MODESTORE

DELIVERABLE D3:

EVALUATION REPORT OF WP2

MONITORING AND EVALUATION OF THE 1ST GENERATION SYSTEM INSTALLED IN AUSTRIA

AEE INTEC

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1 Summary

In this workpackage, the Austrian 1st generation sorption system built within the EU-HYDES project was put back into operation. Then, a detailed analysis of the system was carried out with the goal to gain information useful for a re-design of the system leading to a 2nd generation prototype system that will be developed in workpackage 4.

Numerous adsorption and desorption test runs were carried out during this analysis. The test runs showed how difficult it is to accurately determine the current charging level of the adsorber. However, for a detailed analysis it is important to know the charging level. The experiences made with the 1st generation test setup led to an improved design of the test facility that will be used for the 2nd generation tests in workpackage 4.

In addition, a numerical simulation model was developed and validated with the experimental data collected in this workpackage. The model shows quite good agreement with the measured data. However, it will have to be validated again and adjusted to the 2nd generation system as soon as data are available including reliable charging level values.

The experiences made during the monitoring and evaluation of the 1st generation system as well as in the HYDES project have led to the 2nd generation prototype system as described in Deliverable D6. The main result is to include both the adsorber and the evaporator/condenser unit in a single container. The reason for that is to decrease the distance that the water vapor has to travel between the components and to increase the cross area that is available for vapor transport.

2 Introduction

The system installed in Austria in the framework of the HYDES project has been operated and monitored in this work package. The system had already been tested within the HYDES project and first charging and discharging cycles have proven the suitability of the installation for long-term heat storage purposes. The tests showed that long-term heat storage using solid sorption processes with water vapor as working fluid is technically feasible.

The aim of this workpackage was to run a test and evaluation program to study the performance of the installed system in more detail. The results of these measurements have been used for the design of the 2nd generation prototype system to be developed in WP4 as well as for the development of control strategies to be used for both the laboratory testing of the 2nd generation prototype in WP4 and the field test in WP6.

Task 2.1: Testing and monitoring

In this task test runs for specific operation modes were defined and carried out. Detailed experimental data of all tests were obtained. The experiences with the 1st generation test facility was used not only to design the 2nd generation system itself but also the experimental setup that will be used for the 2nd generation laboratory test in WP4.

Task 2.2: Analysis and evaluation

The obtained experimental data were analyzed and evaluated regarding energy flows, temperature and charging level achieved. Recommendations for the design of the next generation prototype as well as for the experimental setup for the next generation laboratory tests were formulated.

3 Basic Principles of an Adsorption Heat Storage System

In sensible and latent heat storage devices heat is stored together with its corresponding amount of entropy. In these so-called direct heat storage media, heat – i.e. energy – is transferred directly to the storage medium. The achievable energy density is limited by the entropy storage capacity of the material. Adsorption is a reversible physico-chemical process suitable to store heat in an indirect way. This kind of thermal storage allows to separate energy and entropy flow. The storage capacity is not limited by the maximum of entropy intake. The energy density can be much higher if entropy is not stored directly in the medium. Therefore, a heat source and a heat sink are necessary during both the charging and discharging process to withdraw or collect the necessary entropy. The storage works like a heat transformer on the principle of a chemical heat pump. During adsorption of water vapor, a phase change occurs between vapor and liquid phase on the surface of a porous solid (In this project silica gel has been used). The released adsorption enthalpy consists of the evaporation enthalpy of the working fluid and the bond energy of the adsorption pair.

The working principle involves several different phases illustrated in figure 1.

1. **Charging process (desorption, drying of silica gel):** heat from a high temperature source is fed into the device, heats the silica gel and vapor is desorbed from the silica gel. The desorbed vapor is led to the condenser and condensed at a lower temperature level. The heat of condensation has to be withdrawn to the environment.
2. **Storage period:** the dry adsorbent is separated from the liquid working fluid (the connecting valve is closed). As long as these components stay separate heat storage without losses is possible if the sensible heat involved is neglected.
3. **Discharging process (adsorption, loading of silica gel with water vapor):** the valve between the evaporator and the adsorber is opened. The liquid working fluid evaporates in the evaporator taking up heat at a low temperature level. The vapor is adsorbed and releases the adsorption heat at a higher temperature level. This is the useful heat.
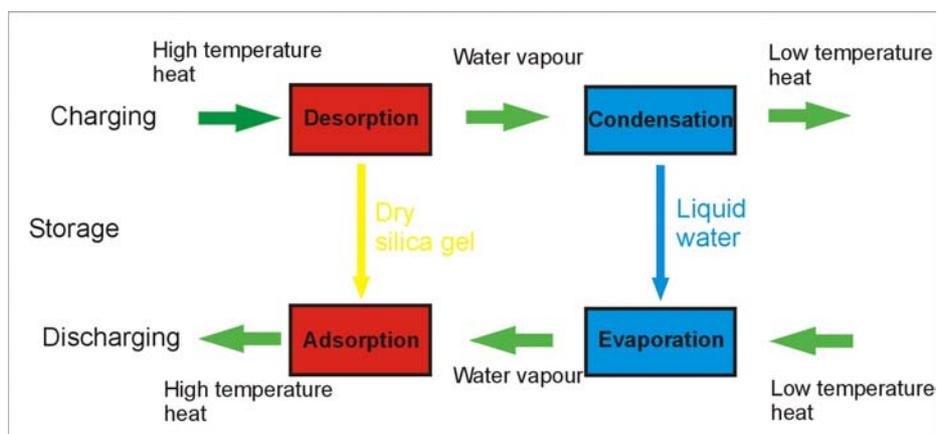

Figure 1: Working principle of an adsorption heat storage

Several quantities and process parameters are important when the potential energy density of a sorption pair for heat storage applications is evaluated. The main ones are:
1. **Temperature lift:** It depends on the current charging level of the sorbent and is a material property.
2. **Adsorption enthalpy:** It consists of the evaporation enthalpy of the working fluid and the bond energy of the adsorption pair.
3. **Sensible process and heat management:** An intelligent system design and process management along with good insulation is essential.
4. **Energy density:** The stored energy per unit volume is the quantity of primary interest. It is the product of specific energy (energy per mass of sorbent) and the bulk density ρ_s.

After due consideration, the process of thermo-chemical heat storage with the adsorption pair silica gel and water was selected. Silica gel is a very porous substance with a large inner survace. The material consists mainly of SiO_2 and is produced by condensation of aqueous silicic acid. The equipment installed in the laboratory of AEE INTEC in Gleisdorf/Austria is filled with commercial silica gel GRACE 127 B. This silica gel consists of spherical particles with a diameter of two to three millimeters. Its bulk density is 790 kg/m^3, the interior surface is 650 m^2/g. The system is evacuated to enable water vapor transport without use of mechanical energy. The vapor pressure adds up to 10 to 50 mbar in the system.

4 Mass and Energy Balances

Figure 2 shows the mass balance of a sorption storage system in schematic terms. The left rectangle represents the adsorber container, the right rectangle the evaporator/ condenser container. The mass balance is now fairly simple: In desorption mode, water vapor is transferred from the adsorber to the evaporator/condenser, in adsorption mode water vapor is transferred in the opposite direction. Because of the mass transport the state variables in the control volumes (see dashed rectangles) change: the water content m in the evaporator/condenser container and the charging level x in the adsorber container.
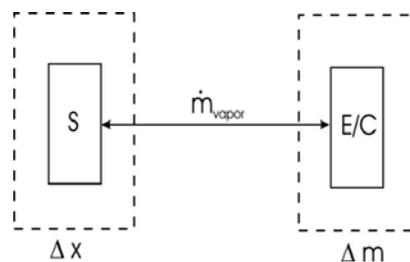

Figure 2: Mass balance for the sorption storage system

The energy balance is slightly more complicated. There are more terms involved and some of the terms depend on the amount of water that is transferred between the containers.

