

# THERMALLY DRIVEN COOLING: TECHNOLOGIES, DEVELOPMENTS AND APPLICATIONS

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**Abstract:** In the present paper we present the different thermally driven cooling technologies. We give an overview of the technologies, the state of the art for each technology and present research topics as well as typical performance data. We discuss advantages and disadvantages of each technology and present different applications. We analyze essential constraints of the systems in order to roughly estimate the suitability of a particular application in terms of energetic performance, primary energy demand and economic potential. In order to illustrate the potential of small scale units we present some operation results of a 5.5kW solar driven system installed at the Fraunhofer-Institute for Solar Energy Systems ISE in Freiburg, Germany.

**Keywords:** thermally driven cooling, absorption, adsorption, solar cooling, combined heating, cooling and power, CHCP.

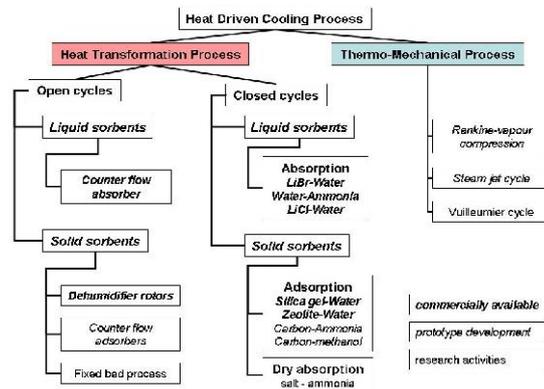
## 1. INTRODUCTION

Energy demand for cooling and air-conditioning is growing world wide. Especially in southern European countries the demand for small room air conditioners has grown more than expected in the last few years. The electricity demand of these units put a significant stress onto the electricity grids mainly on daily peak power demand in summer when the cooling needs are high. Chillers driven by thermal energy can be an alternative to electricity driven units in these cases, especially when they are driven by solar thermal energy or waste heat sources. Solar thermal energy, district heating networks or waste heat from industrial processes or CHP plants can be used to drive these chillers reducing significantly the electricity demand for air-conditioning purposes.

## 2. TECHNOLOGY CLASSIFICATION

Different thermally driven cooling technologies exist. They can be classified into heat transformation processes and thermo-mechanical processes. In Fig. 1 the classification of heat driven cooling processes is shown. In this paper we will present and discuss only the heat transformation processes as they are the most developed and used systems. These processes are all sorption cycles where a sorption material – either liquid or solid – acts as a chemical compressor for the refrigerant. They can further be divided into open and closed cycles. In the

open cycles the refrigerant is exposed to the atmosphere and thus can only be non-poisonous and is pure water. In closed cycles the refrigerant is in a closed circuit and isolated from the environment. Different refrigerants and pressure regimes can be used. Further, the systems can be classified according to the type of sorbent which is used: liquid and solid sorbents.



**Fig. 1 Classification of heat driven cooling processes**

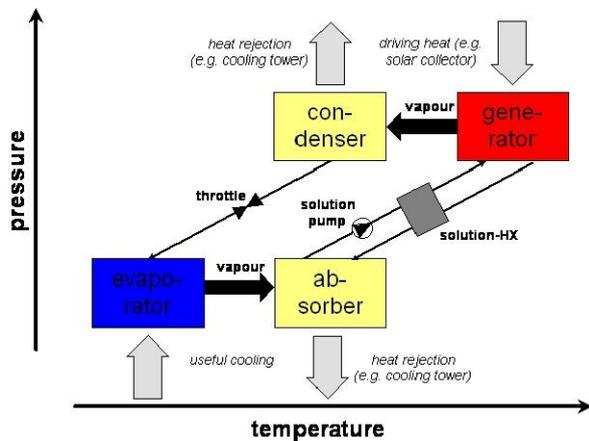
In the following sections we will present each of the technologies, discuss advantages and disadvantages and the application potential.

## Absorption

In the group of closed systems the best known technology is absorption. Three material pairs are used in the machines available on the market: Lithium-Bromide (LiBr)-Water solution, Water-Ammonia and Lithium Chloride (LiCl)-Water systems. In all cases the first material is the sorption agent and the second the refrigerant. Absorption technology is a well developed technology, the origins come from the 19<sup>th</sup> century when the process was discovered and first prototypes developed. The absorption cooling was invented by Ferdinand Carré in 1858.

### Lithium-Bromide – Water systems:

The best known pair is LiBr-water and most absorption chillers work with this pair. The absorbing material is a lithium-bromide –water solution that has the capability of further water absorption depending on the concentration of the solution, the temperature and the water vapour pressure. The absorption cooling process is described in a pressure vs. temperature diagram. In Fig. 2 a schematic of the absorption process is shown.

