26. OPEN ABSORPTION SYSTEMS FOR AIR CONDITIONING AND THERMAL ENERGY STORAGE

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Abstract. Open absorption systems for thermal energy storage have been investigated over the last years. Open sorption systems using liquid desiccants like Lithium chloride are able to dehumidify an air stream. By adiabatic humidification this dry air can be cooled down and used for air conditioning of buildings. These systems provide cool and dry air to the rooms. At the same time these systems are able to store thermal energy very efficiently. The thermal energy can be stored within the difference of salt concentration between the diluted solution (after absorption) and the concentrated solution (after regeneration).Examples of demonstration projects will be given. A solar application for the dehumidification of an office building and an application connected to a district heating net for the cooling of a jazz club will be presented in detail.

Keywords: Absorption, thermal energy storage, desiccant cooling, Lithium chloride

26.1. Motivation

External cooling loads of buildings can be reduced efficiently by shading, insulation and cold recovery. Internal heat gains have to be removed actively. So a significant incoherence of solar irradiation and cooling load can result, even if air conditioning of the building is necessary only at daytime. In this case, energy storage can increase the solar fraction of the energy supply significantly. Energy for dehumidification can be stored efficiently and none dissipatively in desiccants.

Figure 260 shows the primary energy demand depending on electricity net efficiency on the upper x-axis for conventional vapour compression chillers and on the solar fraction for solar thermal driven air-conditioning systems. Each curve is representing a vapour compression chiller or a single (or double) effect absorption chiller with different thermal COPs. It is interesting to see that single effect absorption chillers using solar energy have to reach high solar

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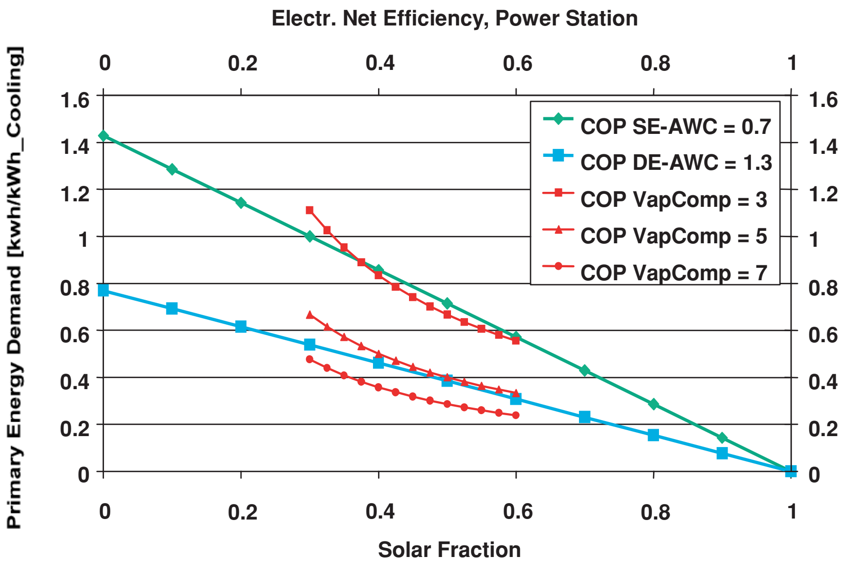

Figure 260. Primary energy demand for vapour compression and absorption chillers

fractions around 0.8 in order to compete with conventional systems. Solar fractions of 0.8 cannot be reached without efficient thermal energy storage.

The water removed from the air $\Delta Y = Y_{abs\ in} - Y_{abs\ out}$ is absorbed by the desiccant. The system of absorbed and regenerated desiccant has the potential to remove the latent enthalpy $\Delta H_{lat} = M_{air\ reg} \cdot \Delta Y \cdot h_{lat}(T)$ from the air flow. Neglecting the small amount of sensible heat of the absorbed vapour, the storage capacity SC for dehumidification enthalpy per volume desiccant V_{des} can be defined as

$$\mathrm{SC} = M_{air\ reg} \cdot \Delta Y \cdot h_{ev}\,(T = 0)/\,V_{des} \tag{1}$$

where in the case of a liquid desiccant the volume of the diluted solution is taken $V_{des} = V_{dil.\ sol.}$.

26.2. Absorption Process

Figure 261 shows the absorption and the regeneration process schematically. During Absorption the concentrated salt solution is distributed over an exchange surface, which is in contact with an air stream. The air will be dehumidified and the salt solution will be diluted by the absorbed water vapour. During regeneration the diluted solution becomes concentrated again by desorption from a hot air stream.