Figure 3 shows this energy balance for a sorption storage system. Some terms only occur in adsorption mode, others only in desorption mode.

The energy balance of the adsorber container in desorption mode includes the following terms. The adsorber is heated by the collectors (Q_{coll}). The water vapor leaving the adsorber, contains internal energy (U_m) and its heat of adsorption (Q_{ads}) that was needed to desorb the water from the silica gel. The heat of adsorption consists of the bond energy and energy needed to evaporate the water molecules during the desorption process. The heat of evaporation needed for the desorption of water vapor molecules depends on the current charging level of the silica gel (the so-called characteristic curve).

The water vapor entering the evaporator/condenser container contains its internal energy (U_m) and its heat of evaporation (Q_{ev}). In this case the heat of evaporation is a thermodynamic property for bulk water vapor which is not the same value as the heat of evaporation for real adsorbates needed in the desorption process. The energy withdrawn from the condenser (Q_{cond}) leaves the evaporator/condenser container.

In adsorption mode, the evaporator is heated by the collectors (Q_{coll}), at the same time heat is withdrawn from the adsorber to the load (Q_{load}). The energy transferred by the water vapour is the same as in the desorption mode.

In both operating modes, there will be losses to the environment from both containers. The state variable for the energy balance is the internal energy of each container (U_s and $U_{e/c}$) which depend on the energy and mass transport.
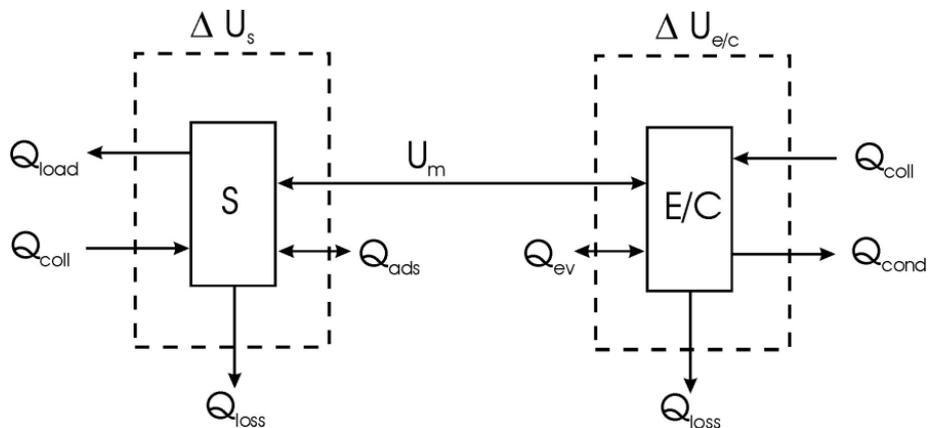

Figure 3: Energy balance for the sorption storage system

5 Test Facility

5.1 System

The first generation prototype system (see Figure 4) has been installed in the laboratory of AEE INTEC in Gleisdorf/Austria. The system consists of two adsorbers and one evaporator/condenser container. The three containers have a nominal volume of 1.25 m^3 each. Each of the two adsorbers is filled with 1.1 m^3 of silica gel (Grace 127 B) and is equipped with an internal heat exchanger. For the adsorber heat exchangers, spiral plate heat exchangers were used. The evaporator/condenser contains two plate fin heat exchangers of different size located in the upper (condenser) and lower (evaporator) part of the container.

The adsorbers and the evaporator/condenser container are connected by a vacuum pipe that contains electro-pneumatic valves that can close each of the three containers separately. Pressure sensors are installed in the connecting pipe so that the pressure in the respective container can be measured when the valves to the other containers are closed.

The hydraulic system consists of two distribution manifolds. There are two heat sources (a solar thermal collector and an electrical flow heater) and three heat sinks (low temperature heat delivery system in a test apartment, 300 l - hot water boiler in the test facility and a rain water cistern) available. Figure 5 shows the four individual components in schematic terms as well as the heat flows between components.
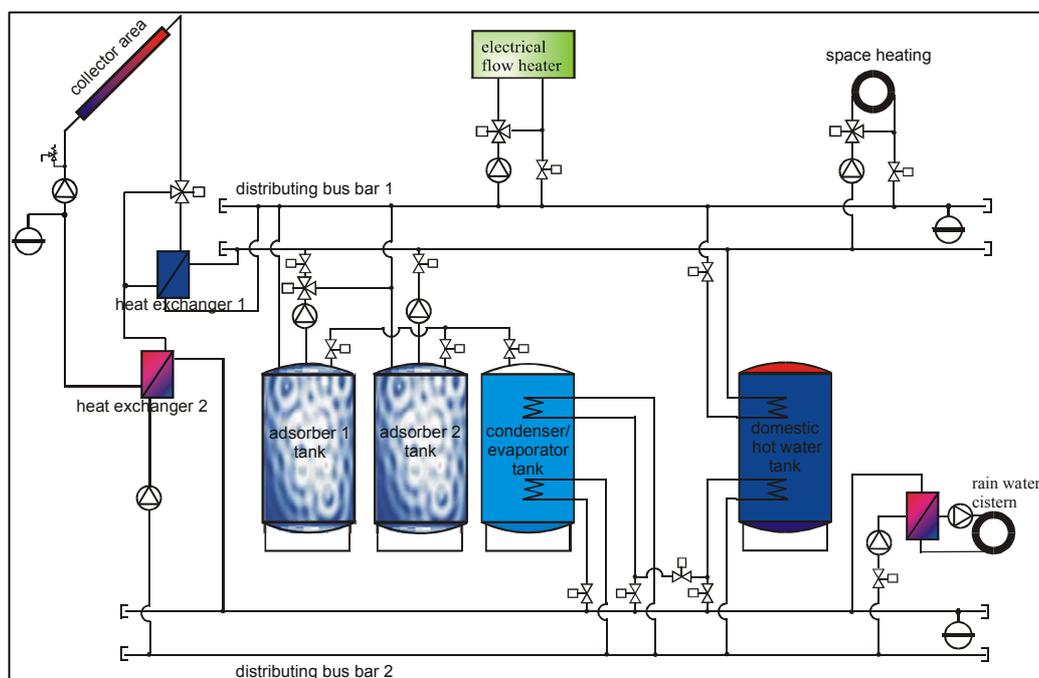

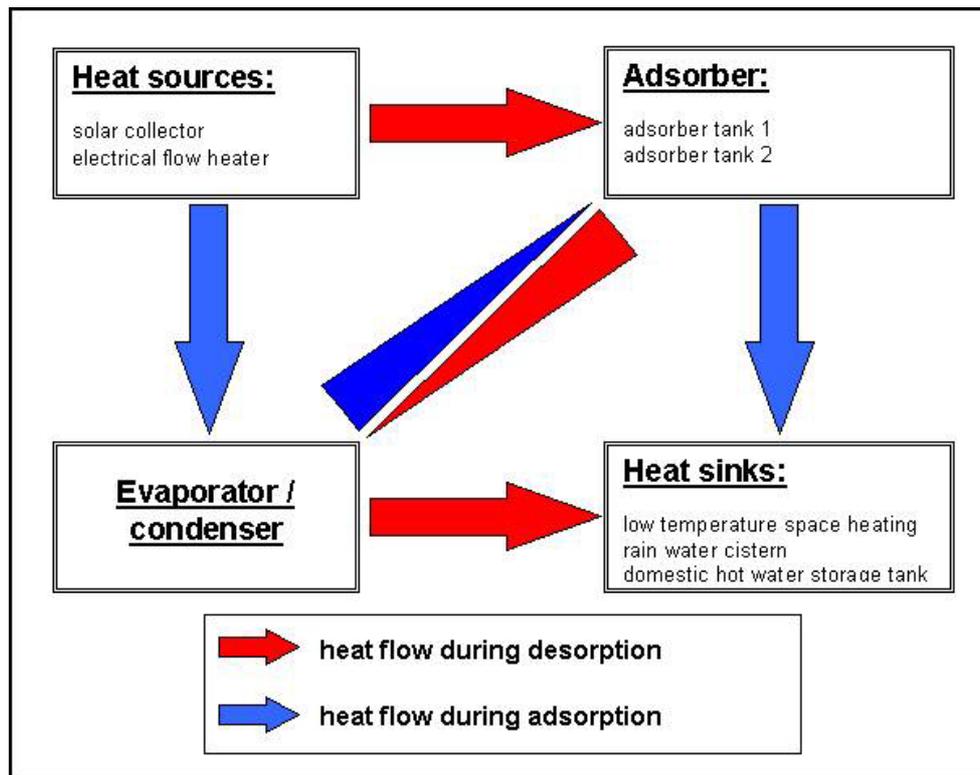*Figure 4: Hydraulic scheme of the experimental setup*

Figure 5: Scheme of the sorption system

5.2 Data Acquisition

At the sorption storage test facility, a large number of physical quantities of the system is recorded.

