

## 25. ADSORPTION SYSTEMS FOR TES—DESIGN AND DEMONSTRATION PROJECTS

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**Abstract.** Adsorption systems for thermal energy storage can be designed as closed or open systems. The two possibilities are described in chapter V.2. In this chapter some examples of complete systems will be given. There will be two examples for closed systems. One is a commercially available self cooling beer keg (ZeoTech Zeolite Technology, <http://www.zeo-tech.de>) and the other one is a seasonal storage for solar heat. For open systems one adsorption storage is described, which is installed in the district heating net and is able to provide heat for heating purposes in winter and air conditioning in summer.

**Keywords:** Adsorption, thermal energy storage, Silicagel, Zeolite

### 25.1. Closed Adsorption Storage Systems

#### 25.1.1. SELF-COOLING BEER KEG

The self cooling beer keg is based on the principle of closed sorption systems shown in chapter V.2 Figure 8. Figure 244 shows the beer keg from the outside and the inside.

During the adsorption—the discharging—cold is produced in the evaporator. In the beer keg the evaporator is located in the lower part of the keg and is in contact with the beer. As soon as the valve is opened the water in the evaporator will evaporate and starts getting cold. The heat of evaporation will be extracted from the beer and by this process the beer will be cooled. Figure 2 shows the falling temperature of the beer down to 8 °C. The process can be stopped and restarted by closing and opening the valve.

At the same time the adsorber will become hot by the released heat of adsorption. The adsorber is located at the outside of the keg. The heat of adsorption will be released through the outer surface of the keg. Figure 245 shows the temperatures in the adsorber. They can reach more than 80 °C.

Looking at the beer keg sorption system as an indirect heat storage, the system would look like Figure 246. The first part of Figure 3 shows the charging

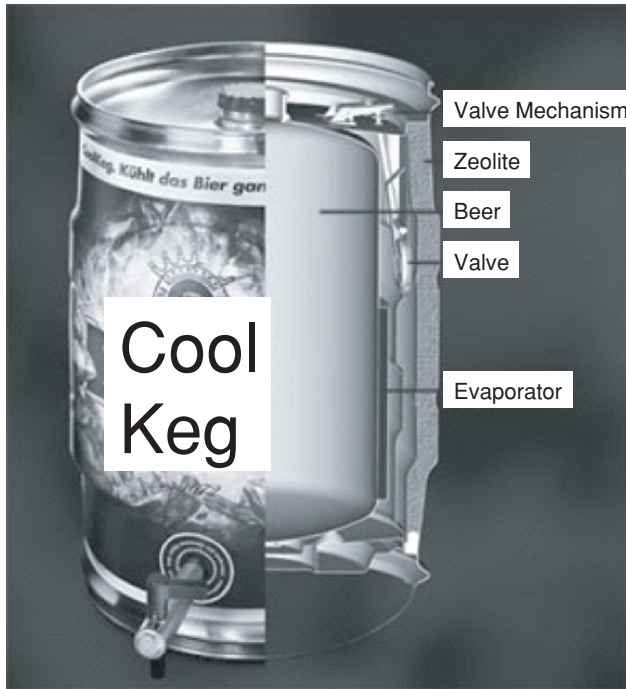


Figure 244. Outside and inside the beer keg

process. For this purpose a big oven was built at the brewery. Discharged kegs refilled with beer are slowly moved through an oven with a temperature of around 500 °C. The Zeolite on the outside adsorber will be desorbed and the evaporated water vapour will be condensed at the condenser/evaporator inside the keg. The beer, in good contact with the condenser/evaporator, is providing the cold side, which is important for an efficient charging process. The heat of condensation will be distracted by the beer until the beer reaches a temperature of about 40 °C. At that point the Zeolite is almost completely desorbed, the water vapour is condensed in the condenser/evaporator and the charging process is over.

The lower part of Figure 246 shows the discharging process, where the heat for evaporation is taken from the beer and the heat of adsorption is released through the surface of the keg.

### 25.1.2. SEASONAL STORAGE OF SOLAR ENERGY

Seasonal storage with sorption storage systems is strongly influenced by the changes in ambient temperature between winter and summer. A reduction of the thermal  $COP_{th}$  (beside the reduction due to the irreversibilities of the converter at charging and discharging) will be demonstrated in the following