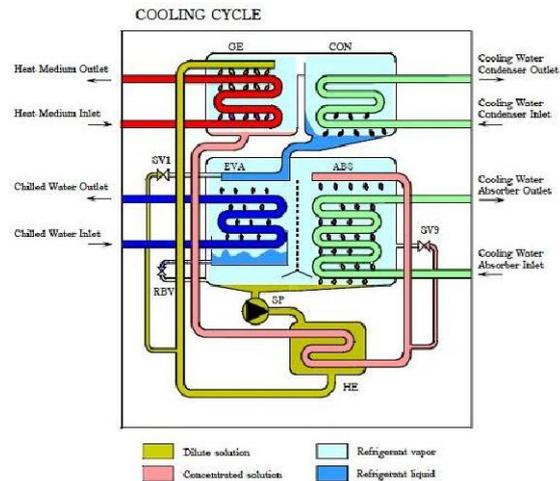


**Fig. 2 The absorption process in the pressure versus temperature diagram.**

The system consists of four main components: the absorber, the generator the evaporator and the condenser. The concentrated absorbing solution absorbs refrigerant vapour in the absorber and is thus diluted. This is an exothermic process and the heat of absorption has to be rejected to the environment. The evaporating refrigerant in the evaporator produces the cooling effect. The diluted solution is pumped to the generator. The solution is heated up in the generator by the driving heat and the refrigerant vapour is desorbed. Thus the solution is concentrated again. The refrigerant vapour flows to the condenser where it condenses releasing the heat of condensation to the heat rejection system, and back to the evaporator through a throttle. The concentrated solution flows back to the absorber to close the solution cycle. In order to increase the efficiency of the system a solution heat exchanger is installed between the flows of the cold and diluted solution from the absorber to the generator and the hot and concentrated solution back to the absorber recovering some of the sensible heat in the solution. Fig. 3 shows a scheme of a single-effect absorption chiller. The thermal efficiency of the system is defined by the ration of cold produced in the evaporator and driving heat used in the generator and is called ‘Coefficient of Performance  $COP_{th}$ ’:

$$COP_{th} = \frac{\text{cold produced}}{\text{driving heat}}$$

The process described above and shown in Fig. 2 corresponds to a so called single effect chiller as the solution is concentrated in only one stage. This is the most common process as it is suitable to be driven by low temperature heat of about 75 to 95°C.



**Fig. 3 Scheme of a single-effect absorption chiller**

Typical characteristics of single-stage absorption chillers are:

- COP of about 0.7 to 0.8
- Driving temperatures of 75 to 95°C
- Heat rejection temperatures of around 27°C
- Chilled water temperatures in the range of 7 to 15°C.

Lithium Bromide single stage absorption chillers are well developed and introduced to the market. Capacities from 10KW to hundreds of KW are available. While small capacity chillers have only been introduced recently to the market and only a few manufacturers are active, large chillers are produced by a many different companies, mainly in Asia and North America. The relatively low driving temperatures below 100°C make them suitable to be combined with CHP plants based on internal combustion engines, district heating networks, industrial waste heat and last but not least low temperature solar thermal systems with flat plate and evacuated tube collectors.

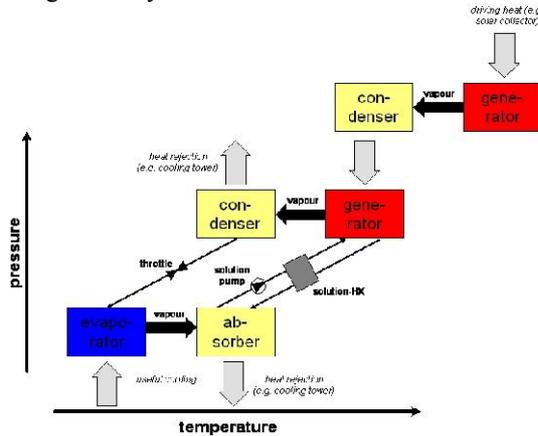
If higher driving temperatures are available several stages can be set on top or beside each other producing multi-effect and multi-lift systems. A detailed analysis of all possible combinations is presented in the patent of G. Alefeld [1]. In Fig. 4 the process of a double effect chiller is presented. This is also the second most common system, mainly used in direct fired and steam driven systems with driving temperatures of above 160°C. In the double-effect chiller a second generator at higher pressure and temperature is used to concentrate the solution even more. The heat in the condenser is used to drive the first regeneration stage. As a result a higher  $COP_{th}$  is possible as part of the driving heat is used twice.

The characteristics of these systems are:

- $COP_{th}$  of 1.2 to 1.3
- Driving temperatures above 160°C
- Heat rejection temperatures of 27°C
- Chilled water temperatures in the range of 7 to 15°C

Double effect chillers are available only in large capacities: they start at about 170KW.

An interesting and new development is an integration of a double-effect and single-effect absorption chiller into one machine which used two different temperature levels for the driving heat [2]. This development is particularly suitable for tri-generation systems where the different temperature levels of the jacket cooling water and the flue gases in an internal combustion engine are used in a very advantageous way.