The data are recorded as 5 min-average values for temperature and pressure measurements. Volumetric flow rates are measured using a pulse counter.

The following data were measured:
- flow and return temperatures in all hydraulic circuits
- temperatures in four different locations of the silica gel fill
- temperatures in the liquid and the vapor phase in the evaporator/condenser container
- volumetric flow rates in all hydraulic circuits
- pressures in the connecting vacuum pipe
- liquid level in the evaporator/condenser container

A data logging and control system supplied by the Austrian company Bernecker and Reiner (B&R) is used (type B&R 2003).

5.3 Changes since the HYDES measurements

The first measurements conducted in WP2 showed inconsistencies in the temperature measurements in the different circuits. Therefore all temperature sensors were replaced.

A second pressure sensor with a higher accuracy has been installed in parallel to the existing pressure sensor in the vacuum connection pipe between the stores. The new sensor has a higher accuracy but a reduced measuring range between 0 and 50 mbars. It is therefore better suited to measure equilibrium pressures in the adsorber tanks at low charging levels.

5.4 Control System

The data logging system by B&R has been used as a controller for the automatic operation of the system. This way all measured temperatures and pressures were available as inputs for the controller.

The following control tasks have been implemented:
- Switching on and off of pumps
- Switching of electromagnetic and electro-pneumatic valves

The control strategies that were used for the test runs, are described in more detail in the respective chapters below.

5.5 Experimental Setup

The test runs were all carried out using an electrical flow heater as energy source rather than solar thermal collectors. The reasons for this are on one hand the unfavorable local weather conditions during most of spring and summer 2004 and on the other hand the advantage of constant and reliable temperature conditions.

A drawback of using the electrical flow heater in the current setup are the maximum achievable adsorber temperatures of around 90°C. A solar collector would be able to reach higher temperatures on a clear day. Therefore, the test facility for the 2nd generation system will be modified to be able to reach higher temperatures in the adsorber.

The energy sink used in the experiments was the 300 l-storage tank that can be cooled using the rain water cistern or fresh water if necessary.

5.6 "Measurement" of the Charging Level of the Adsorbers

To analyze the experimental data, it is important to know the charging level of the silica gel at least at the start and end of each test run. Even better would be to know the development of the charging level throughout the test.

Unfortunately, it is not possible to measure the charging level directly. There are two possibilities to determine the current charging level during a test run. The first possibility is to measure the pressure and temperature in the adsorber at equilibrium conditions. The second possibility is to determine the change in charging level by measuring the change in liquid level in the evaporator/condenser tank.

5.6.1 Equilibrium Conditions

If a closed container contains only silica gel and water vapor, the system reaches a state of equilibrium with temperature, pressure and charging level as state variables. That means if the system is in the equilibrium state, it is sufficient to measure the temperature and the pressure to determine the charging level of the silica gel.

Figure 6 shows isobars for a system silica gel / water vapor in equilibrium at different vapor pressures. If the system is at room temperature (20°C) and almost completely dry, the equilibrium pressure is in the order of 1 mbar. Therefore, the pressure measurement has to be very accurate. A measurement error of 2 mbars means an error in charging level of several percentage points. Another source of error is the fact that it is not possible to exclusively measure vapor pressure but only total pressure. If there are small amounts of inert gases in the system that are not detrimental to for the proper functioning of the system, they can still amount to an additional few mbars of total pressure and therefore hamper the precice vapor pressure measurement.
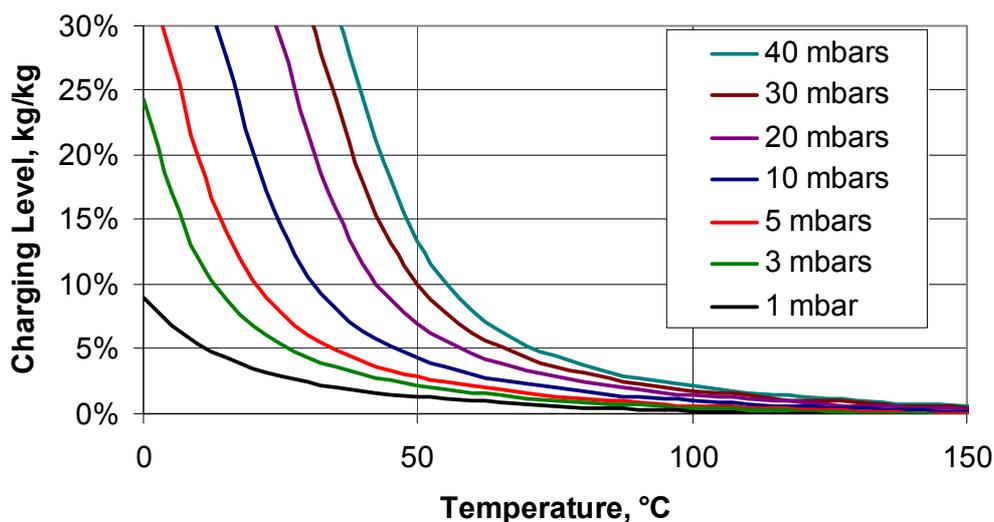

Figure 6: Isobars of silica gel GRACE 127 B at different vapor pressures

The first test runs were conducted in a way to allow a relaxation period of at least 10-12 hours between tests in order to reach equilibrium conditions before and after each test run. The measurements revealed that even after long relaxation periods the equilibrium state had not been reached in most test runs. In addition, the problems with potential inert gases and an insufficient measurement accuracy mentioned above led to the conclusion that it is not possible to accurately determine the charging level simply by measuring temperature and pressure in the adsorbers.

5.6.2 Liquid Level Sensor

In the HYDES project a capacitive liquid level sensor had been installed in the evaporator/condenser container. The sensor has an output signal of 4 to 20 mA and is equipped with a protective coating for vacuum applications. Figure 7 shows a schematic drawing of the liquid level sensor arrangement.

The reason for installing a liquid level sensor was to quantify the amount of water transferred from the adsorber containers to the evaporator/condenser container or vice versa. This should allow to determine the change in charging level of the adsorber.
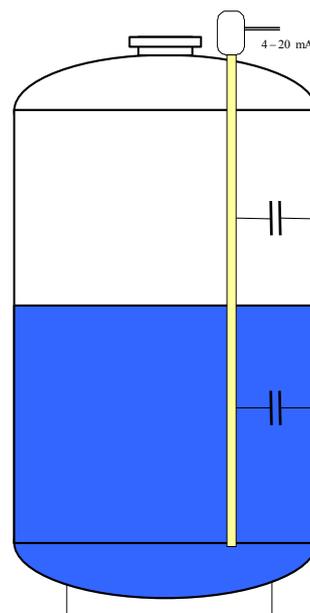

Figure 7: Scheme of the liquid level sensor installed in the evaporator/condenser container

Preliminary test runs showed that the measured amount of energy in and out of the system did not match the measured amount of water transferred from one container to the other when using the liquid level sensor.