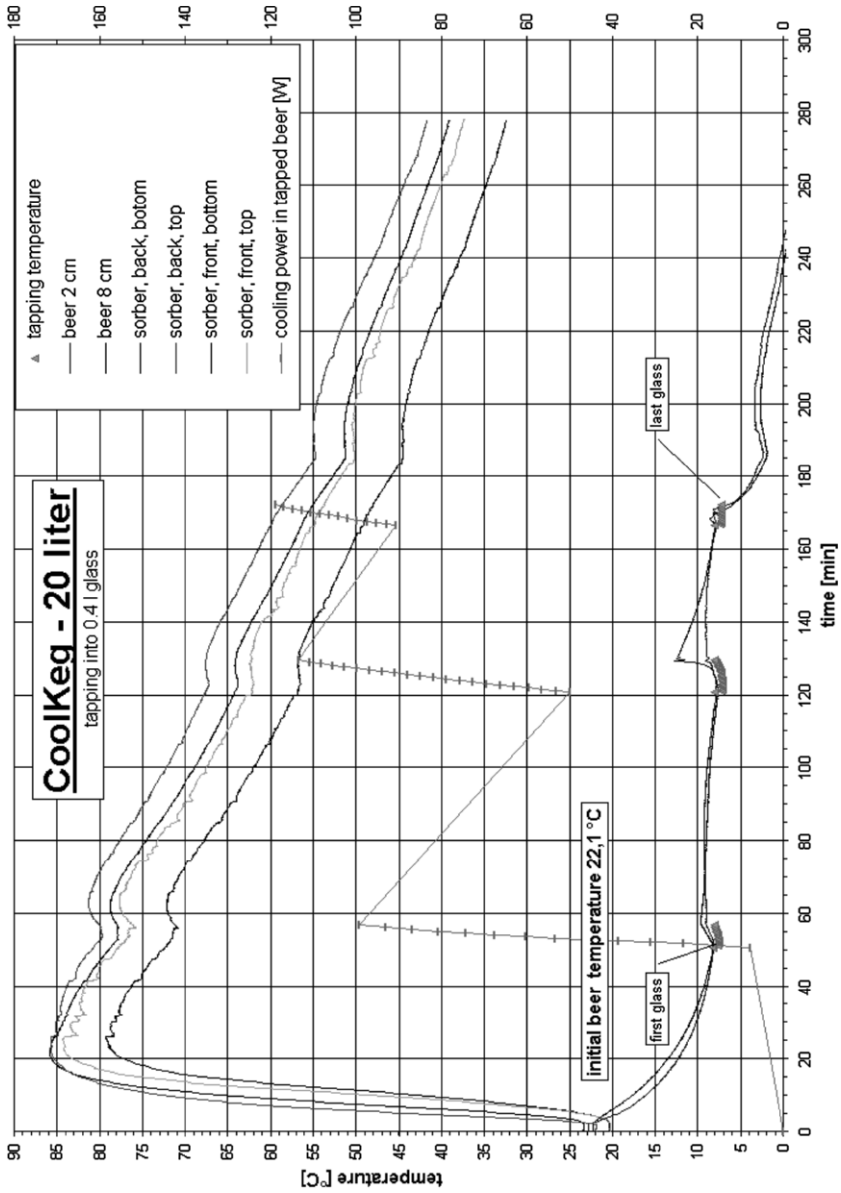


Figure 245. Temperature during the adsorption/discharging of the self-cooling beer keg

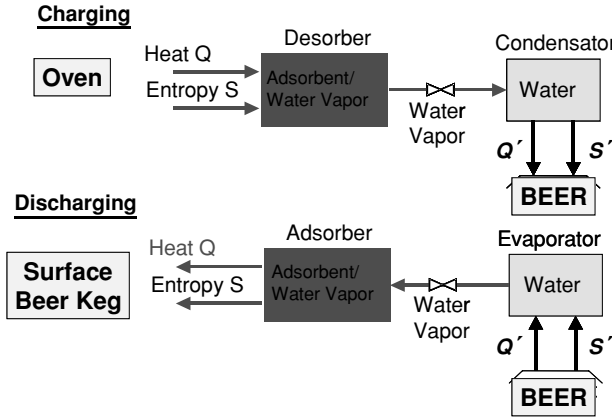


Figure 246. Self-cooling beer keg as an indirect heat storage

example: The charging process takes place in the summer time at ambient temperature  $T_{AC} = 30\text{ }^\circ\text{C}$ , while the discharging is happening in winter at  $T_{DC} = -20\text{ }^\circ\text{C}$ . This leads to a reduction of the ideal ratio between the discharged amount of heat  $Q_D$  and the heat charged to the storage  $Q_C$ :

$$\frac{Q_D}{Q_C} = \frac{\left(1 - \frac{T_{AC}}{T_C}\right)}{\left(1 - \frac{T_{AD}}{T_D}\right)} = 0.6. \tag{1}$$

In this example [2] the charging  $T_C$  and the discharging temperature  $T_D$  are both chosen to be  $100\text{ }^\circ\text{C}$ . In most applications  $T_C > T_D$ , which leads to a further decrease in the  $\text{COP}_{th}$ . The system is schematically shown in Figure 247.

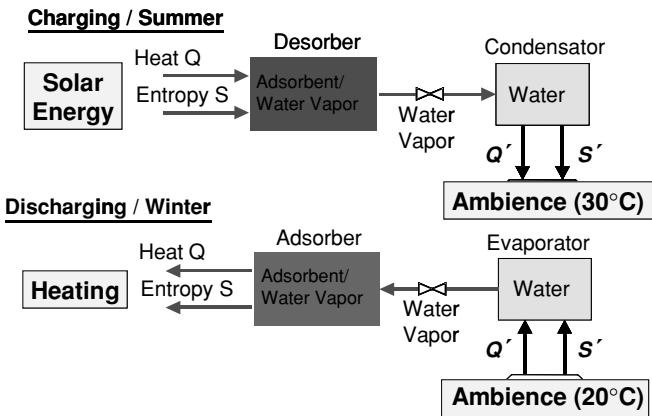


Figure 247. Seasonal storage of solar energy as an indirect heat storage

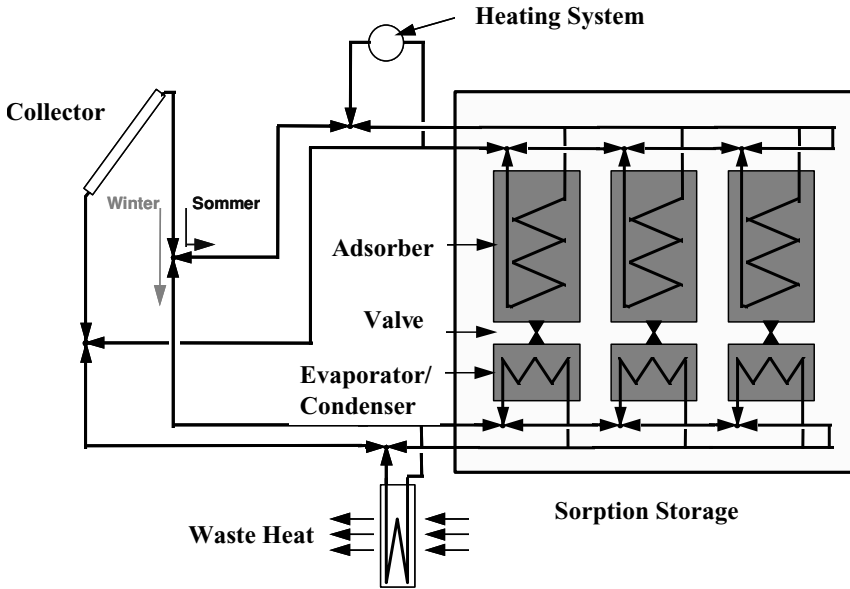


Figure 248. Closed sorption storage system for seasonal storage

Nevertheless long-term heat storage is one of the main challenges for an effective year round use of thermal solar energy. Therefore, high energy density heat stores are the focus of an increasing amount of research efforts.