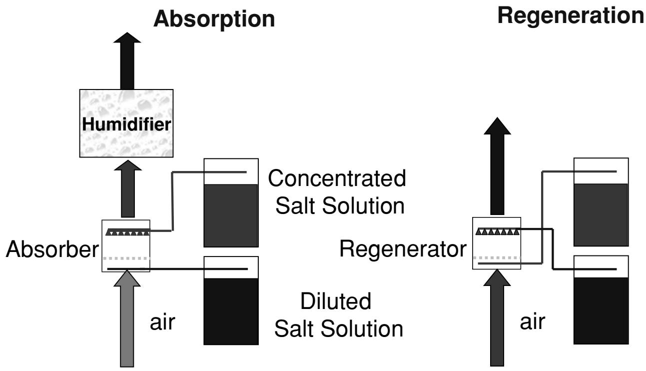

Figure 261. Absorption and regeneration of an open absorption storage

In open cycle desiccant cooling systems, DCS, air is dehumidified by solid or liquid desiccants and cooled subsequently by heat exchange and water evaporation. The desiccants absorb water when drying the air and have to be regenerated to continue the process. In open cycle systems the desiccants have to be regenerated against the ambient water vapour pressure, corresponding to the dew point of the ambient air [1, 2]. Closed cycle absorption systems have to regenerate against a temperature well above the ambient wet bulb temperature [3]. Consequently open cycle regeneration requires lower regeneration temperatures, which results in higher collector efficiency. A different method to achieve lower regeneration temperatures is cooling the absorption process [6, 7].

In Figure 262 plots for a cooled (P_1) and an adiabatic sorption process (P_2) are compared in a psychrometric chart, with parametric lines indicating different concentrations (C_1, C_2) of an arbitrary desiccant. Both processes dehumidify air from ambient humidity ratio of 14.5 g/kg to a humidity ratio of 8 g/kg (solid lines). The dotted lines continuing the process lines, point to the different concentrations, (C_1, C_2), required to drive the processes. If the absorption process is cooled, low humidity ratios can be achieved using a desiccant of concentration C_1. At a given ambient humidity ratio the desiccant can be regenerated with an ideal equilibrium regeneration temperature Treg1. In the adiabatic absorption process the temperature increases significantly and a higher concentration is required to achieve the same humidity ratio. Consequently T_{reg2} a significantly higher (equilibrium) temperature is required to regenerate the desiccant. This statement is almost independent of the nature of the desiccant. For example, C_1 corresponds to a 40% solution of LiCl–H_2O, as well as to Silicagel of a water content of 10.5% as well as to Zeolite M13X of a water content of 25.5%. C_2 corresponds to Silicagel of a water content of 3.1% or to Zeolite M13X of a water content of 20.3%. A LiCl–H_2O solution at a concentration corresponding to $C_2 = 65\%$ will crystallize.

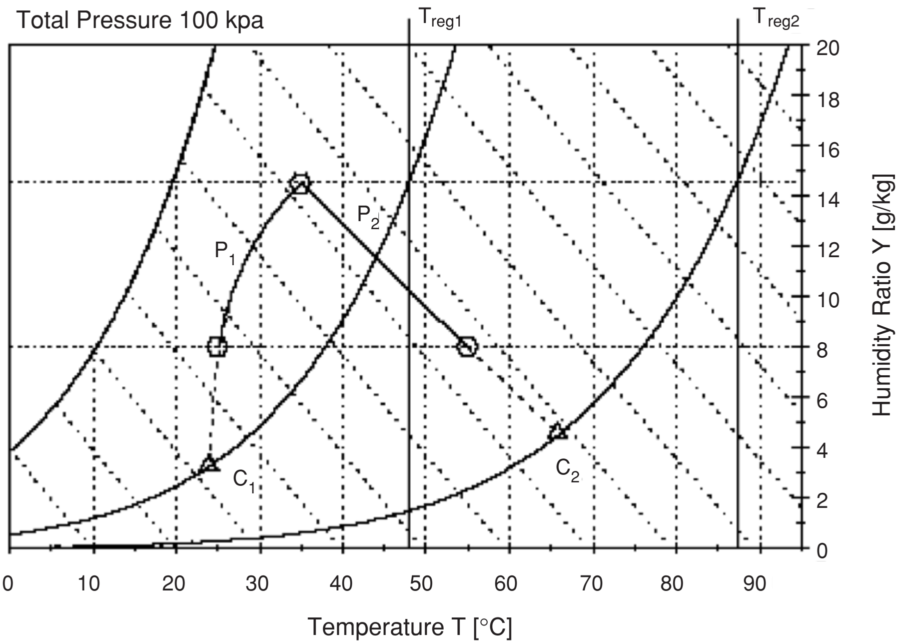

Figure 262. Comparison of cooled (P_1) and uncooled (P_2) absorption process. T_{reg} indicate the equilibrium regeneration temperatures at ambient humidity for different concentration C

Most of the commercial systems installed use rotary dehumidifier wheels with solid sorbents as e.g. Silicagel for air dehumidification. This is a design, which cannot be cooled easily. Absorption processes using liquid desiccants can easily be cooled, either by precooling the desiccant and supplying a sufficiently large desiccant flow, or by spraying the desiccants over a heat exchanger. These systems are also commercially available [4].