**Fig. 4 Process of a double-effect absorption chiller**

The main disadvantages of LiBr-Water absorption systems are:

- The use of water as refrigerant results in a low pressure system. This requires high tightness of the system and expensive manufacturing.
- Water as refrigerant limits the chilled water temperatures to values above 0°C.
- There is a risk of crystallisation of the solution under certain pressure and temperature conditions. Crystallisation of the solution can destroy the machine, thus reliable and robust safety control systems are required.
- The circulation pump for the solution requires electricity and is a potential source of failure.
- LiBr solution is corrosive, anti-corrosion measures (additives) are required.

The main advantages are:

- Proven and reliable technology available on the market.
- Low driving temperatures.
- High thermal performance.

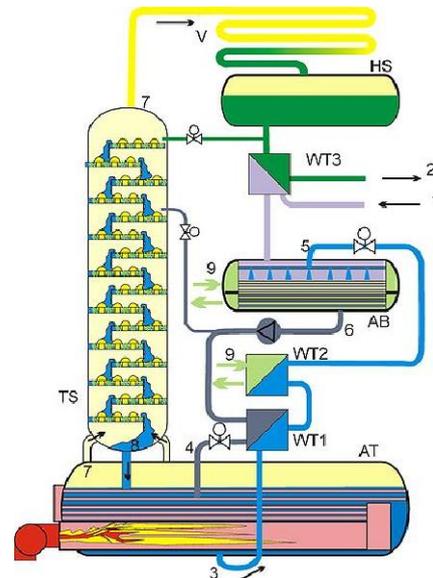
**Water – Ammonia Systems:**

The water-ammonia pair basically works as the LiBr-Water system described above. In this case the water is the absorbing material and the ammonia is the refrigerant. In contrast to the LiBr Systems, this is a high pressure system which works at pressures of several bars. As in the regeneration of the water-ammonia solution also water evaporates, a rectification is necessary to recuperate the water from the vapour mixture. This is necessary in order to avoid the contamination of the ammonia refrigerant in the condenser and evaporator circuit. Fig. 5 shows a scheme of a single stage water-ammonia absorption chiller.

In the so called GAX cycle systems a heat recovery heat exchanger between generator and absorber is installed improving the thermal efficiency (GAX= Generator-Absorber heat eXchanger). The water-

ammonia absorption technology has the advantage of being a pressurized system avoiding complex vacuum vessels. Further, chilled temperatures below 0°C are possible. Water-ammonia chillers are more flexible in the chilled water and heat rejection temperatures compared to LiBr systems as there is no risk of crystallization of the solution. This means lower chilled water temperatures are possible and also higher heat rejection temperatures are allowed. But these come along with higher driving temperatures.

Nevertheless, water-ammonia chillers have a slightly lower COP<sub>th</sub> compared to LiBr chillers in the same conditions, achieving typical COP<sub>th</sub> values of 0.5 to 0.6.



**Fig. 5 Scheme of a direct fired, single stage water-ammonia absorption chiller. TS: recuperator, AT: desorber, AB: absorber, V: condenser; HS: ammonia storage. Several heat exchangers (WT) are used for heat recovery**

**ADSORPTION**

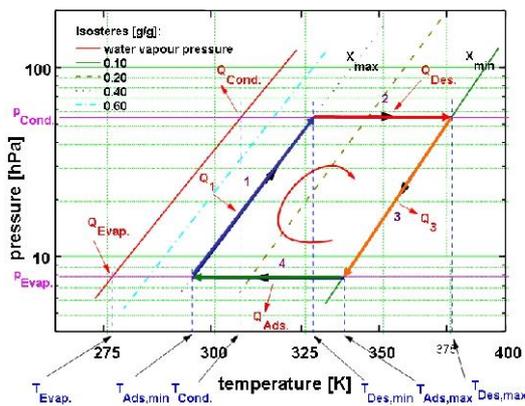
A less known technology for cooling is adsorption technology. But in recent years adsorption technology has attracted increasing attention as it is generally believed that the technology has a quite high untapped potential and is still much less developed compared to absorption technology. Adsorption technology is very similar to absorption, the difference is that the sorbing agent is not a liquid but a solid. This has major consequences for the cycles as the adsorbent can not be pumped any more and a batch process has to be carried out. The adsorbents are highly porous materials with a very large internal surface. Typical internal surfaces of technical adsorbents are several hundreds of square meters per gram of material. The main requirement for the adsorbent is a high affinity to the refrigerant. Two material pairs have been used up to now for adsorption chillers: silica gel-water and zeolite-water. Less developed pairs are activated carbon - ammonia and activated carbon - methanol. While traditionally conventional adsorbents developed for

chemical separation processes like drying and molecular sieves for gas purification have been used for energy transformation purposes in adsorption chillers, recently new materials developed specifically for these applications have been presented [3],[4]. These new materials, new compounds, component and machine developments as well as new cycles promise significant increases in efficiency and power density. Thus we can expect important new developments in this field in the coming decade.

The adsorption cycle is described in the isostere diagram. The isosteres are lines of equal adsorbent loading in a  $\ln(p)$  vs.  $1/T$  diagram.