In the period from 1998 to 2001 the European Union funded the Project “High Energy Density Sorption Heat Storage for Solar Space Heating” (HYDES). The major objectives of the project HYDES were the development of a high energy density heat storage system based on closed cycle adsorption processes suitable for the long-term storage of low-temperature heat and the testing of this system in the application of seasonal storage of solar thermal energy for space heating purposes under different climatic and system conditions [3].

The complete system is shown in Figure 248. In summer, during the charging of the storage, heat from the solar collectors is delivered to the three adsorbers. The heat input has to be realized by heat exchangers, which are located within a packed bed of Silicagel. The desorbed water vapour is condensed at the evaporators/condensers and the heat of condensation is transferred as waste heat to a cooling fan. During the discharging in Winter low temperature heat from the solar collectors is used for the evaporation of the water in the evaporators/condensers. The heat of adsorption is collected by the inner heat exchangers within the adsorbers and is delivered to the heating system of the building. In this constellation the heat needed for evaporation during the

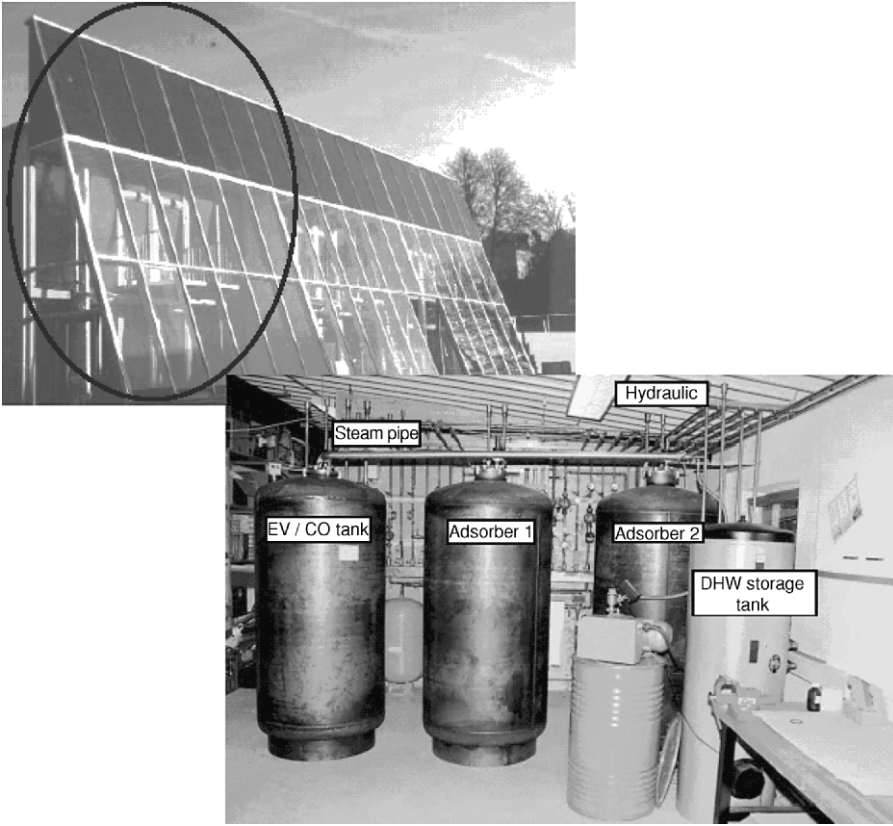


Figure 249. Pilot plant in Gleisdorf/Austria

discharging is not coming from the ambience (see Figure 247), because the temperature level would be too low. It is provided by the solar collectors at a higher temperature.

In order to study the performance of the sorption heat storage in different climatic conditions two prototype systems were planned and constructed. One test plant was installed in Austria (Figure 249). This system is operated by solar collectors and provides heating and domestic hot water production for a low energy house next to the office of the Austrian partner AEE. Due to the expected load profile of this long-term heat storage application a prototype system consisting of two adsorbers and one evaporator/condenser was built. A thermal solar plant with an aperture area of  $20.4 \text{ m}^2$  is available for the test plant as the primary source of energy. The solar plant faces to the South with a  $10^\circ$  deviation towards the West. The collectors have an inclination of  $72^\circ$  and are optimized for their use in the autumn and winter.

For desorption the vapor desorbed from the silica gel has to be condensed. For this reason a low temperature heat sink is required. The hydraulics of the plant provides two heat sinks: a 10 m<sup>3</sup> rain water cistern and the thermal solar plant. With these heat sinks two desorption modes could be carried out: a desorption with simultaneous condensation of the vapor and a second mode in which the desorption and condensation were not done simultaneously. If desorption and condensation of the vapour occur at the same time, then the condensation heat is rejected via the rain water cistern. The condensation heat can also be removed by the solar plant when the desorption and condensation operation are discontinuous. In this case the solar plant heats up the adsorber during daytime but no condensation is done. The condensation takes place through the solar system during the night given correspondingly low outside temperatures.