For ideal cooled absorption processes (cooling temperature 20 °C) a comparison of air dehumidification and energy storage capacity of different solid and liquid desiccants is given in Figure 262 [5]. In cooled absorption processes, the equilibrium humidity ratio is only a function of the temperature T_{reg} at which the desiccant has been regenerated (at given air humidity ratio). There is no difference in air dehumidification potential between different desiccants, either liquid or solid (left diagram of Figure 261). The energy storage capacity, however, achieved in liquid desiccants, is significantly greater compared to solid desiccants (right diagram of Figure 261) [6]. The highest applicable regeneration temperature to prevent from crystallization is indicated by symbols.

The absolute values of the storage capacities of liquid desiccants are high compared to other storages used in air-conditioning systems, in general 3–5

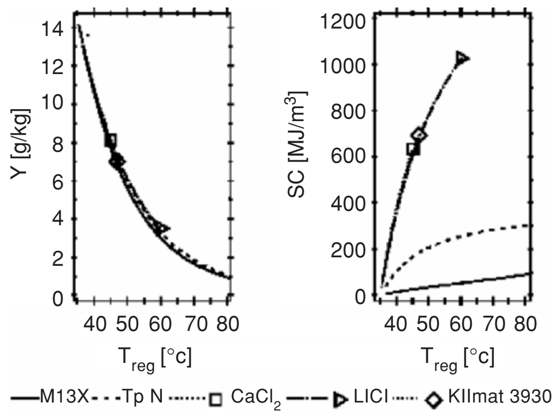

Figure 263. Dehumidification and storage capacity for different liquid and solid sorbents

times higher as the storage capacity of an ice storage. As Figure 263 shows the energy storage capacity in solid desiccants is not competitive.

In Figure 264 the dehumidification potential ΔY of a 40% LiCl–H_2O solution is plotted as a function of the air to solution mass flow ratio MR for certain operating conditions and ideal mass exchange, solid line (1). In addition the energy storage capacity SC is plotted, dotted line (2). Up to a

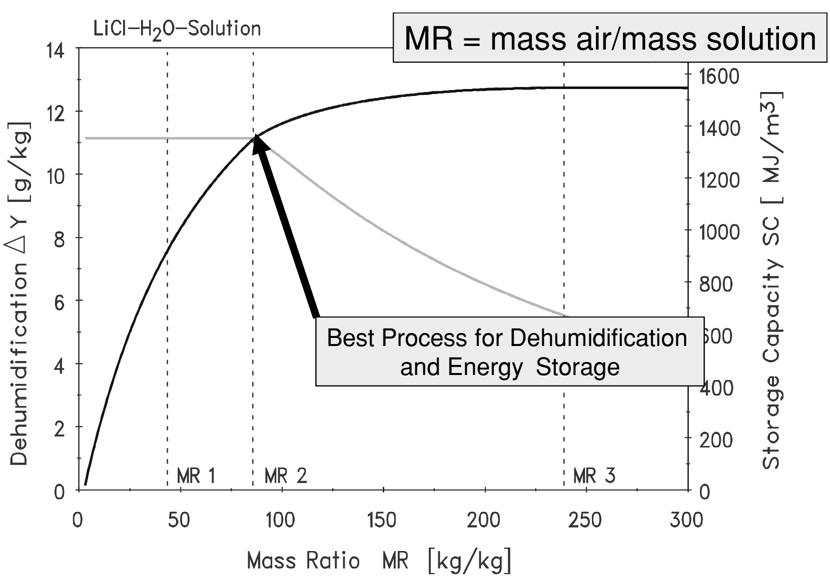

Figure 264. Air Dehumidification and energy storage capacity in an ideal absorption process as a function of the air to solution mass ratio (cooling temperature 24°C, inlet humidity ratio 14.5 g/kg, LICL–H_2O solution)

mass ratio MR 2 = 84 the theoretical dehumidification potential ($\Delta Y = 11.2$ g/kg) is not affected by the mass ratio, the solution flow is still sufficiently large to dehumidify the air. On the other hand the storage capacity increases with the mass ratio and reaches about 1,360 MJ/m^3 which is about 87% of its maximum value of 1,560 MJ/m^3 at MR 3. In ideal cooled absorption processes with 40% LiCl–H_2O solution, inlet air humidity of 12–20 g/kg and cooling temperatures of 20–35 °C energy storage capacities of about 800–14,00 MJ/m^3 are achievable. For efficient dehumidification the temperature of the absorption process and the concentration of the salt solution are of major importance, where as for high energy storage capacities a high air to solution mass ratio 50–100 is decisive [6]. High MR correspond to very small specific solution flows of about 0.2–0.5 l/(h m^2)! Therefore serious technical problems have to be solved, developing adequate exchanger surfaces which are reliably wetted by this very small solution flow in order to achieve high energy storage capacities [6, 7].