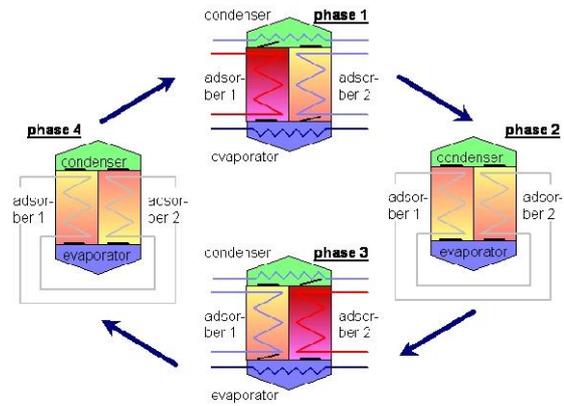
The ideal cycles consist of four steps (Fig. 6):

1. **Isosteric heating:** The adsorbent is heated up without changing the loading
2. **Desorption process:** The adsorbent is heated up and regenerated at condenser pressure  $p_{Cond}$ . The adsorbent changes its loading from the maximum value  $x_{max}$  to the minimum loading  $x_{min}$ . In this process the desorption heat  $Q_{des}$  is taken up. At the same time the desorbed refrigerant is condensed in the condenser releasing the heat of condensation at the temperature  $T_{cond}$ .
3. **Isosteric cooling:** cooling down of the regenerated adsorbent to reach the conditions for the following adsorption process. The loading stays constant at  $x_{min}$ .
4. **Isobaric adsorption:** The adsorbent adsorbs refrigerant at the pressure  $p_{evap}$  of the evaporator. In this process the loading increases from  $x_{min}$  to  $x_{max}$  and the heat of adsorption is release. The refrigerant evaporates in the evaporator producing the cooling effect.



**Fig. 6 Adsorption cycle in the isostere diagram**

As the adsorbent can not be pumped, these steps have to be carried out consecutively. This implies that the system only produces cooling intermittently in the adsorption step. In order to provide a quasi-continuous cold production a two-adsorber system where one reactor is regenerated while the other is adsorbing is used in adsorption chillers today. A heat recovery process is included to recover some heat from the hot regenerated reactor to preheat the fully loaded adsorber. The whole operation is thus carried out in four phases as shown in Fig. 7.



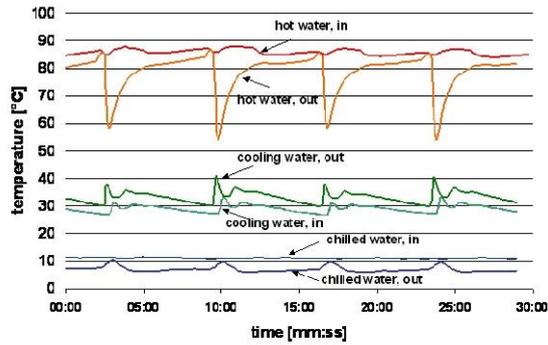
**Fig. 7 The four phases of a two reactor adsorption chiller. Phases 2 and 4 are heat recovery, 1 and 3 cooling/regeneration phases**

Several factors affect the thermal  $COP_{th}$  of an adsorption chiller:

1. The material characteristics: the higher the loading differences achieved between the adsorption and desorption process the higher the  $COP_{th}$ .
2. The ratio between the thermal mass of active material (adsorbent) and non-active components (e.g. heat exchangers).
3. The efficiency of the heat recovery process.
4. Internal and external heat losses.

Further, an optimization of the process is necessary in order to achieve a good  $COP_{th}$  with a reasonable cooling power. The main challenge is to increase the cycling speed without reducing the amount adsorbed. Thus a higher power with the same  $COP_{th}$  is obtained. To achieve this, the heat and mass transfer in the reactor but also in evaporator and condenser have to be improved. Currently there are several research groups working in this field. Several specific aspects of adsorption chillers are important in the integration of these machines into systems:

1. Strong varying temperatures occur in the three circuits due to the discontinuous process and the different phases. Fig. 8 shows a typical temperature diagram of an adsorption chiller. Suitable measures have to be taken when an adsorption chiller is integrated into a system. Internal combustion engines for example often cannot handle these variations, especially the relatively high return temperatures in the hot water outlet at the end of each phase. A damping storage in this line could be a solution.
2. Due to the alternating ad- and desorption process for each reactor the fluids of the driving and heat rejection circuits get mixed. Thus the same hydraulic fluid with the same operation pressure has to be used.