To achieve a high rate of utilization when operating the sorption storage tank, a heating system which operates with low temperatures is essential. This can be a wall or floor heating system or a combination of both. The floor and wall heating in the test apartment is a low temperature heat delivery system, with design temperatures of 40/30 °C at -12 °C ambient temperature and a maximum heating power of 2.2 kW. In addition the heating system of the laboratory room is connected to the hydraulic network of the test plant so that the radiator heating, designed for 45 °C/35 °C, can be used as alternative heat sink for the energy from the adsorber tanks.

Due to delays in manufacturing the adsorber heat exchanger containers the test period had to be shortened. The installation of the plant and start of the measurement was in May 2001, therefore a coupling to the system with room heating was not possible. In the first test runs the heat exchanger characteristics and the operational capability of the plant hydraulics were examined and initial adsorption and desorption tests were carried out. It could be shown that the test plant in general and the adsorption heat storage system in particular is a technically feasible solution for long-term storage. Due to the short duration of the tests, the adsorbers were not charged in the best possible way. The experimental results up to now show that the achieved energy density is about 20% below the value expected from simulation (150 kWh per m<sup>3</sup> of silica gel). The planned monitoring over the heating period could not be carried out within the time schedule of HYDES.

Seasonal heat storage leads in general to severe problems concerning the economics of storage system. If it is not a very inexpensive technology, like the storage of sensible heat in a large water tank, one of the most important factors is the number of charging/discharging cycles. A large number will reduce the actual cost for the stored thermal energy.

Recently a follow-up project entitled “Modular High Energy Density Sorption Heat Storage” (MODESTORE) was approved by the European

Commission. The work in this project will start in April 2003 and will continue for three years. One of the objectives is the development of a gas fired adsorption heat pump coupled to an underground storage system. That means the size of the sorption storage system is reduced significantly, a large number of cycles is possible and the actual seasonal storage is now realized by the UTES system. The economics of this concept are expected to be much better.

## 25.2. Open Adsorption Storage Systems

### 25.2.1. TES FOR HEATING AND COOLING IN A DISTRICT HEATING SYSTEM

#### 25.2.1.1. *Introduction*

An open adsorption storage was installed in Munich/Germany connected to the local district heating net [4]. To use this thermochemical storage system for heating in winter and air conditioning in summer leads to an increase in operation time. This can provide substantial economic advantages. A thermochemical storage using Zeolite as adsorbent has been installed in order to heat a school building in winter and to cool a jazz club in summer time. The school building and the jazz club are connected to the district heating system of Munich.

About one-third of the total energy consumption of Germany is used for space heating. The use of district heating systems with cogeneration is a possibility to save primary energy and reduce pollution. Local district heating systems are frequently operated at the upper limit of their capacity. Therefore new technologies are required to connect additional consumers without expanding the system. Decentralized thermal storage devices installed close to the consumer can shift the on-peak demand into off-peak periods. The power demand of the district heating system can be averaged and the number of consumers may be increased. The Zeolite system is designed to shift the peak demand for one day of the school building from day to night.

For the heating of buildings the heat of adsorption can be used in the adsorption mode. Depending on the used adsorbent and the desorption and adsorption conditions temperatures up to 160 °C can be reached. Under certain desorption conditions thermal energy can be delivered to the buildings heating system in the charging mode as well.

Looking at open sorption system as an indirect heat storage, the system would look like Figure 250. The charging process is driven by the district heat input. While the district heat return flow, the condensate, is providing the low temperature heat input to the humidifier for the evaporation.



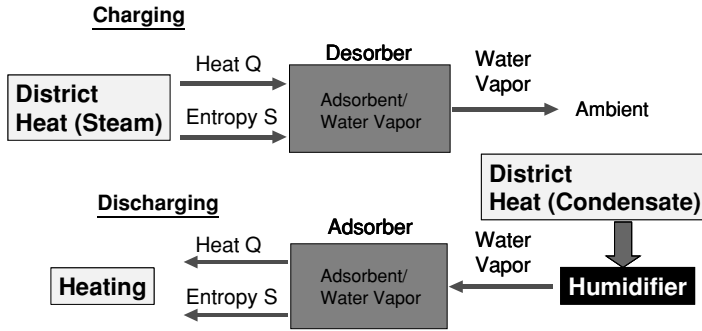


Figure 250. Open sorption storage for heating connected to a district heating system

The need for air conditioning is increasing remarkably over the last years. Reasons for that are architectural motives (like the use of large glass elements, a rising internal load caused by technical equipment and last but not least higher comfort standards. Cooling load consists of two part: The latent and the sensible load. The latent cooling load can be matched by dehumidification of the buildings supply air. Sensible cooling can be achieved by lowering the air temperature in the building. The cooling demand of the jazz club connected to the sorption storage system is caused by the large number of persons in the room. Therefore about  $\frac{3}{4}$  of the cooling load is latent, which makes it an ideal application for an open adsorption system.

The application of open sorption systems can provide dehumidification by the adsorption of water vapor and sensible cooling by adiabatic humidification (after a cold recovery for the dried air) at temperatures between 16 °C and 18 °C. Conventional systems have to reach temperature as low as 6 °C or lower in order to start dehumidification by condensation. For comfort reasons this cold air has to be heated up to about 18 °C before released into the building. This shows that open sorption systems can provide in general an energetically preferable solution.

25.2.1.2. Adsorption Process

1. *Heating:* In order to reach a coefficient of performance  $COP_{heat}$  of about 1.0 or more it is important to utilize the heat of condensation  $Q_{cond}$  during the charging process.

The thermochemical storage system can be charged off-peak. At on-peak times it uses only low temperature heat extracted from the return flow of the district heating system. By lowering the temperature of this return flow, the power transported is increased and heat losses of the net are reduced. In addition to that, thermochemical storage systems offer high energy storage densities without degradation due to heat losses in long-term storage.