A possible explanation for this phenomenon was that the sensor reading depends on the temperature and/or pressure of the water vapor in the evaporator/condenser container and therefore on the amount of water vapor in the space above the condensed liquid. The capacity reading was therefore gauged by liters to verify this assumption.

Figure 8 shows the measured temperatures, pressures and changes in liquid level during the test of the liquid level sensor. During the test, the vapor valves of the two adsorbers were closed. At the beginning of the test, the evaporator/condenser container was evacuated and the temperature in the liquid phase was 26.5°C. Then the container was opened completely to the ambient. The pressure was increased to ambient conditions but there was no significant change in level sensor reading. The pressure alone is obviously not the factor causing a false level sensor reading.

To calibrate the capacity reading manually, a defined volume of liquid (24 l) was added to the tank. While the container was still open to the ambient, the liquid level sensor recorded a change in liquid level of 23.5 l which is within the accuracy of the sensor. Consequently, the container was evacuated which – again - resulted in an only insignificant change in liquid level.

As a final test, the evaporator/condenser was heated to 35°C using the evaporator heat exchanger at the bottom of the tank. This caused a small amount of water to evaporate and therefore increased the vapor pressure above the liquid phase. Although only a very small amount (below the accuracy of the sensor) was evaporated the liquid level reading decreased by about 3.7 l. Apparently, the vapor pressure in the evaporator/condenser has a significant impact on the liquid level sensor reading.
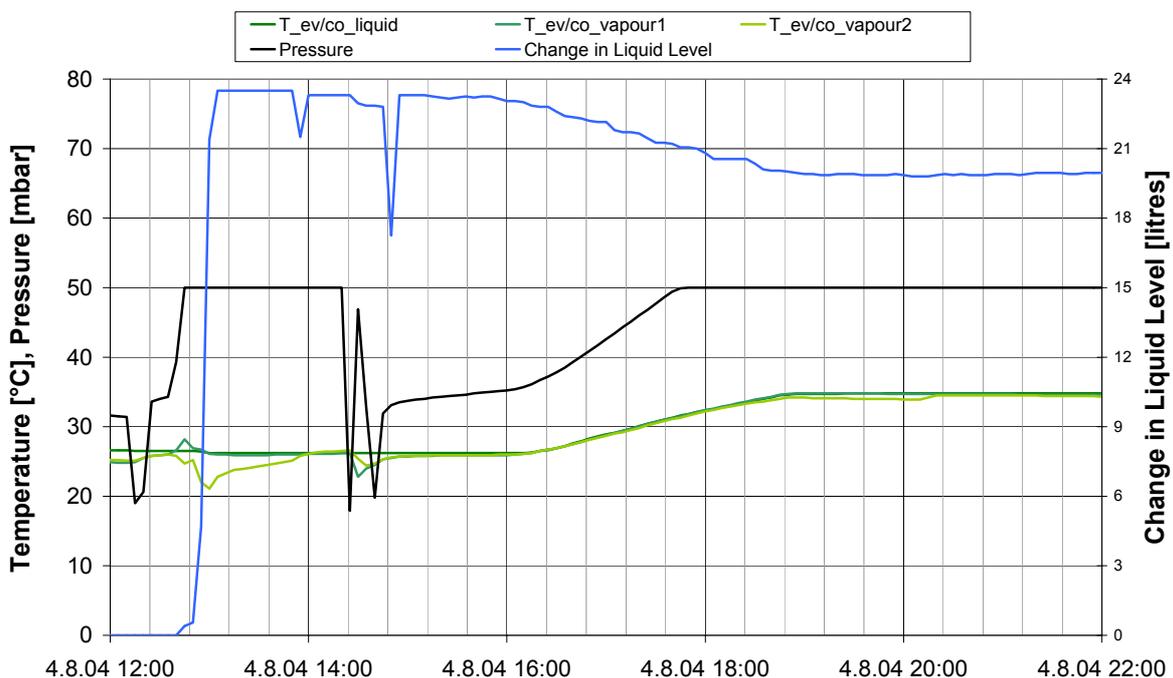

Figure 8: Test of the capacitive liquid level sensor

5.6.3 Conclusions

As a result of the findings during the preliminary tests, at the end of each test run the evaporator/condenser container was brought back to its initial conditions (the temperature and pressure conditions it had before the start of the experiment). This way the change in liquid level from the start to the end of a test run is known but no reliable information on the liquid level and therefore the charging level throughout the test is available.

The mass of transferred water vapor obtained with this method matches the measured energies in and out of the system during the test significantly better than it was the case before. This means that it is now possible to determine the amount of water vapor transferred during a test run with a reasonable accuracy. However, an exact energy balance of a test run requires the knowledge not only of the transferred water vapor but also the absolute value of the charging level during the test. The reason for that is that the amount of bond energy consumed or released depends strongly on the current charging level of the system.

These experiences made during the monitoring phase of the 1st generation system have been used for an improved design of the experimental setup for the laboratory measurements of the 2nd generation system: There will only be one adsorber which will be completely dried before the start of the laboratory tests. This way the charging level will be known with a reasonable accuracy. During the actual tests, the water reservoir that stores the condensate will be weighed continuously. This allows to determine the change of water level and therefore charging state with a much better accuracy than with the liquid level sensor used for the 1st generation system.

6 Store Losses

For a good analysis of the test runs it is important to know the store losses of the adsorption containers and the evaporator/condenser container. The evaporator condenser container was operated at a temperature not significantly above ambient temperature. Therefore, these store losses were considered to be negligible.

The store losses of the adsorber tanks were measured by cooling the store down with the steam valve closed and no flow in the adsorber heat exchanger (see Figure 9). The heat loss depends on the logarithmic temperature difference and the UA-value as follows:

$$\frac{Q}{t_{end} - t_{start}} = UA \cdot \frac{T_{end} - T_{start}}{\ln \frac{\Delta T_{start}}{\Delta T_{end}}}$$

with $Q = m_{silica\,gel} \cdot (c_{p,silica\,gel} + x \cdot c_{p,water}) \cdot (T_{end} - T_{start})$
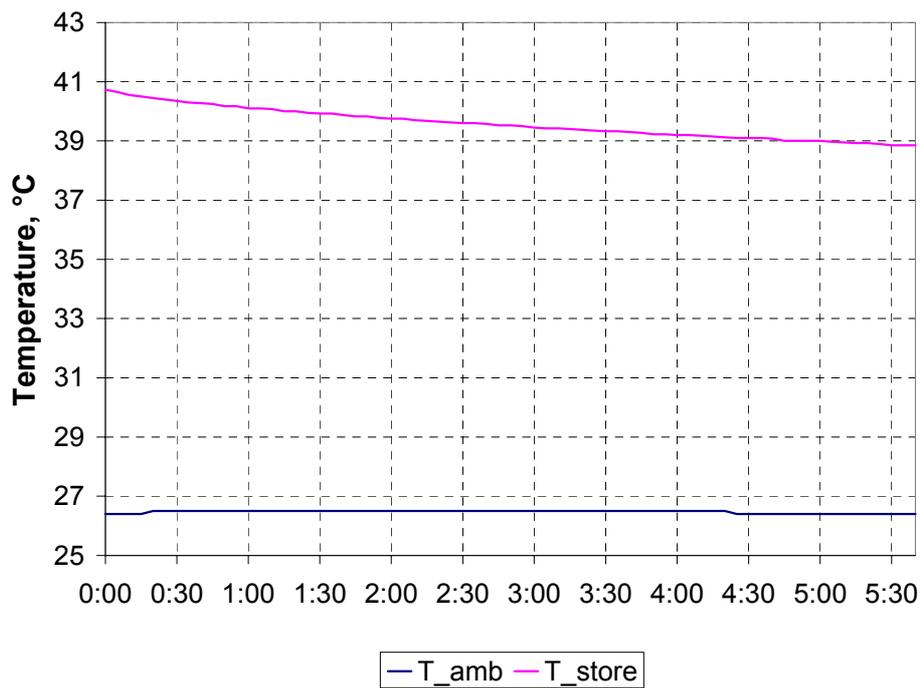

Figure 9: Measurement of the storage losses of the adsorption tank

The UA-value was found to be approximately 6.3 W/K which is a typical value for storage tanks of this size.