**Fig. 8 Inlet and outlet temperature of the three circuits of an adsorption chiller**

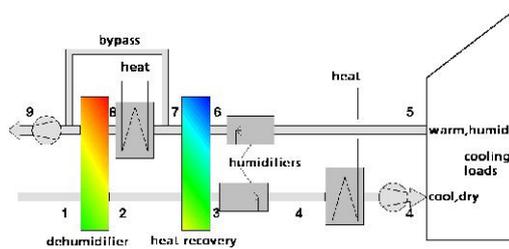
The typical characteristics of adsorption chillers are:

- COP<sub>th</sub> of 0.5-0.6
- Driving temperatures starting from 60°C
- Heat rejection temperatures of 27°C
- Chilled water temperatures in the range of 12 to 18°C

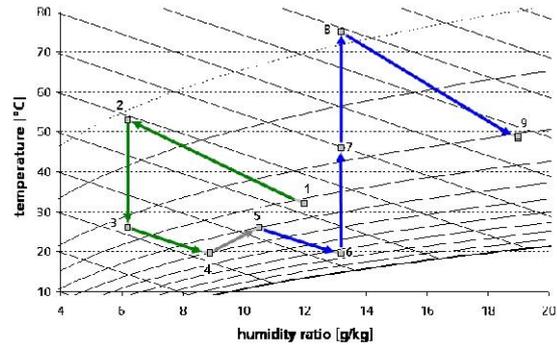
Adsorption chillers have been traditionally available only in large capacities (>70KW) from Japanese manufacturers. In the last few years several start-up companies in Germany have presented their newly developed products with capacities from 8KW to 15KW [5],[6], a very small machine with 3KW chilling power has been developed by the Dutch Research Institute ECN [7].

**OPEN SYSTEMS**

The best known open cycle process is the Desiccant Evaporative Cycle (DEC). The basic of this cycle is a dehumidification of the supply air in a sorption process and the posterior cooling through direct and direct evaporative cooling. The most common desiccant units are dehumidification rotors coated with silica gel as adsorbent or impregnated with lithium chloride solution. A scheme of the process is shown in Fig. 9.



**Fig. 9 Scheme of the Desiccant Evaporative Cooling (DEC) cycle**

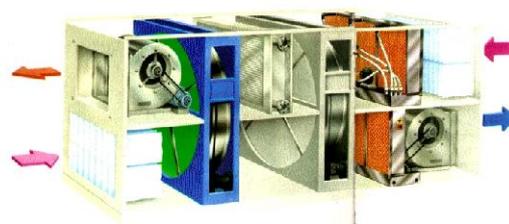


**Fig. 10 Humidity-temperature diagram of the DEC process**

The process is best explained in a humidity-temperature diagram as shown in Fig. 10. The process steps are:

1. Ambient air (1) is dehumidified in the dehumidifier. In this process it heats up due to the heat of adsorption (2).
2. The air is cooled in the heat recovery wheel (3).
3. A humidifier cools the air by direct evaporative cooling (4). This dry and cool air is the supply air to the building. The heater in the supply channel is only used in the heating mode.
4. The return air from the building is warm and humid (5) due to heat and humidity sources in the building.
5. The humidifier humidifies and cools the return air almost to saturation (6). Its cooling potential is used in the heat recovery wheel where it is heated (7) taking up heat from the supply air in process 2.
6. The return air is further heated up in the heat exchanger (8) in order to regenerate the desiccant wheel taking away the humidity from the wheel (9).

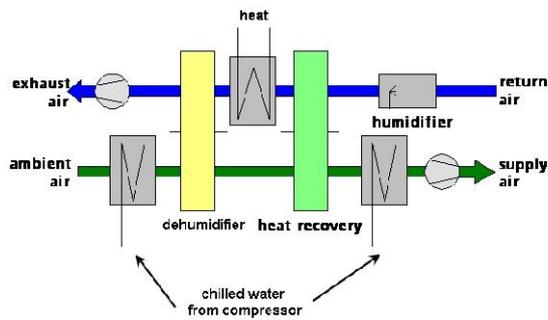
Thus, the supply air is dehumidified and cooled. Low temperature heat I needed as driving energy in the heat exchanger for the regeneration of the desiccant wheel. For commercial desiccant rotors temperature from 45°C up to around 70°C can be used, making this process especially suitable for solar applications with flat plate collectors or air collectors. Fig. 11 shows an outline of a typical DEC system. DEC systems can be conveniently integrated into conventional air handling units.



**Fig. 11 Desiccant Evaporative Cooling (DEC) system**

The conventional DEC process is suitable for climates with moderate temperature and humidity. In more humid climates the dehumidification capacity of the desiccant wheel is often not sufficient to allow a

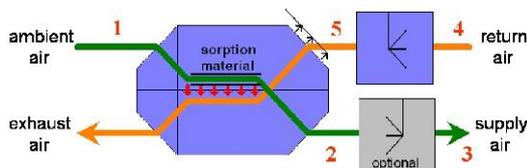
subsequent cooling by evaporation. In this case a modified process as shown in Fig. 12 could be used.