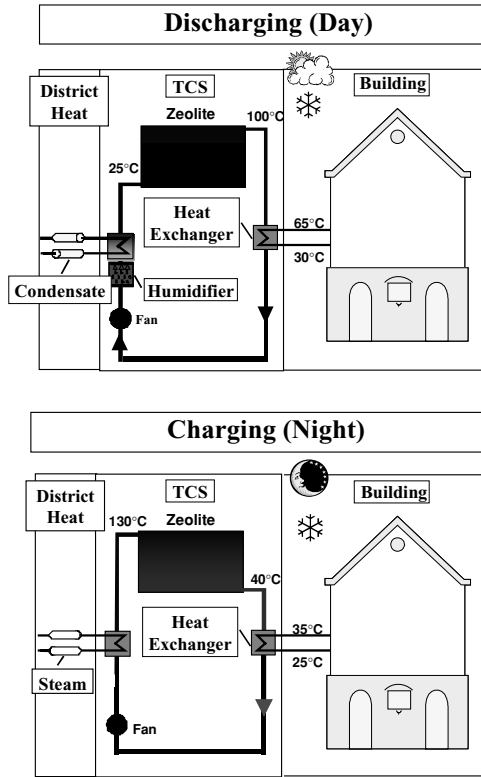


Figure 251. Charging and discharging mode for heating

Figure 251 shows heat fluxes during charging and discharging mode. At night Zeolite is charged by air, heated up to about 130–180 °C using the steam line of the district heating system (heat of desorption  $Q_{Des}$ ). Under these conditions the final water content of the Zeolite reaches  $0.09 \text{ kg}_{Water}/\text{kg}_{Zeolite} - 0.05 \text{ kg}_{Water}/\text{kg}_{Zeolite}$ .

The waste heat of the charging process (temperature level 35–40 °C and above) and the heat of condensation  $Q_{Cond}$  is supplied to the heating system of the school.

The storage system is discharged in times of peak power demand. At first the air is heated up to 25–30 °C and saturated with water vapor by a humidifier. The energy for this process is provided by the low temperature return flow of the district heating system (heat of evaporation  $Q_{Evap}$ ). The steam line of the district heating system is not used. The humidified air is blown into the tank containing desorbed Zeolite. The air temperature is raised to 100 °C (heat of adsorption  $Q_{Ads}$ ). The thermal energy is transferred

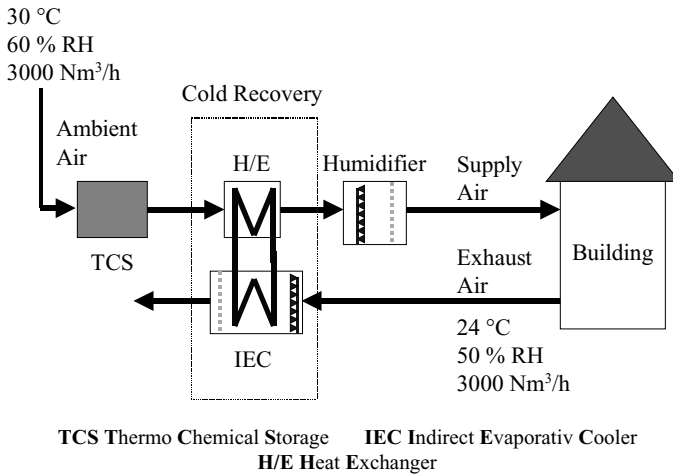


Figure 252. Additional components for air conditioning

to the heating system of the school (flow temperature 65 °C) by heat exchanger.

2. *Cooling:* In order to use the Zeolite storage system as a desiccant cooling system two additional components have to be integrated. Figure 252 shows the complete desiccant cooling system including the cold recovery device and the supply air humidifier. As shown in Figure 252, the air stream exiting the Zeolite bed has to be cooled down (cold recovery device) before entering the supply air humidifier.

The cold recovery device consists of an exhaust air humidifier with an integrated heat exchanger and the supply air heat exchanger, which are connected by a fluid circuit. The first can be described as an indirect evaporative cooler. The cold recovery device is able to transport 83% of the maximum possible enthalpy difference from the exhaust air to the supply air.

### 25.2.1.3. Adsorption System

1. *Thermochemical storage:* The storage system is designed to cover a heat load of 95 kW over a period of 14 h (from 7 a.m. to 9 p.m.) each day. This was achieved by using 7,000 kg of Zeolite 13X for the storage tank. The tank consists of three connected cylinders arranged in a horizontal line (see background of Figure 253). The storage system is connected to a combined air/radiator/floor heating system. The result is a flow temperature of 65 °C and a return temperature not higher than 35 °C. The maximum thermal power is 130 kW, the storage capacity is 1,300–1,400 kWh at

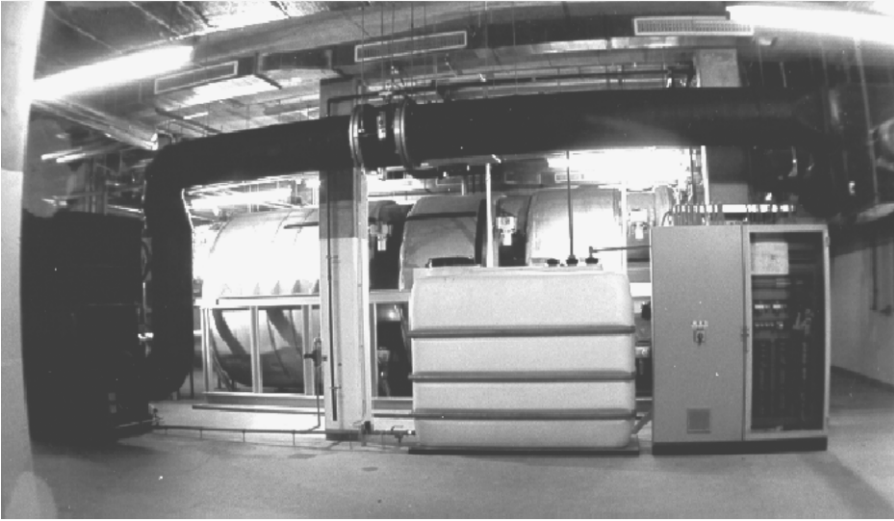


Figure 253. Thermochemical storage system (Humidifier, water tank and control unit in the front from left to right, three Zeolite modules in the back)

130 °C charging temperature.<sup>4</sup> Table 32 shows the relevant data of the thermochemical storage.