26.3. Absorption System

For solar applications, according to the reasons mentioned before: low regeneration temperature, high cooling system COP and high energy storage capacity, the ZAE Bayern suggests a liquid desiccant cooling system dehumidifying air by a small flow of a concentrated salt solution, Figure 265.

The air-conditioning system on the right hand side of Figure 6 (wet bulb temperature of dehumidified air: 15.6 °C) can be driven if concentrated e.g.

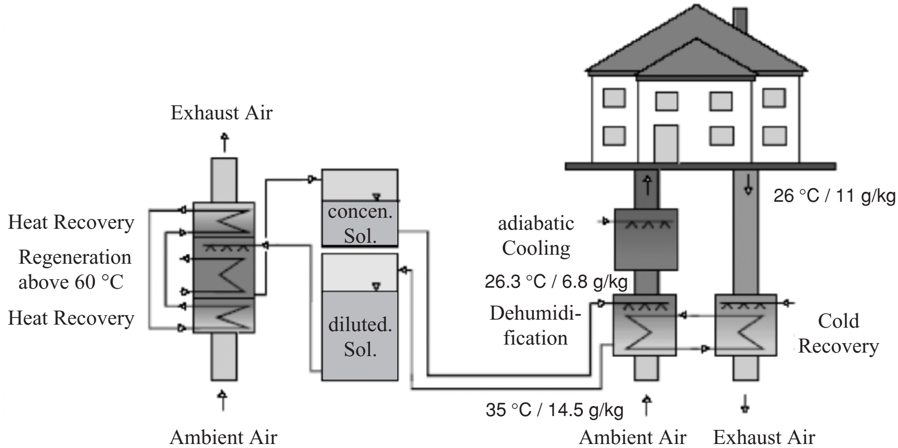

Figure 265. Example of a liquid desiccant cooling system L-DCS with energy storage in the desiccant solution

40% LiCl–H_2O solution is available. Diluting the solution to 26% an energy storage capacity of SC = 1,000 MJ/m^3 is achieved. If heat for regeneration (e.g. solar energy) is available the diluted solution can be concentrated (heat recovery 0.6). The $COP_{th}(M_{air\ cool} = M_{air\ hyg})$ is 1.1.

The absorption process is cooled by the exhaust air using an indirect evaporative cooler. A numerical example for achievable air states is given in Figure 6. Supply air and return air are coupled by a water circuit, dehumidifier and regenerator are coupled by a solution circuit. So the devices can be installed at separate locations within the building or outside. Regeneration is possible at temperatures above 60 °C under the specified ambient conditions (see Figure 265). Figure 7 shows the required specific regenerator surface as a function of the regeneration inlet temperature. Higher temperatures reduce the required surface. The optimal regeneration temperature can be found by a cost optimization analysis taking into account specific costs for collectors and exchanger surfaces.

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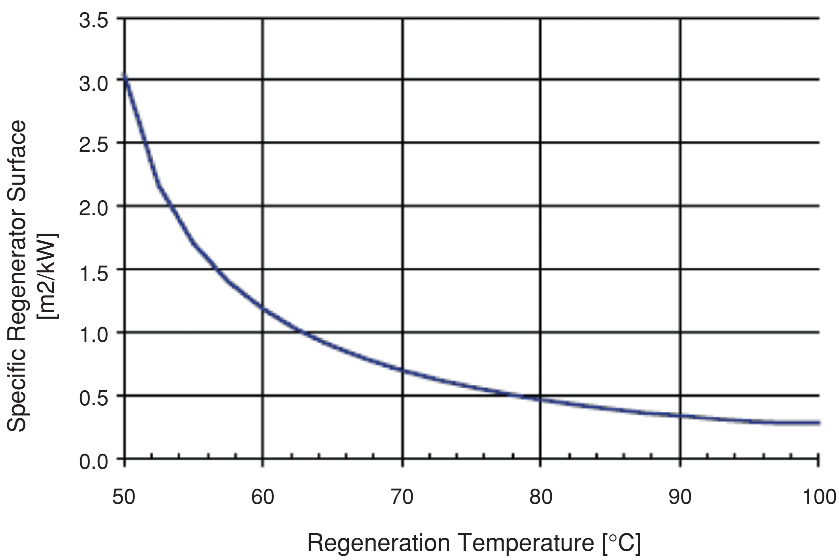

