooling used in the standard desiccant cooling does not take full use of the high potential of enthalpy uptake of the building return air.

Goal of the development of a novel desiccant concept, called indirect Evaporative COoled Sorptive heat exchanger (ECOS), was to overcome those disadvantages. The design of the process results in a far higher dehumidification potential in comparison with conventional systems. It is particularly intended as a desiccant cooling system for climates with high ambient air humidity (e.g., Mediterranean and tropical). Moreover the novel system avoids the complexity of the rotating parts necessary in standard systems and gives the possibility to apply the DEC concept even at small scale plants.

The process is based on simultaneous sorptive dehumidification and indirect evaporative cooling of the supply air stream. Moreover, the indirect evaporative cooling is obtained through a continuous humidification process on the return air side of the heat exchanger, ensuring a high heat exchange potential.

The system implementing the process is based on a counter-flow air-to-air heat exchanger technology, see Fig. 18. The heat exchanger is divided in sorptive (black line in Fig. 18, top) and cooling (grey line) 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. In the cooling channels a continuous humidification of the cooling stream takes place. The latter, used for indirect evaporative cooling of the supply air stream, is for this

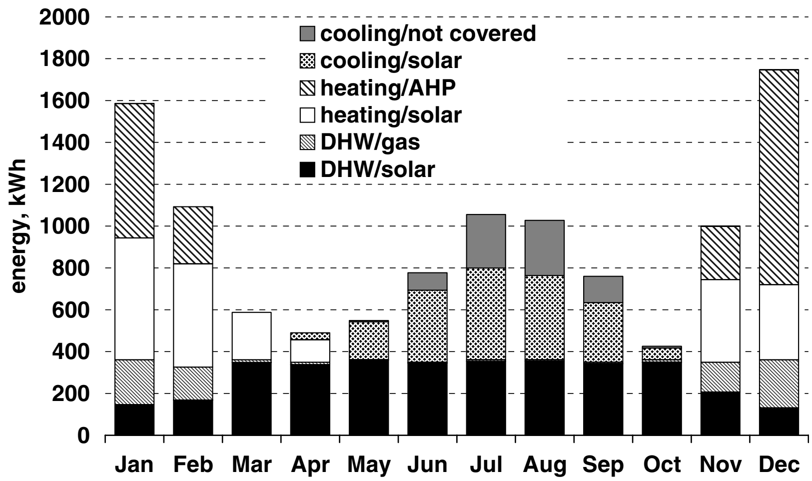

Fig. 17. Results from the system simulations. Monthly values of the energy provided by the solar collectors and the adsorption system in order to meet the domestic hot water demand, the heating load and some proportion of the cooling demand. Solar system of 16 m^2, 1.5 m^3 buffer storage and adsorption system from company SorTech.

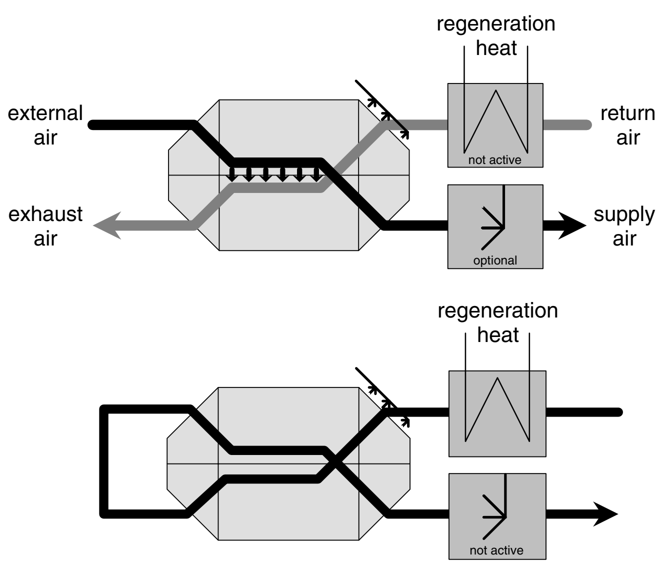

Fig. 18. Schematic of the evaporative cooled sorptive heat exchanger (ECOS) during air dehumidification (top) and regeneration (bottom).

purpose always kept in close-to-saturated conditions during the process.

A complete system consists of two sorptive heat exchangers, operated periodically. The periodic operation of two heat exchangers enables a quasi-continuous air-conditioning process. 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. In the regeneration the water vapour load of the sorbent material is released to the environment by means of a hot air stream (60–95 °C). A subsequent 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. Optionally a humidifier can be installed on the supply air side in order to exploit the potential for direct evaporative cooling of the process.

A simple experimental setup has been constructed in order to verify the principle. A prototype of a sorptive heat exchanger has been constructed for a nominal air flow rate of 60 m^3/h. Results of a measurement are shown in Fig. 19. During this measurement the humidity ratio of the supply air was in the range of 0.018 kg of water vapour per kg of dry air. The return air had a temperature of about 26 °C and a humidity ratio of about 0.01–0.011 kg/kg which corresponds to typical room air conditions during summer. The system was regenerated using air with a temperature of 90–95 °C. The results show that a large dehumidification from 0.018 kg/kg down to about 0.004 kg/kg is achieved at the beginning of process. Then the humidity of the supply air increases constantly and reaches a value of 0.01 kg/kg after about 500 s after the minimum has been reached.