The additional components for the air-conditioning application are shown in Figure 254.

2. *School building*: The thermal energy storage was installed in a school building in Munich, Germany, by 1996. The school building is a former brewery in Munich, converted by the *Münchner Gesellschaft für Stadterneuerung (MGS)* and is connected to the district heating system (guaranteed steam temperature of 130–140 °C). The thermochemical energy storage system is used as a buffer between the district heating system and space heating system of the school. Table 33 shows the relevant data of the school building.
3. *Jazz club*: A jazz club with a reasonable cooling load is located close to the storage system. The club has a floor area of 160 m<sup>2</sup> and a volume of 800 m<sup>3</sup>.

TABLE 32. Data of the thermochemical storage

Mass of zeolite	7,000 kg
Max. air flow	6,000 m <sup>3</sup> /h
Max. heating power	130 kW
Max. cooling power	50 kW
Energy density (heating)	Up to 200 kWh/m <sup>3</sup>
Energy density (cooling)	Up to 100 kWh/m <sup>3</sup>



Figure 254. Heat exchanger and humidifier of the supply air and the indirect evaporative cooler of the exhaust air

The maximum capacity is about 200 persons. The room temperature should not exceed 26 °C at a relative humidity of 50%. The maximum cooling load was calculated assuming 4.5 kW for lighting and 1 kW for other technical equipment. The result is a maximum latent cooling load of 22 kW (73%) and sensible of 8 kW (27%).

25.2.2. RESULTS OF THE DEMONSTRATION PLANT HEATING

In the beginning of 1997 the automatic operation of the storage system started in the heating application. Since then the required room temperatures and heating power were covered by the storage system. Problems detected in the first operation period were removed. The control strategy during discharging mode was constantly improved.

The upper part of Figure 255 shows on a desorption /charging process of two storage modules (indicated above the diagram). During this process the heating system of the building is supplied at a temperature level of about 40 °C (see flow line temperature). As soon as this temperature starts rising the next module is charged. The thermal energy supplied to the heating system during desorption keeps the building from cooling down at night time. Therefore a heating demand peak in the morning can be avoided.

The discharging process, at the lower part of Figure 255, shows inlet and outlet air temperatures of the storage. Saturated air from the humidifier enters

TABLE 33. Data of the school building

Heated floor space	1625 m <sup>2</sup>
Max. heat load (at -16 °C)	95 kW
Specific heat demand	65 kWh/m <sup>2</sup> a
Heating system	radiator/floor /air heating
Fresh air flow rate	30 m <sup>3</sup> /h person

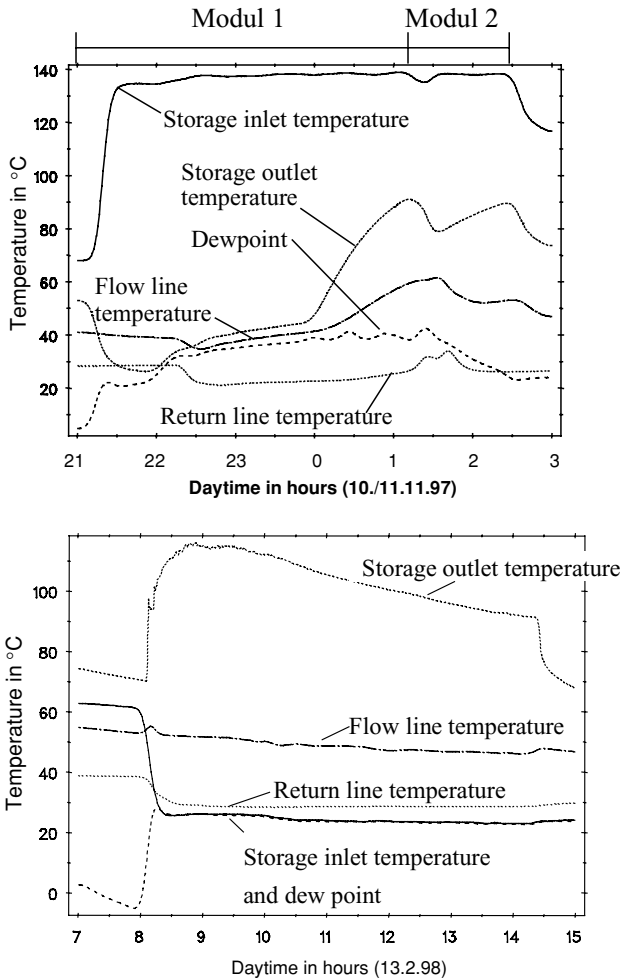


Figure 255. Experimental data of a desorption and an adsorption (air temperatures and dew points, flow and return line temperatures of the heating system)

the storage at 25 °C and exits at about 100 °C or more. The hot air transfers heating power to the heating system at about 50 °C. The discharging of the first module lasts for 6.5 h.