7 Adsorption Test Runs

Adsorption is the operation mode that takes place in the winter months in a seasonal storage application. The collectors deliver energy to the evaporator generating water vapor that adsorbs on the silica gel. The released heat can then be withdrawn from the adsorber to the load. Numerous adsorption cycles were carried out during spring and summer 2004.

7.1 Control Strategy

The adsorption test runs were carried out using a constant set temperature for the adsorber, a constant volume flow rate to the load and a constant return temperature from the heat sink. The adsorber temperature was controlled by opening and closing the designated valves between the adsorber and the evaporator. As long as the adsorber temperature is above the set temperature, the valves stay closed. If the temperature goes below that temperature, the valves open. In addition, a hysteresis of 1 K was used in the control cycle of the adsorber temperature as well as the return temperature from the load.

The electrical flow heater was used to heat the evaporator. An constant flow temperature was used. The flow in the evaporator was controlled to maintain a constant temperature of the liquid in the evaporator/condenser container.

7.2 Measurement results

The goal was to maintain a constant adsorber temperature of 40°C. This is about the maximum value that can be expected in a real application with a design flow temperature for the space heating loop of 35°C. The return temperature was controlled to be approximately 31°C with a hysteresis of 1 K. The average heat load withdrawn from the adsorber was 1.5 kW.

The evaporator was heated to maintain a constant liquid temperature of 25°C. Figure 10 shows an adsorption cycle under these conditions as an example.

The dotted line in Figure 10 shows the opening and closing of the steam valve. A value of 10 means that the valve was open during the entire measuring time step, 0 means it was closed.

During the first eight hours of the measurement, the adsorber temperature was maintained at 40°C by opening and closing of the steam valve. Subsequently, the adsorber temperature fell below 40°C and the steam valve remained continuously open. The flow temperature to the load was kept at about 34°C during most of the test run. Only at the end it decreases to about 33°C. The return temperature is kept at 31°C with the set hysteresis of 1K. The liquid temperature in the evaporator/condenser tank is kept very constant at just below 25°C.
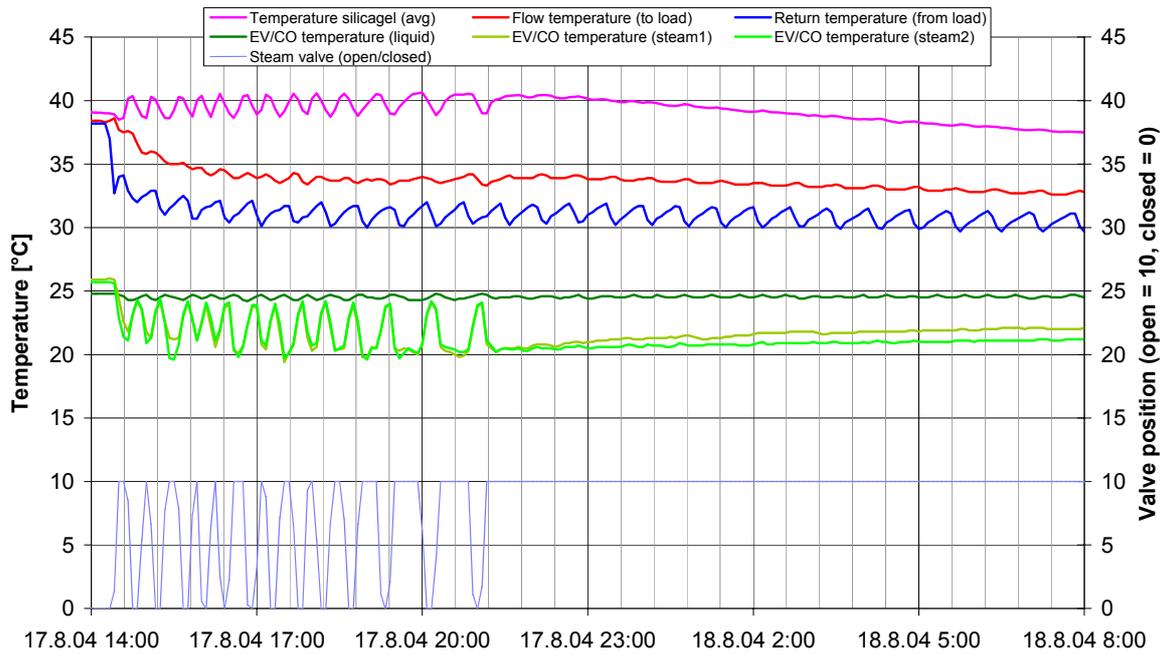
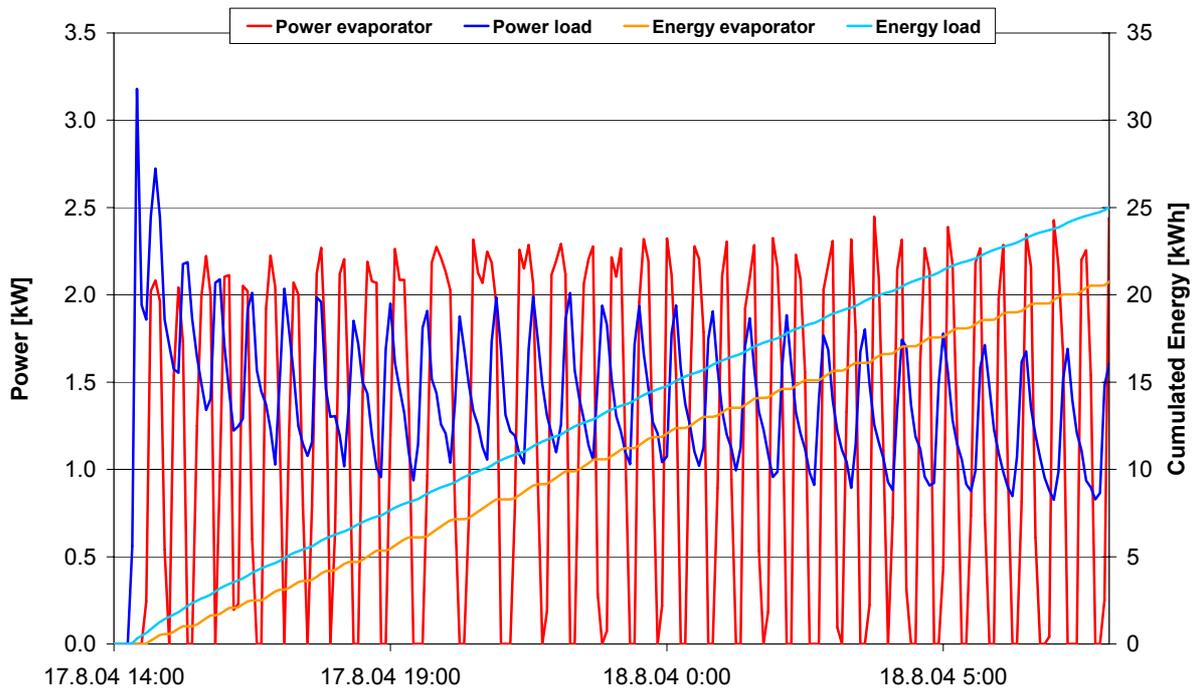*Figure 10: Measured temperatures during an adsorption cycle*

Figure 11: Measured power and cumulated energy during an adsorption cycle

Because of the fairly high hysteresis for the return temperature from the load, the power going to the load oscillates between 1 and 2 KW (see Figure 11). The power transferred by the evaporator varies between 0 and 2.3 kW.