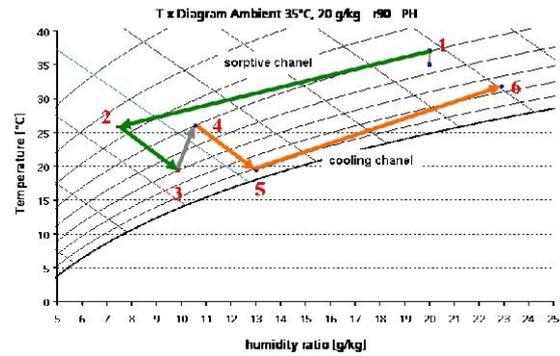
**Fig. 12 Modified DEC cycle for humid climates: a first dehumidification is done by condensation through a chilled water heat exchanger.**

In this process a first dehumidification is done by condensation in a conventional water-to-air heat exchanger fed by chilled water. This heat exchanger can be operated by relatively high (above 20°C) chilled water temperatures increasing the efficiency of the compressor. After the first dehumidification step a conventional DEC cycle is carried out replacing only the supply air humidifier by a second chilled water heat exchanger. With this combination of desiccant and conventional cooling a much higher efficiency is achieved as the compressor needs to work only at relatively moderate conditions compared to the conventional 6°C required for dehumidification.

A further option to increase the efficiency of the DEC cycle is to actively cool the sorption process in order to increase the dehumidification potential and reduce the need of sensible cooling after the dehumidification step. A new component, the so called “indirect Evaporative COoling counter-flow heat exchanger with Sorption” (ECOS) is currently under development at the Fraunhofer ISE [8]. A scheme of the unit and the corresponding process in the psychometric chart is shown in Fig. 13 and Fig. 14.



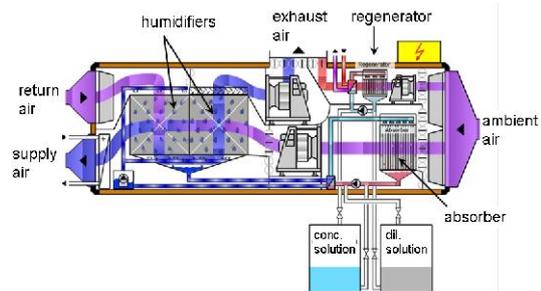
**Fig. 13 The „indirect Evaporative Cooling counter-flow heat exchanger with Sorption” ECOS**



**Fig. 14 The process of the ECOS system in the psychometric chart**

The system consists of a counter-flow air-to-air heat exchanger that is coated with a sorptive layer on the supply air channel. In the return air channel the air is constantly humidified in the heat exchanger in order to remove the heat of adsorption in process. The result is a cooled adsorption process reducing simultaneously the humidity and temperature of the supply air (2). With an optional humidifier the humidity and temperature of the supply air can be further controlled. The system works in a batch process: after the adsorbent is fully loaded and is not able to dehumidify the inlet air any more, it is regenerated by hot air. Thus, for a whole system two of these heat exchangers are necessary and operated alternatively in order to provide quasi continuous air conditioning.

Alternatively to the conventional DEC system, also liquid desiccant systems (LDS) have been developed.



**Fig. 15 Scheme of a liquid desiccant system (LDS): two solution tanks store diluted and concentrated solution for later use**

In these systems the dehumidifying agent is not a rotor but the air is directed through an absorber getting in contact with a liquid desiccant, normally lithium chloride solution. The solution is regenerated in a generator. The advantage of this system is that the absorption and regeneration processes can be carried out independently storing the concentrated and diluted solution in respective tanks for later use (Fig. 15). The system thus can operate in the desiccant mode without simultaneous regeneration what is especially interesting when solar energy is used due to its intermittent character. A commercial system of this kind is offered for example by the German company Menerga [9] but also other developments are close to market.

### 3. APPLICATIONS

All technologies presented above are suitable to be combined with various sources of heat. In the following section some examples are presented.

#### CHCP Systems

A very interesting application is to combine these technologies with Combined Heat and Power (CHP) units forming Combined Heat Cooling and Power (CHCP) system. While these systems are commercially available in large scale mainly combined with LiBr Absorption chillers, small and micro-CHCP systems are still under development. A large European project called PolySMART<sup>®</sup> [10] has been addressing this topic setting up a number of micro-CHCP systems with the newly developed thermally driven chillers in the power range of 5KW to 10KW. In this project also operation of small thermally driven chillers in a district heating network is investigated. The combination of a CHP unit and desiccant systems has also been demonstrated already [11], showing the advantage of advanced DEC cycles for humid climates.

#### Solar Cooling

The use of solar thermal collectors to drive a thermally driven cooling cycle is an application which is under investigation since about a decade [12]. International cooperation in the framework of the International Energy Agencies Solar Heating and Cooling Program (IEA-SHC) is being carried out, in the past in the Task 25 "Solar Assisted Air-Conditioning of Buildings" [13] and presently in the "Task 38 Solar Air-Conditioning and Refrigeration" [14]. The main focus of the work in this field up to now was air-conditioning of buildings and a "Handbook for Planers" [15] has been published as a result from the IEA-SHC Task 25. A revised edition is planned in the frame of the Task 38.

Regarding the systems, several combinations are possible: To drive a DEC system standard flat plate collectors or solar air collectors which heat up the air directly can be used. Flat plate collectors or evacuated tube collectors are also suitable to drive single stage absorption or adsorption chillers as the driving temperatures are below 100°C which are easy to reach with a reasonable efficiency with this technology. Around 300 solar cooling systems have been reported worldwide in the survey carried out in the Task 38 but there might be more systems installed that have not been reported. Most of these systems are demonstration systems or systems installed in the frame of research projects. From a market point of view, the technology is considered in an early market introduction phase with some niche markets but not yet developed due to the high costs and thus long payback times.