The thermal coefficient of performance  $COP_{heat}$  is defined as the ratio of thermal energy supplied to the building (heat of condensation  $Q_{cond}$  and adsorption energy  $Q_{ads}$ ) and thermal energy input for charging the storage (desorption energy  $Q_{des}$ ). The utilized thermal energy in the experiments is the actually transferred heat to the heating system including all losses. The experimentally achieved thermal energy density is the actually transferred

TABLE 34. Comparison of experimental and theoretical results of the thermochemical storage system for heating

Thermal coefficient of performance $COP_{heat}$	
Theoretical $COP_{heat}$	1.07
Experimental $COP_{heat}$	0.92
Energy density $\rho_Q$	
Theoretical $\rho_Q$	552 MJ/m <sup>3</sup> (153 kWh/m <sup>3</sup> )
Experimental $\rho_Q$	446 MJ/m <sup>3</sup> (124 kWh/m <sup>3</sup> )

thermal energy divided by the volume of the Zeolite. Table 34 compares the experimental results to the theoretically calculated values<sup>4</sup> for the given conditions.

Table 34 shows that 86% of the theoretical maximum  $COP_{heat}$  and 81% of the maximum thermal energy density were reached in the demonstration plant.

25.2.2.1. *Cooling*

Simulations of the storage have shown that desorption temperatures below the possible 130 °C from the district heat can lead to higher  $COP_{cool}$ . Experiments with 130 °C, 100 °C and 80 °C were carried out. Figure 256 shows the 100 °C desorption as an example.

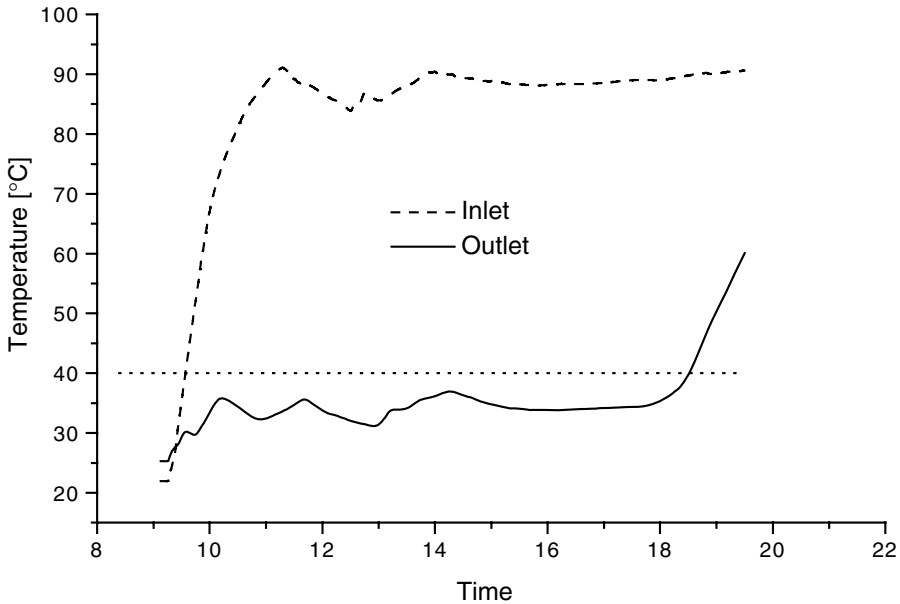


Figure 256. Desorption at 100°C for air conditioning

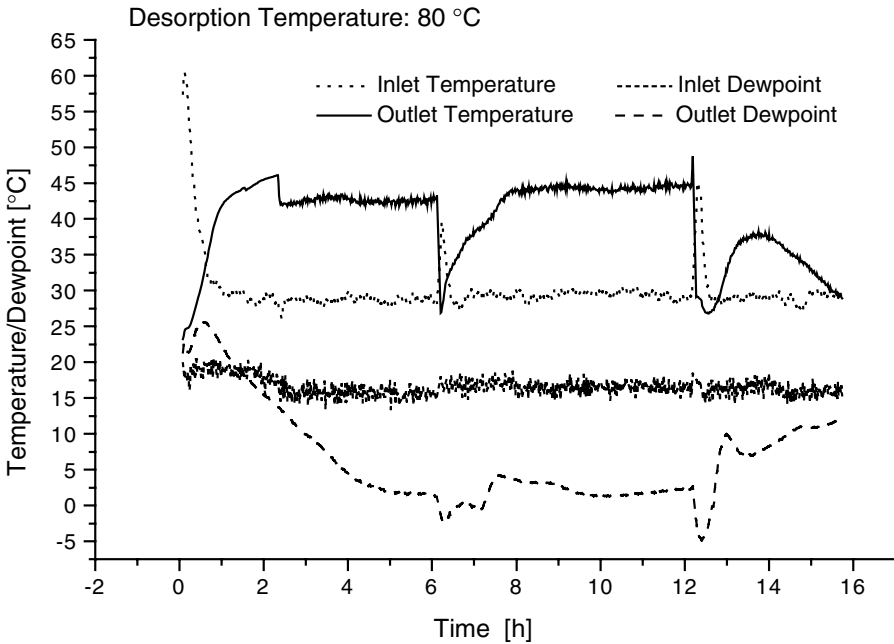


Figure 257. Adsorption following an 80 °C desorption

The inlet air temperature shown is measured right on top of the Zeolite bed. It has already cooled down to about 90 °C between the district heat exchanger and the Zeolite. The outlet air is almost saturated at about 35 °C for about 9.5 h. The desorption was stopped after the outlet air temperature has reached 60 °C. At the same time the humidity ratio of the outlet air has dropped and the equilibrium is almost reached. A continuation of the desorption is not efficient.

Figure 257 shows an adsorption following an 80 °C desorption. The adsorption was stopped after 6 h. This is a typical period for cooling demand in an office building in Germany. The adsorption was continued the next day. Figure 14 shows two and a half of these air-conditioning periods (in the picture directly succeeding one another). The starting phase of each period (of about 45 min) was included in the calculation of the thermal COP.

The inlet air had a temperature of 29 °C and a dew point of 16 °C (a relative humidity of about 47%). The outlet air temperature was rising to about 45 °C, while the outlet dew point went down to less than 5 °C.