7.3 Interpretation of Results

The adsorber was well desorbed before the start of this experiment. However, because of the problems with the charging level measurement, we do not know the exact value of the charging level. From the material properties of Silica gel GRACE 127 B the charging level that can be reached with a given adsorber and evaporation temperature can be calculated. An adsorber temperature of 40°C and an evaporation or steam temperature of 25°C corresponds to a charging level of approximately 18 %.

The change in charging level measured during the test was 3.7%. Assuming a start charging level of 4.5% leads to a final charging level of 8.2%, i.e. far away from the theoretical value of 18%. That means that is should still be possible to adsorb more water vapor under the given temperature conditions.

7.3.1 Measurement of the Liquid Temperature

One reason for this is that the vapor temperature measured in the evaporator/condenser container is approximately 4-5 K lower than the temperature measured in the liquid phase as shown in Figure 10. The temperatures in the vapor phase are measured at the outlet of the container and the other one a little bit lower next to the condenser heat exchanger. The vapor phase temperatures increase each time the steam valve is closed but decrease again when the valve is opened. The liquid phase temperature is not measured at the surface of the liquid volume but somewhere below. While the temperature at the surface of the liquid is at the same temperature as the vapor phase above, it is well possible that the temperature in lower layers of the liquid is above that value knowing that the liquid phase is not heated at the surface but the evaporator is located further down in the liquid volume.

That means that there is not 25°C steam available but only around 21°C. Calculations with the material properties shows that with 21°C steam a charging level of 15% should be reach which still far above the value that was actually reached.

7.3.2 Energy Balance

Figure 11 shows the cumulated energies in and out of the system during the measurement period. One can see that over the entire period, more energy has been withdrawn to the load than was added to the evaporator/condenser container. Knowing that the bond energy released by the adsorption of water vapor on silica gel is only in the range of 3 kWh for 30 kg of steam and there is also a store loss from the adsorber of approximately 1 kWh, it is clear that not enough water vapor has been adsorbed to be able to maintain the adsorber temperature of 40°C. That means the vapor pressure in the evaporator/condenser container was not high enough to allow enough water vapor to be transferred to the adsorber. A possible explanation for this is a relatively high pressure drop between the evaporator and the silica gel particles. The pressure drop in the connecting pipe is negligible as long as the system is evacuated. Inert gases can

increase the pressure drop significantly and thereby hamper the vapor diffusion in the pipe. In addition, the pressure drop in the silica gel packing is a factor that has considerable influence on the mass transport between the stores.

7.3.3 Conclusions for the Design of the 2nd Generation Prototype

Non-ideal vapor diffusion between the containers is also a possible explanation why the theoretically expected charging level could not been reached in the practical test runs. To improve this situation, the 2nd generation system has been designed to include both the evaporator and the adsorber in a single container. This way, the distance that the vapor has to travel from the evaporator to the adsorber is much smaller and cross-section through which the vapor has to travel is much larger. With this construction, the contact between water vapor and silica gel is much more direct and the temperatures needed for evaporation are expected to be much smaller (closer to the theoretical values).

7.4 Comparison with Simulation Model

A simulation model based on the mass and energy balances described above was developed. In the simulation environment TRNSYS (TRNSYS – A transient system simulation program, University of Wisconsin-Madison), two new components were developed representing the adsorber container and the evaporator/condenser container respectively.

To be able to make reliable performance predictions, the model has to be validated with the adsorption and desorption measurement cycles. For an adsorption cycle, the measured load withdrawn from the adsorber and the measured power input to the evaporator were used as inputs. In addition, the initial values of the state variables have to be known, i.e. the temperatures of the containers, the water mass in the evaporator/condenser and the charging level in the adsorber.

In adsorption mode, the amount of water vapor transferred to the adsorber is calculated using the additional internal energy needed to keep the adsorber at the desired temperature (ΔU_s) and dividing by the specific energy content of the water vapor (internal energy u_s and heat of adsorption q_{ads}).

$$\overset{\bullet}{m}_{vapor} = \frac{\Delta U_s}{u_s + q_{ads}}$$

The development of the state variables (temperatures, charging level) was calculated and compared with the measured values. The dotted lines are the calculated values in Figure 12.
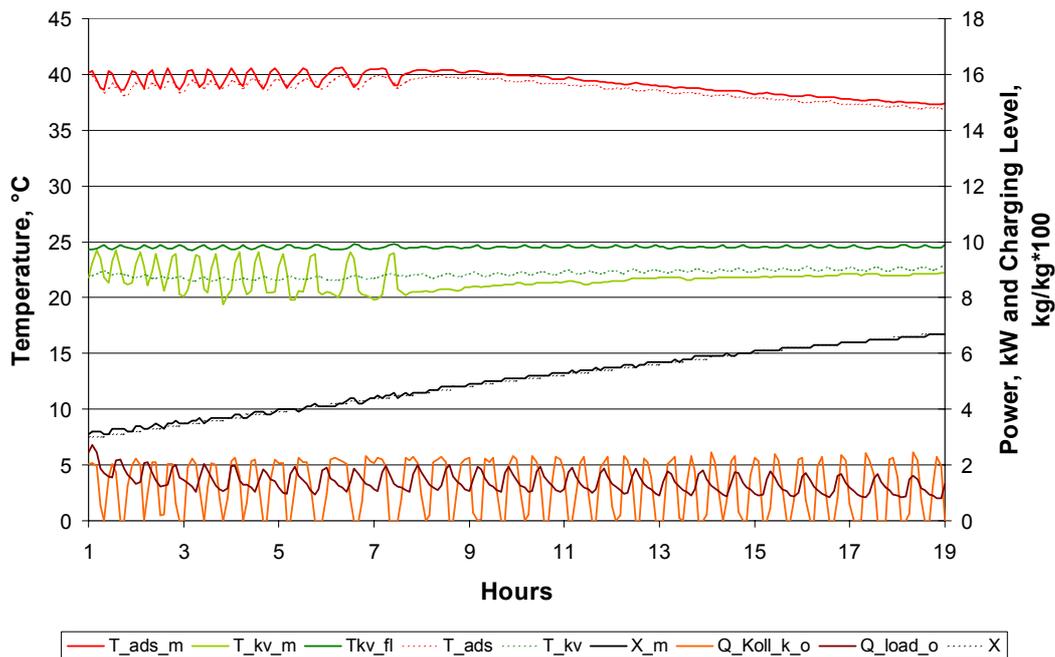
Figure 12: Validation of the simulation model in adsorption mode