Figure 266. Specific regenerator surface as a function of the regeneration inlet temperature. According to the example of Figure 263, the diluted LiCL–H_2O solution of 26% is regenerate to 40%. The heating water is assumed to be isothermal

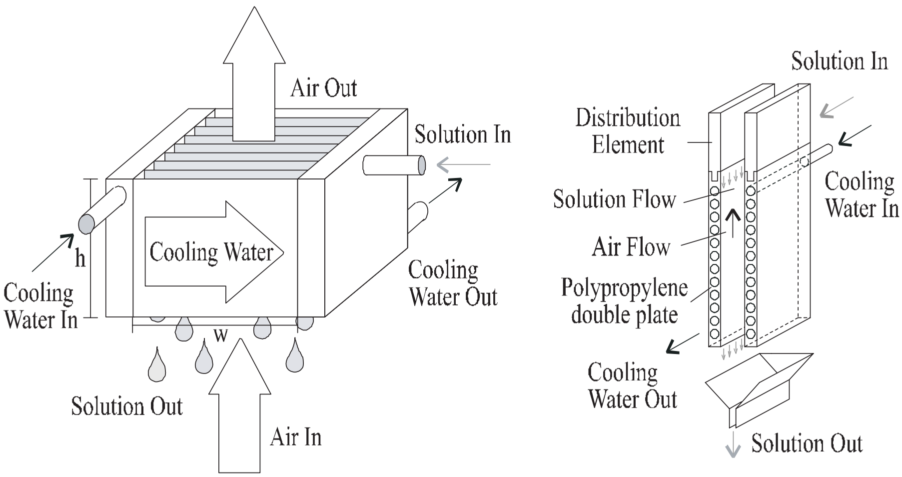

Figure 267. Ddehumidifier design and single channel exchanger design

Key component of the system is the dehumidifier shown in Figure 267. The absorptive dehumidifier has to cool the salt solution sufficiently to guarantee a low water vapour pressure. A small specific solution flow has to be distributed uniformly over the dehumidifier surfaces to achieve a high energy storage capacity. Furthermore the dehumidifier has to withstand the corrosive forces of the salt solution and has to be build of inexpensive materials which can easily be manufactured.

First prototypes have been built of separate water cooled exchanger plates, based on polypropylene double plates, which have been developed and tested within the last years. Since 1997 the tests has shown very satisfying results. A special coating of the plates and a special solution distribution element (no sprays are used) provide a uniform and almost complete coverage of the surface by the solution.

26.4. Example: Office Building Amberg/Germany

26.4.1. Abstract

An office building of 5,700 m^2 floors space has been built in Amberg, Germany, by architects Hart & Flierl for Prochek Immobilien GmbH. The innovative air-conditioning concept using solar energy has been worked out by M. Gammel engineering consultants. The comparatively low heating (35 kWh/m^2/a) and cooling demand (30 kWh/m^2/a) of the building is covered by thermally activated ceilings, assisted by appropriately conditioned ventilation air.

Well water of 12–14 °C with a cooling capacity of 250 kW is used for cooling the ceilings in summer. A solar driven liquid desiccant cooling system, developed by ZAE Bayern, dehumidifies outside air by a liquid desiccant, a concentrated salt solution, LiCl–H_2O, with a capacity of 70 kW and cools 30.000 m^3/h of supply air with a capacity of 80 kW by cold recovery from evaporatively cooled exhaust air. The liquid desiccant is regenerated by solar thermal energy from a 70 m^2 flat plate collector array at 70–80 °C with a maximum capacity of 40 kW. Solar energy for air conditioning is stored efficiently in about 10 m^3 of desiccant solution. Summer air conditioning uses only solar energy, except from electricity for pumps and fans.

26.4.2. INTRODUCTION

Prochek Immobilien GmbH in Amberg, Germany, has built an office building called the "email-fabrik", with a floorage of 5,700 m^2, see Figure 268. The building has been designed by architects Harth & Flierl in Amberg, Germany. The consulting engineers M. Gammel in Abensberg, Germany, prepared an energy saving heating and air-conditioning concept, using solar energy. Due to this concept the building should have an annual energy demand for heating as low as 35 kWh/m^2. The high comfort standard requested and the internal heat loads require air conditioning in summer. The predicted specific annual cooling and dehumidification load is about 30 kWh/m^2.