At the same time the temperature of the process air is reduced from about 32–36 °C at the inlet to about 21 °C at the outlet. This experiment shows that the system is able to obtain a simultaneous strong reduction of temperature and humidity in a single component.

A numerical model has been created in order to assess how the system works under different climatic conditions (Motta, Henning, Kallwellis, 2004). Results are shown in Table 2.

6. Summary, future perspectives

Several thermally driven air conditioning technologies are market available by today, which enable the use of solar thermal energy for this application. Based on current technologies, i.e., market available thermally driven cooling devices and market available solar collectors, solar assisted air conditioning can lead to remarkable primary energy savings, if the systems are properly designed. Precondition to achieve primary energy savings is a sufficient collector size and a suitable size of energy storage in the

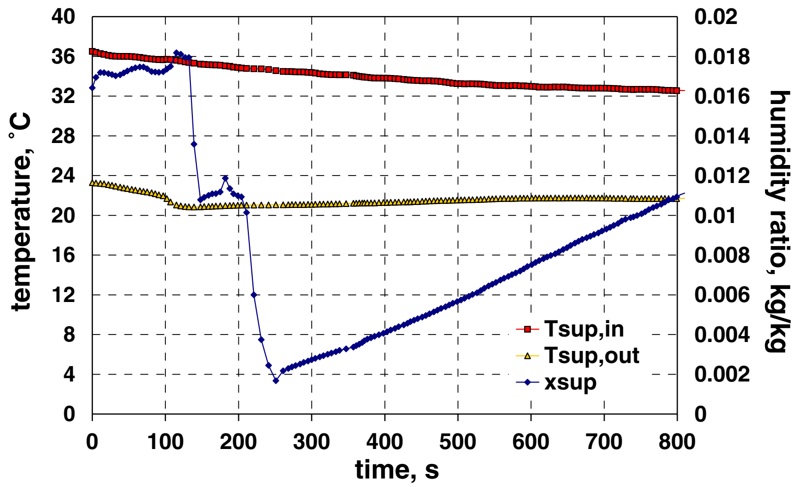

Fig. 19. Experimental results of measurements carried out with the ECOS prototype. $T_{sup,in}$ denotes the inlet temperature of supply air (process air) and $T_{sup,out}$ the respective outlet temperature (corresponds to building inlet); x_{sup} denotes the supply air humidity measured with a dew point mirror.

Table 2
Results of the ECOS simulation for different meteorological conditions

Ambient air							
Temperature	°C	35.0	30.0	35.0	29.0	32.0	26.0
Humidity ratio	g/kg	20.0	20.0	15.0	15.0	12.0	12.0
Regeneration air							
Temperature	°C	90.0	90.0	80.0	80.0	80.0	80.0
Humidity ratio	g/kg	20.0	20.0	15.0	15.0	12.0	12.0
Cycle time (adsorption)	s	240.0	240.0	240.0	240.0	300.0	300.0
Supply air (without direct evaporative cooling in the supply air)							
Temperature	°C	25.8	25.5	24.4	24.0	23.2	22.8
Humidity ratio	g/kg	7.5	7.4	6.3	6.2	5.0	5.0
Supply air (with direct evaporative cooling in the supply air)							
Temperature	°C	19.4	19.2	17.7	17.2	15.9	15.6
Humidity ratio	g/kg	9.9	9.9	8.9	8.8	7.9	7.7

system. It is essential to maximize the use of solar thermal energy by supplying other services like the heating system or the domestic hot water production with the solar heat as far as possible in order to optimize the economics.

Today, about 70 solar-assisted air-conditioning systems are installed in Europe. This underlines the fact that this technology is still in an early stage of development. Almost no standardised design guidelines exist and there is still a lack regarding common practices for design and construction. Field data and experience gained from installations under real operating conditions has shown that there are frequent shortcomings in the system's hydraulic design, as well as with the controls. Furthermore, in some cases, the expected energy savings could not be achieved in practice. Some basic design guidelines and information on proper system sizing can be found in [3]. However, it is very important to note that a solar-assisted air-conditioning system requires a greater effort during the design phase than a conventional system for the same application. Often, it will be necessary to perform annual computer simulations of several different system configurations in order to identify the one with the best energy-cost performance. In addition, based on today's experience, it is highly recommended to keep the hydraulic design as simple as possible. Then a comprehensible operation strategy and a transparent control scheme can be implemented, reducing the risk of error or malfunction. An appropriate commissioning process for the entire installation will also have to be implemented given the greater complexity of systems using solar energy compared to conventional systems. Finally, field monitoring of operating conditions and performance, e.g., web-based or by means of telecommunications networks, is strongly recommended to allow troubleshooting and prompt identification of component malfunctions or control failures. Although this is valid for any modern large HVAC installation, it is even more essential in the case of solar-assisted air-conditioning systems.

Improvements in the performance of thermally driven chillers and open cooling cycles play a key role in order to approach economic feasibility. New developments of chillers with small capacity will open new market segments. One example are so called solar combi-systems, i.e., systems which use solar energy for domestic hot water production and heating. Those systems are gaining increased market shares but their problem is that the solar heat during summer can not be fully exploited since the solar collector is too large for domestic hot water production only. In these cases using a small thermally driven chiller may be a promising new component in order to increase living comfort by solar cooling. Such systems might be a future option particularly for sunny climates such as in the Mediterranean zone.

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