Because the exact value of the charging level is not known, the simulation was run using different values for the initial value for the charging level. The simulation run shown in Figure 12 is one which showed quite good agreement with the measured values. Because the adsorption energy per unit mass of transferred water vapor depends on the current charging level of the silica gel during the test. A simulation run using a higher initial value for the charging level is shown in Figure 13. Here, the calculated temperature in the evaporator/condenser decreases continuously (see grey lines) throughout the simulation which was not the case in the test. This shows that the energy balance fits much better for lower initial charging levels.
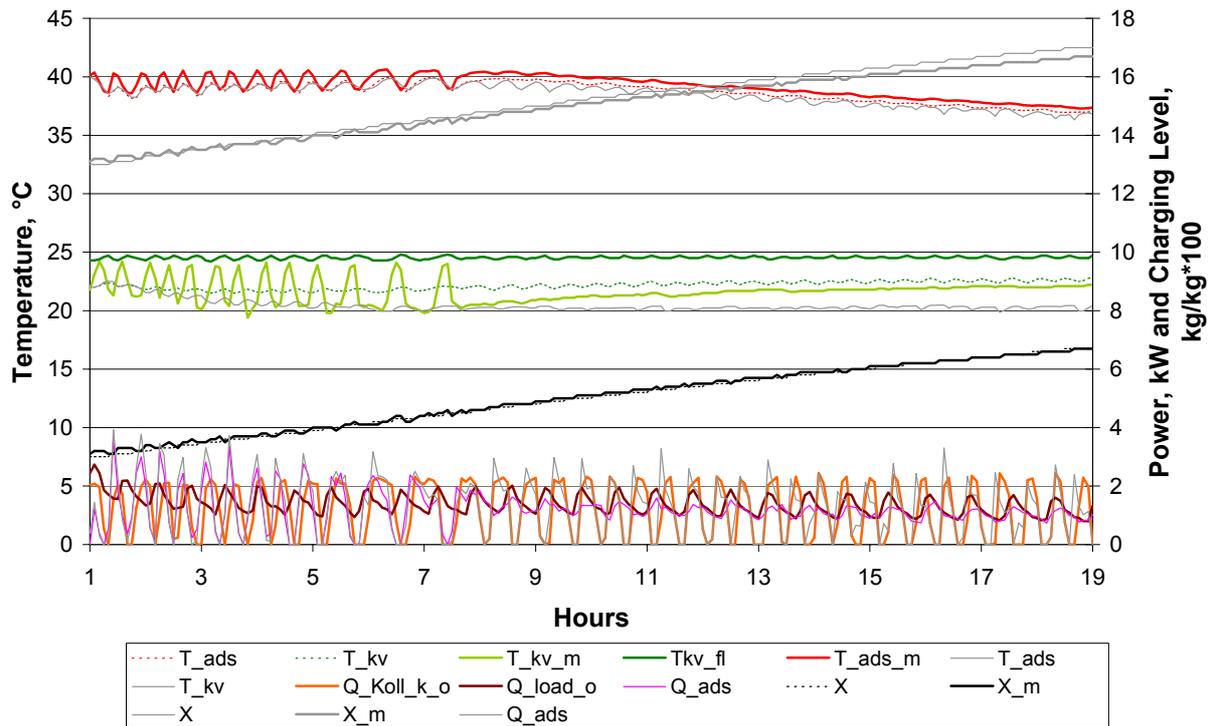
Figure 13: Validation of the simulation model in adsorption mode, variation of initial conditions

Apparently, the absolute charging level is an important factor for a reliable validation of the model. Therefore, the model will be validated again when the first measurements with the 2nd generation system are available. The experimental setup for the laboratory tests of the 2nd generation system includes a better way to measure the charging level throughout the experiments.

8 Desorption Test Runs

Desorption is the mode of operation that takes place during the summer months in a seasonal storage application. Numerous desorption cycles were carried out during spring and summer 2004. While in the HYDES project the system was operated manually, a control strategy was now implemented that allows to operate the system in a reliable and automatic way.

8.1 Control Strategy

During summer operation, the adsorber will be heated by the solar thermal collectors whenever there is enough solar energy available. Whether desorption can actually take place and water vapor can be transferred to the condenser depends on the pressure difference between the two containers. The pressure in the condenser tank depends on the temperature of water vapor in the tank whereas the pressure in the adsorbers depends on the temperature and the charging level in the tank.

The control cycle developed for the desorption mode consists of 4 phases lasting 5 minutes each:

- The pressure in the evaporator/condenser container is measured by opening the valve to this container and closing the valves to the adsorbers.
- The pressure in the adsorber used in the test is measured by opening the valve to this container and closing the valves to the other two containers.
- The measured pressures are compared and both valves between the adsorber and the condenser are opened if the pressure in the adsorber is higher than in the evaporator/condenser container.
- A fourth step was reserved for the future adaptation of the control cycle but has not been used so far.

The pressure is used as the only control parameter in the control cycle. This control strategy worked well for the 1st generation system. However, for the second generation system a different control strategy has to be developed because there will not be a valve separating the adsorber and the condenser.

8.2 Test of the control cycle

Figure 14 shows an example of a desorption cycle where the 4 phase control cycle has been used. The dashed lines show the opening and closing of the valves. The adsorber temperature was maintained at a temperature of 62°C. The black and the grey lines show the measured pressures in the two containers. The pressure in the adsorber is always well above the pressure in the condenser. That means that water vapor will be transferred as soon as the valve opens.
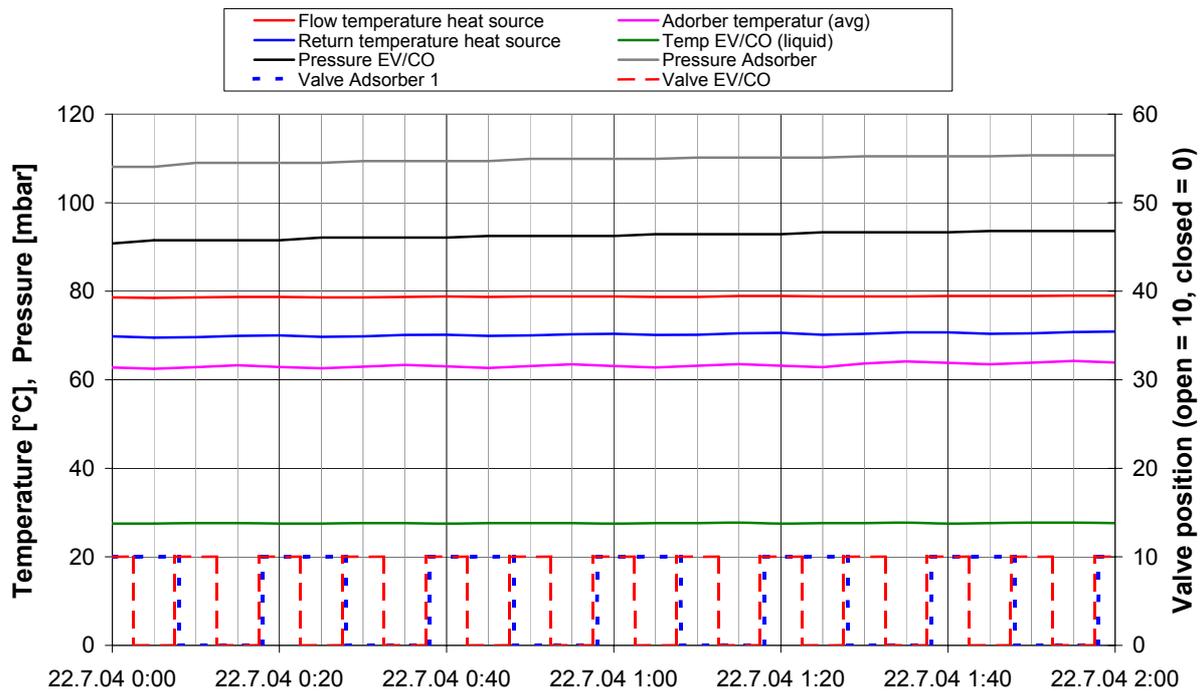
Figure 14: Test of the 4 phase-control cycle for desorption

8.3 Measurement Results

The following figures show an example desorption cycle where the adsorber heat exchanger was heated with a constant flow temperature of 80°C. The condenser was cooled to maintain a liquid temperature of 28°C. The valves between the containers were opened and closed according to the 4-phase control cycle described above.

Figure 15 shows the measured temperatures and pressures during the test run. The liquid temperature in the evaporator/condenser stays constant at 28°C. However, the temperatures measured in the vapor phase are significantly higher (around 40°C) and vary strongly with the valve position. As soon as the valve opens hot steam comes in from the adsorber and the temperature increases to 43°C which is still significantly lower than the temperature of the silica gel. The silica gel temperature rises first quickly to 60°C and then slowly towards 80°C. The black and the grey line show the pressures in the evaporator/condenser and the adsorber respectively measured at time intervals when only the valve to the respective container was open. As expected, the pressure in the adsorber is significantly higher than in the evaporator/condenser. Therefore, vapor transfer always occurs when both valves are open.