Thermally activated ceilings are used to heat and cool the building. In summer the ceilings are cooled by well water. Therefore humidity control is required to prevent humid air from condensating at the ceilings. The humidity is controlled by a solar driven liquid desiccant cooling and dehumidification

Figure 268. Office Building "email-fabrik" in Amberg, Germany

system. A special dehumidifier, developed by ZAE Bayern, using evaporative cooling from the exhaust air flow, provides high system efficiency and low desiccant regeneration temperatures, which can be efficiently delivered by economic flat plate collectors. Extremely low desiccant flow rates in the dehumidifier provide a high, non dissipative energy storage capacity in the desiccant. Thereby a high solar fraction and a maximum saving of fossil energy can be achieved. Both systems, the thermally activated ceilings and the desiccant cooling system, need only small amounts of electricity for pumps and controls. The Bavarian Ministry of Economics, Traffic and Technology has funded a demonstration project in which the liquid desiccant cooling system has been built as a prototype. The building and the active ceiling system is in use since June 2000. The solar desiccant cooling system has been installed and will start operation in spring 2003. Component tests and long-term system monitoring are planned and prepared. Details of the system concept and projected performance data are outlined in this article, the state of the project is reported.

26.4.3. THERMALLY ACTIVATED CEILINGS FOR HEATING AND COOLING

The structure of the building has been thermally activated by molding polypropylene pipes into the concrete ceilings, see Figure 269. The thermally active ceilings provide base load heating and cooling. Peak load is covered by separate air handling units for different bureau departments in the building. The hygienically necessary air flow is sufficient to deliver the additional

Figure 269. Plastic pipes are molded into the concrette ceilings for heating and cooling

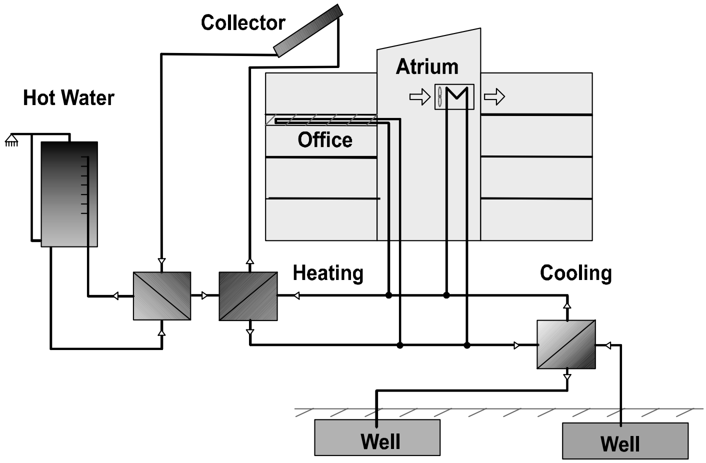

Figure 270. Sketch of the heating, cooling and hot water system, where ell water is used for cooling

heating or cooling. So, only small air channels are required. The heating is fueled by natural gas. Cooling is provided by well water.

A sketch of the system for heating, cooling and hot water production for a restaurant within the building is shown in Figure 270. The thermally activated ceilings are divided into 16 zones, the air handling system into 20 zones which allows separate cost calculation for different departments even if the division of the floor space should be changed in future. In summer the ceilings are cooled to about 18 °C. The maximum cooling capacity delivered by the well water is 250 kW.

26.4.3.1. *Solar Liquid Desiccant Cooling System*

In summer the ventilation air has to be dehumidified to keep the required comfort and to prevent from condensation at cold ceilings. The air dehumidification is done by a liquid desiccant dehumidification and cooling system, sketched in Figure 271. Warm and humid outside air is cooled and dried in a special dehumidifier by a concentrated Lithium Chloride salt solution ($LiCl–H_2O$) before it is blown into the atrium of the building. From there several air handling units draw the air into the offices and provide additional cooling on demand.

The exhaust air of the building is collected in three exhaust air handling units. Indirect evaporative coolers exploit the remaining cooling capacity of the exhaust air and cool the supply air in the dehumidifier via a water loop. This cold recovery makes the system more efficient. Depending on ambient

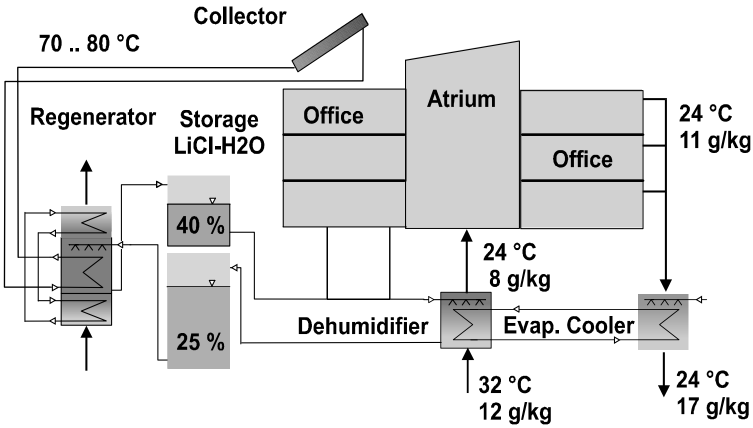

Figure 271. Air dehumidification by a liquid desiccant storage system

conditions the predicted thermal coefficient of performance of the system is 1.2–2[1]. The thermal coefficient of performance, COP, is defined as the enthalpy difference between outside and supply air related to the thermal energy used to drive the system.