Two different coefficients of performance for dehumidification  $COP_{dehum}$  and for cooling  $COP_{cool}$  were defined:

$$COP_{dehum} = \frac{Q_{dehum}}{Q_{Des}} \quad \text{and} \quad COP_{cool} = \frac{Q_{cool}}{Q_{Des}}. \quad (2)$$



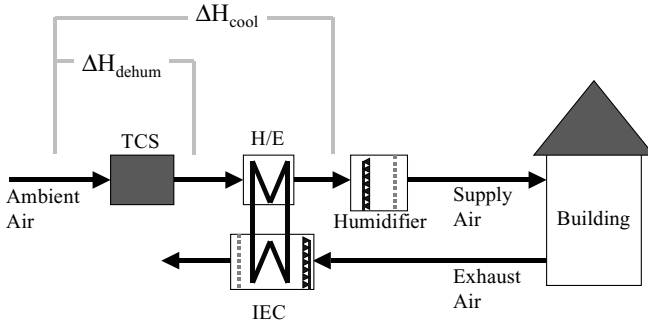


Figure 258. Definition of  $\Delta H_{dehum}$  and  $\Delta H_{cool}$

where  $Q_{dehum}$  and  $Q_{cool}$  are:

$$Q_{dehum} = \int_{t_i}^{t_f} \Delta H_{dehum} \cdot \dot{m}_{air} \cdot dt$$

$$Q_{cool} = \int_{t_i}^{t_f} \Delta H_{cool} \cdot \dot{m}_{air} \cdot dt$$

Figure 258 shows this definition schematically.  $\Delta H_{dehum}$  is the enthalpy difference of the air stream caused by the adsorption within the zeolite tank only.  $\Delta H_{cool}$  includes the cooling effect caused by the cold recovery.

The energy density  $\rho_{cool}$  is defined as

$$\rho_{cool} = \frac{Q_{cool}}{V_{Zeo}} \tag{3}$$

where  $V_{Zeo}$  is the volume of the packed bed of Zeolite.

The results for  $COP_{dehum}$ ,  $COP_{cool}$  and  $\rho_{cool}$  for the different desorption temperatures were shown in Table 35.

The best performance was measured using a desorption temperature of 80 °C. Below that temperature almost no dehumidification can be observed.

TABLE 35. Experimental results of the thermochemical storage for cooling

	Desorption temperature		
	130 °C	100 °C	80 °C
$COP_{dehum}$	0.45	0.48	0.50
$COP_{cool}$	0.67	0.80	0.87
$\rho_{cool}$	168 kWh/m <sup>3</sup>	105 kWh/m <sup>3</sup>	100 kWh/m <sup>3</sup>

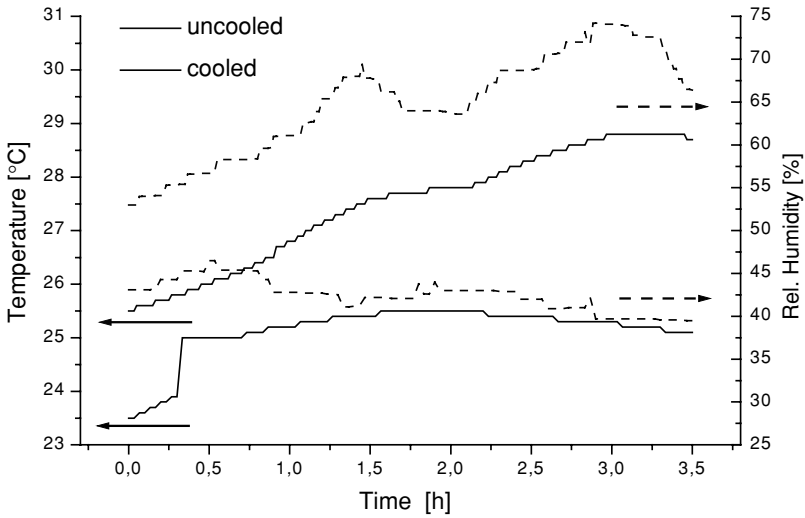


Figure 259. Temperature and relative humidity in the jazz club during a concert

There is a remarkable increase from  $COP_{dehum}$  to  $COP_{cool}$ , which is caused by the heat recovery. This can be explained by the high outlet air temperatures during adsorption, which are supporting the cooling by the indirect evaporative cooler very effectively. At a desorption temperature of  $80\text{ }^{\circ}\text{C}$  a value of 0.87 could be reached. That means 87% of the district heat were converted into cooling energy and were delivered to the jazz club.

Figure 259 shows temperature and humidity inside the jazz club over a sold out evening concert without any air conditioning (ventilation only) and with desiccant cooling by the thermochemical storage. In the first case temperature and humidity are rising until the end of the concert (there is a break at about 22:45 when humidity is decreasing for half an hour), which indicates that sufficient air conditioning cannot be provided by the ventilation system only. The maximum values of almost  $29\text{ }^{\circ}\text{C}$  temperature and 74% relative humidity are far outside the comfort zone ( $26\text{ }^{\circ}\text{C}/50\%$  R.H.). By using the Zeolite system temperature and humidity could be kept at comfortable values over the complete concert.

### 25.2.3. CONCLUSIONS

The demonstration project on thermochemical energy storage showed results in the heating and air-conditioning application with good correspondence with the theoretical calculated values. The operation control strategies have to be improved and simplified in the future.

A rough economic evaluation showed that the pay back time depends strongly on the price reduction for the off peak thermal energy, the investment costs and the number of storage cycles. Under the assumption of an 40% reduction in winter (which is already negotiated) and a 60% reduction in summer for the district heat energy price, investment costs of 60.000 Euro (for the described system) and 150 heating and 100 cooling cycles per year, a pay back time of 7–8 years was found. This shows that thermochemical energy storage systems can be competitive in the near future due to their large development potential.

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