To drive double effect absorption chillers or if temperature below 0°C for industrial application have to be reached higher driving temperatures are needed. These temperatures can be provided by newly developed process heat collectors. These collectors concentrate the solar radiation with mirrors to an absorber tube where temperatures around 200°C are reached. These collectors

are similar to the systems developed for solar thermal power systems (CSP) but much smaller and are thus also suitable to be installed on roofs. Several systems have been installed with this technology (e.g. [16], [17]) but there is still significant research work to be done to put these cooling systems on the market.

#### Example of a small scale solar cooling system

In order to illustrate the achievable performance of small scale solar cooling systems we have selected a 5.5kW adsorption system installed at the Fraunhofer ISE in Germany. The system was originally installed in 2007 and has been operated with different prototypes of an adsorption chiller developed and provided by the company SorTech AG since then.

#### System concept

The system concept is shown in Fig. 16. The core component is the reversible adsorption machine (SorTech ACS05) which can be operated as a thermally driven chiller (5.5KW nominal cooling power with a nominal  $COP_{th}$  of 0.55) or heat pump (14KW;  $COP_{th}$  1.4) and the borehole system (three boreholes of 80m each) that is used as heat rejection system for the chiller mode as well as the low temperature heat source for the heat pump mode. Driving heat is provided through the solar collectors (20m<sup>2</sup> of flat plate collectors and 2m<sup>3</sup> buffer tank) as well as from the heating network of the institute which is fed by a CHP system. In the summer operation mode (Fig. 16) the adsorption machine works as a thermally driven chiller. It provides cooling to a cooling coil in the air handling unit. The waste heat from the chiller is rejected through the borehole system. In the winter operation mode (Fig. 17) the adsorption machine is working as a thermally driven heat pump. It lifts low temperature heat from the boreholes to a useful temperature level used in a heating coil to pre-heat the air in the ventilation system. Details of the system set-up, the operation and control concept and the results obtained with the first prototype in the first operation period has been presented before [18].

#### System performance

In 2008 a new prototype was installed and monitoring data has been collected for the summer and winter periods in 2008 and 2009. Detailed results and discussion of these results have been published in [19] and only an excerpt is presented here. The main evaluation tasks are the energy balance for the system, the electricity consumption and the primary energy ratio (PER) calculation. In Fig. 18 the energy balance for the cooling operation is shown. In this operation mode, about 45% of the driving heat came from the solar collectors. This share could be increased by a larger solar collector field. The thermal  $COP_{th}$  over the whole season was 0.46. In the winter operation mode (Fig. 19) the main driving heat came from the heating network (93%) as in winter the solar collectors seldom reach the required driving temperatures. The thermal  $COP_{th}$  over the whole heating period was 1.25.

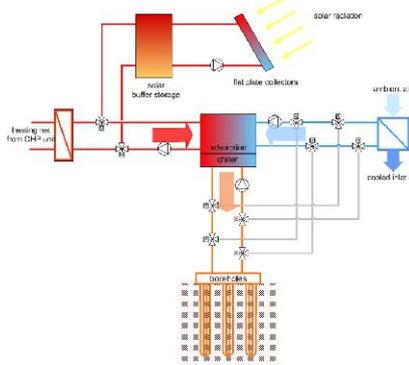


Fig. 16 System schema in the summer operation mode (thermally driven chiller)

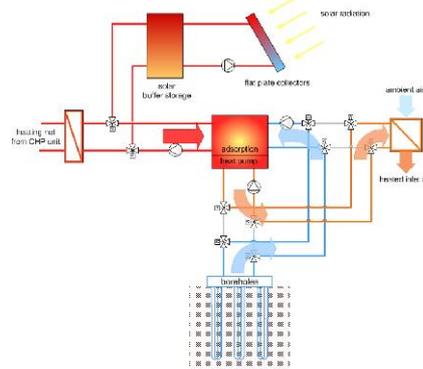


Fig. 17 System scheme in the winter operation mode (thermally driven heat pump)

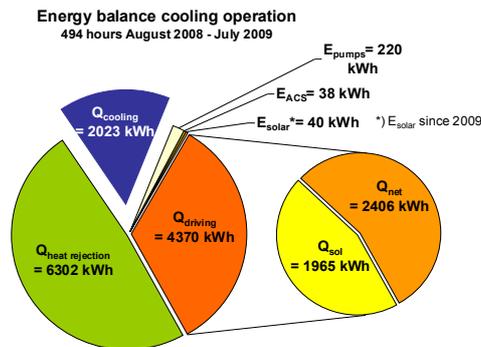


Fig. 18 Energy balance of the cooling operation

The evaluation of thermally driven cooling can not be limited to the evaluation of the thermal performance. Two further factors are crucial when comparing these systems with hypothetical conventional electricity driven systems:

1. the electricity consumption per unit of cold delivered (the electric COP<sub>el</sub>)
2. the primary energy ratio PER which is the cold produces per unit of primary energy used.