A special low flow technique enables the dehumidifier to dilute the desiccant significantly when drying the air. The salt concentration changes from 40% to about 28% wt. Concentrated and diluted solution are stored separately. The dehumidification process can be operated as long as concentrated solution is available. The system of concentrated and diluted solution stores energy very efficiently. The energy storage density reaches up to about 300 kWh/m^3 related to the volume of the diluted solution. Since a chemical potential is stored, the storage is non degrading. No insulation of the storage tanks is required.

When solar energy is available the diluted solution is regenerated to its original concentration in a regenerator, at temperatures of 70–80 °C. At this temperature water evaporates from the desiccant solution and is taken to the ambient by an air flow through the regenerator. The Lithium Chloride does not evaporate. It remains in the solution and in the cycle. Heat recovery for the air flow is used to keep up the thermal coefficient of performance.

26.4.3.2. *Cooling Capacity, Solar Collector and Storage Size*

The desiccant cooling system is designed for a maximum air flow of 30.000 m^3/h. The design point for cooling is defined as 32 °C and 12 g/kg outside air state and 24.5 °C and 8.5 g/kg supply air state. Under this conditions the air cooling demand is about 80 kW the air dehumidification demand is 70 kW. A total air-conditioning capacity of 150 kW is required.

[1] In hot and humid climates the COP will be close to 1.

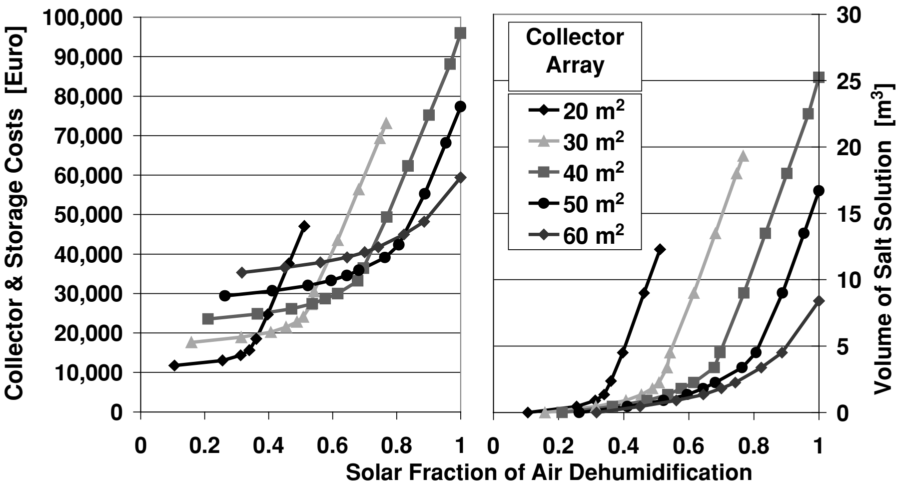

Figure 272. Investment costs of collector array and desiccant storage as a function of the solar fraction and the collector array size

The system concept demanded for a system driven solely by solar, no additional fossil fuel should be used. Therefore, the required storage volume and the investment costs for collector array and storage have been calculated as a function of collector array size and solar fraction. A computer simulation of the system has been made evaluating the seasonal performance of the system under the meteorological conditions of Amberg. Figure 272 shows the results.

On the right hand side of Figure 13 lines of constant collector array size indicate the storage volume needed to achieve a certain solar fraction. The larger the collector array size, the smaller is the required volume of the stored desiccant for a given solar fraction. The left hand side of Figure 13 shows the related investment costs. A collector array size of 60 m^2 and a storage volume of 8.5 m^3 turn out to be the most economic solution to achieve 100% solar operation.

A solar collector array of 70 m^2 of highly efficient flat plate collectors has been installed, providing a maximum thermal power of about 40 kW. Solar energy is collected during sunny periods in the early season and stored for several weeks until the energy is needed in short dehumidification periods in July and August. Separate tanks of 12 m^3 volume are used to store diluted and concentrated solution, containing 3,000 kg of Lithium Chloride salt and a varying amount of water.

26.4.3.3. *Predicted Energy Balance and Investment Costs of the Desiccant Cooling System*

The desiccant cooling system can provide up to 20 MWh per year of cooling and dehumidification energy. This includes the energy delivered by the cold recovery system. In addition to the regeneration of the desiccant solution the collector array has the potential to deliver about 11 MWh per year of hot water for the restaurant or the heating of the building. A connection to the heating system of the building, however, is not yet installed.

The necessary electrical energy for operating the desiccant system has been calculated to be about 1.5 MWh per year. Compared to a conventional system using vapor compression cooling and gas heating about 6 MWh of electrical energy and 11 MWh of thermal energy per year can be saved.

The well water cooling system provides a cooling energy of 150 MWh per year and needs about 10 MWh of electrical energy. A conventional vapor compression system would need about 50 MWh of electrical energy per year.

The total investment costs of the desiccant cooling system including collector array, cold recovery, storage, and controls have been planned to be about 300,000 Euro, this is 2,000 Euro per kW respectively 10 Euro per (m^3/h). The final costs have not yet been evaluated.

26.4.3.4. *State of the Demonstration Project*

The building is in operation since June 2000. The thermally activated ceilings and the air handling units are in operation since the beginning. With high outside air humidities in summer, however, the cooling has to be reduced to prevent from condensation at cold surfaces.

The collector array and the components of the desiccant cooling system, such as dehumidifier, regenerator, storage and desiccant handling system, have

Figure 273. 70 m^2 collector array, in the background: casing of dehumidifier and regenerator

Figure 274. Installation of the dehumidifier

been installed in 2001. The dehumidifier and the regenerator are prototypes. Figure 273 shows the collector array consisting of 70 m^2 highly efficient flat plate collectors (Wagner Eurosolar 20HT). Figure 274 shows the installation of the dehumidifier in October 2001. The dehumidifier is mounted into an air handling unit already installed on the roof of the building.

The desiccant solution has been mixed on-site from salt and water and filled into the tanks in November 2001. The heat and cold recovery system is in automatic operation since December 2001. The dehumidifier is part of this system and is used as heat exchanger in winter.

The measurement and control system of the desiccant system has been set into operation in February 2002. The collector system runs in automatic mode since March 2002 and produces hot water for the restaurant.

The liquid desiccant cooling system is designed, built and installed. A series of problems occurred and caused a significant time delay. Due to that time delay the demonstration project has to be stopped and no reliable data of the component test and the system operation could have been recorded.

26.4.4. OUTLOOK

The presented project was not able to deliver reliable data for the validation of the preliminary simulation results or the experimental results in the laboratory. In 2002 another research project has been started to investigate the cold storage for air conditioning by liquid desiccants. This project deals with cold water production for fan coil units and is integrated in the district heating net of Munich/Germany. The thermal energy from the district heat will be used for the regeneration, the charging of the TES respectively. Experimental results from that demonstration project can be expected end of 2005.

References

[1] Patnaik, S., T.G. Lenz, and G.O.G Löf, 1990, Performance study for an experimental solar open-cycle liquid desiccant system, Solar Energy, 44 (3), 123–135.

[2] Thornbloom, M., and B. Nimmo, 1996. Impact of Design Parameter on Solar Open Cycle Liquid Desiccant Regeneration Performance, In Technical Papers Solar 96, Ashevill, USA, American Solar Energy Society, pp. 107–111.

[3] Ameel, T.A., K.G. Gee, and B.D. Wood, 1995. Performance predictions of alternative low cost absorbents for open-cycle absorption solar cooling, Solar Energy, 54 (2), 65–73.

[4] Beckmann, J., and W. Albers, 1996. Air Conditioning and Dehumidification by a Lithium Bromide/Lithium Chloride Liquid Desiccant Technology, In Ab-Sorption 96,, International Ab-Sorption Heat Pump Conference, Natural Resources Canada, Quebec, Canada, pp. 697–702.

[5] Laevemann, E., and R. Sizmann, 1992. Energy Storage in Open Cycle Desiccant Cooling Systems, Comparison of Liquid and Solid Desiccants, In Solid Sorption Refrigeration, IIR Congress, Paris, International Institute of Refrigeration, pp. 270–275.

[6] Kessling, W., 1997. Luftentfeuchtung und Energiespeicherung mit Salzlösungen in offenen Systemen, Dissertation, Albert-Ludwigs-Universität Freiburg, LS Prof. Luther.

[7] Lowenstein, A.I., and Gabruk, R.S., 1992. The effect of absorber design on the performance of a liquid-desiccant air conditioner, ASHRAE Transactions: Symposia, pp. 712–720.