While the need for evaluating the electricity consumption is obvious, the calculation of primary energy ratio is more subtle: here not only the electricity consumption and the kind of fuel and efficiency used to generate this electricity plays a role (primary energy factors of the electricity grid) but also the back-up fuel used to drive the solar cooling systems in periods where solar energy is not sufficient is important. The same system under a different environment and thus different boundary conditions can give different primary energy ratios.

Further, it is important to differentiate between the consumption of the chiller alone and whole system as this may include the heat and cold distribution circuits which are also present in a conventional system. In order to estimate the potential of reducing electricity consumption we have tried to assign the consumption to two different evaluation boundaries of the system:

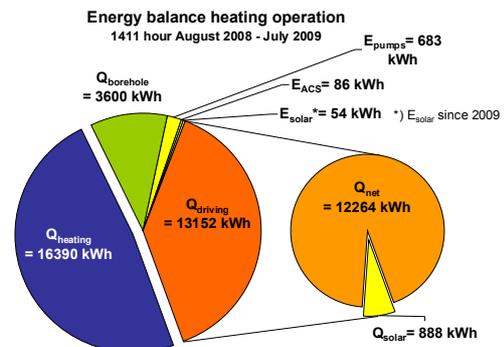


Fig. 19 Energy balance of the heating operation

1. the adsorption machine itself including the electricity requirement of external pumps to overcome the pressure drops in its internal hydraulic circuits,
2. the whole system including heat and cold distribution and the solar system.

As a summary, the formulas to calculate the performance factors for the system are:

The thermal COP<sub>th</sub>:

$$COP_{th} = \frac{Q_{heat/cold}}{Q_{driving}}$$

The electric COP<sub>el</sub> for the chiller (ACS) and system (sys):

$$COP_{el,ACS/sys} = \frac{Q_{heat/cold}}{E_{tot,ACS/sys}}$$

And the Primary Energy Ratio PER for the chiller (ACS) and system (sys):

$$PER_{ACS/sys} = \frac{Q_{heat/cold}}{Q_{driving,CHP} \cdot PE_{Q,CHP} + Q_{driving,solar} \cdot PE_{Q,solar} + E_{tot,ACS/sys} \cdot PE_{el}}$$

With the monitoring data obtained, considering the primary energy factor for electricity of the German grid (PE<sub>el</sub> = 2.78) and taking into account that the back-up heat comes from a CHP plant (PE<sub>Q,CHP</sub> = 0.76) we obtain the results summarized in Table 1. More details about the calculation and used numbers can be found in [19].

Table 1 Thermal, electric and primary energy performance of the system at Fraunhofer ISE

mode	COP <sub>th</sub>	COP <sub>el,ACS</sub>	COP <sub>el,sys</sub>	PER <sub>ACS</sub>	PER <sub>sys</sub>
	kWh <sub>heat/cold</sub> /kWh <sub>heat</sub>	kWh <sub>heat/cold</sub> /kWh <sub>el</sub>		kWh <sub>heat/cold</sub> /kWh <sub>PE</sub>	
Cooling	0.46	16.1	6.3	0.93	0.74
Heating	1.25	45.6	17.7	1.59	1.38

## 4. CONCLUSIONS

Several thermally driven cooling technologies exist and are market available. Absorption technology with lithium bromide – water solution but also with water - ammonia as working pair are well developed in the large capacity range and widely used. Small capacity systems have been developed recently and the first prototypes or small series products are being tested and demonstrated. An alternative is adsorption technology. This technology is not so well known but is considered to have a high technical potential due to new material and component developments and is comparative simplicity and thus potential cost advantage. Intensive research and development activities in this technology in recent years will result in new developments. Open cycles, best know through the DEC system, not only produce cold but can also dehumidify the air and are thus especially interesting in cases where a high amount of treated air is necessary and dehumidification is mandatory. Different cycles which are adapted to a wide variety of climates make these systems suitable for air conditioning of buildings. But the thermally driven chillers are only one component of thermally driven or solar cooling systems: these are complex systems consisting of a large number of components – heat source, heat exchangers, pumps, valves, heat and cold stores, etc. – which need to be adapted in order to be operated efficiently in the whole system. An intelligent operation and control procedure is essential for the overall performance of the system. Further, standardised procedures for the design and dimensioning of solar cooling systems are necessary in order to reduce costs, installation mistakes and operation faults. This is essential for the economic performance of solar cooling system. For small capacity systems complete pre-fabricated and factory assembled solar cooling packages are necessary in order to reduce planning and installation costs. Several companies are developing this kind of ‘Solar Cooling Kits’ today in Europe.

For the evaluation of all thermally driven cooling systems it is not sufficient to look at the thermal performance. Although this is an important factor in all developments, the overall primary energy requirements per unit of cold produced is more important.

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