The power input into the adsorber was around 2 kW during most of the test run. Only in the beginning, when the adsorber was heated from room temperatures, the power input was higher. The power withdrawn at the condenser varies strongly with the valve position. When the valve is open, the power withdrawn is around 3-3.5 kW. When the valve is closed, it decreases to below 0.5 kW.
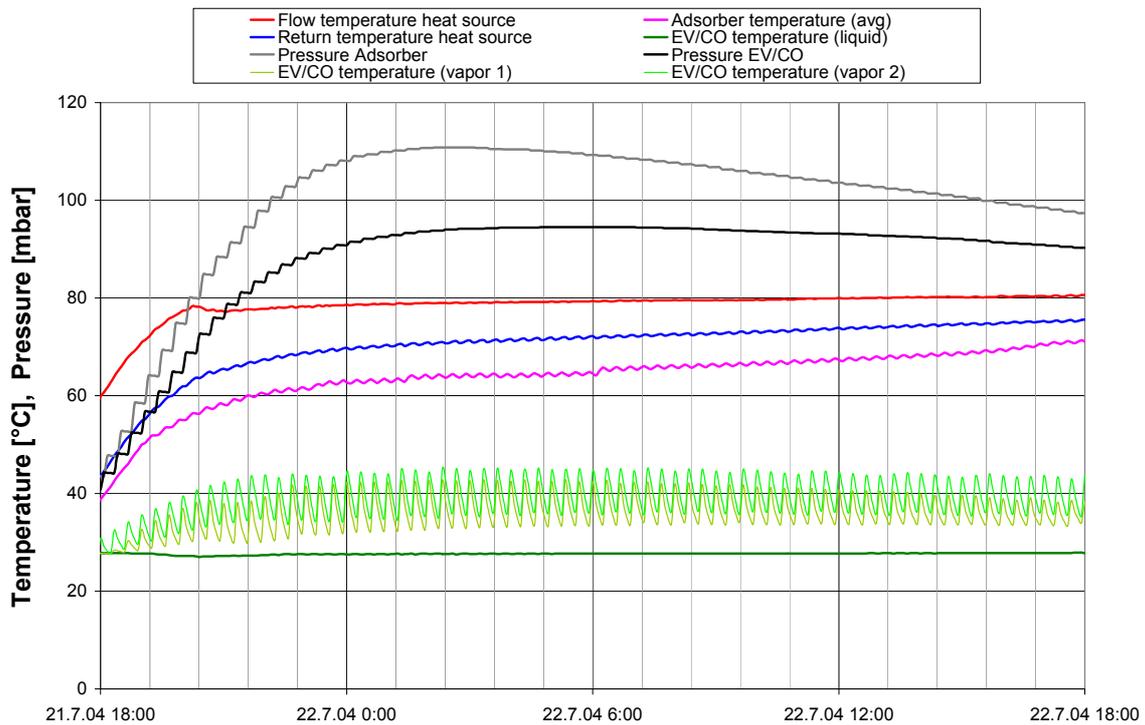
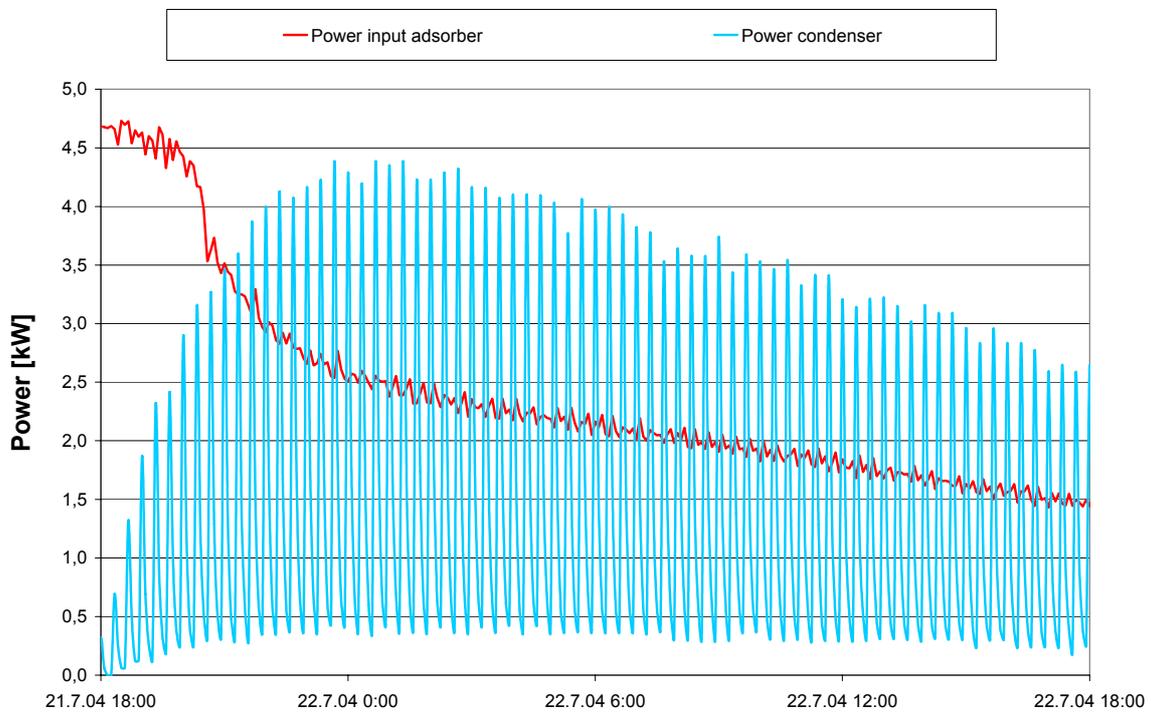*Figure 15: Measured temperatures and pressures during a desorption cycle*

Figure 16: Measured power during a desorption cycle

8.4 Interpretation of Results

The desorption test runs were performed at a much higher temperature lift than the adsorption tests. From the theoretical calculations it has to be expected that desorption takes place without any problems at the temperature levels used for the tests which in fact could be shown with these measurements.

If the temperature lift is big enough, it is apparently no problem to overcome the pressure drop between the containers. For a real application, the main challenge will be to obtain temperatures low enough to condense the desorbed water vapor. However, it can be expected that higher condensation temperatures can be used with the new system design of the 2nd generation system.

8.5 Comparison with Simulation Model

The simulation model for the desorption model calculates the transferred water vapor by multiplying the pressure difference between the containers by a factor z (see equations below). The pressure difference is calculated using the second equation with the saturated vapor pressure in the adsorber and condenser and the adsorption potential ΔF which depends on the charging level.

$$\overset{\bullet}{m}_{vapor} = \Delta p \cdot z$$

$$\Delta p = p^{sat}(T_{ads}) \cdot e^{\frac{-\Delta F}{R \cdot T_{ads}}} - p^{sat}(T_{cond})$$

The inputs for the validation of the simulation model are the heat input to the adsorber, the heat withdrawn from the condenser and the initial values of the state variables.

Factor z is the critical value to get a good agreement between simulation and measurements and has to be determined with parameter identification. Because it is not possible to accurately determine the charging level during the measurement, z was varied to at an approximate agreement as shown in Figure 17. The temperatures agree quite well but there is still a discrepancy in the charging level. Therefore, the validation of the model will have to be repeated as soon as good measurement data are available from the 2nd generation system. In addition, the value of factor z depends on the geometry, e.g. the pressure drop of the water vapor, of the system. Therefore, it has to be expected that z is going to be a different value for the 2nd generation system compared to the 1st generation system.
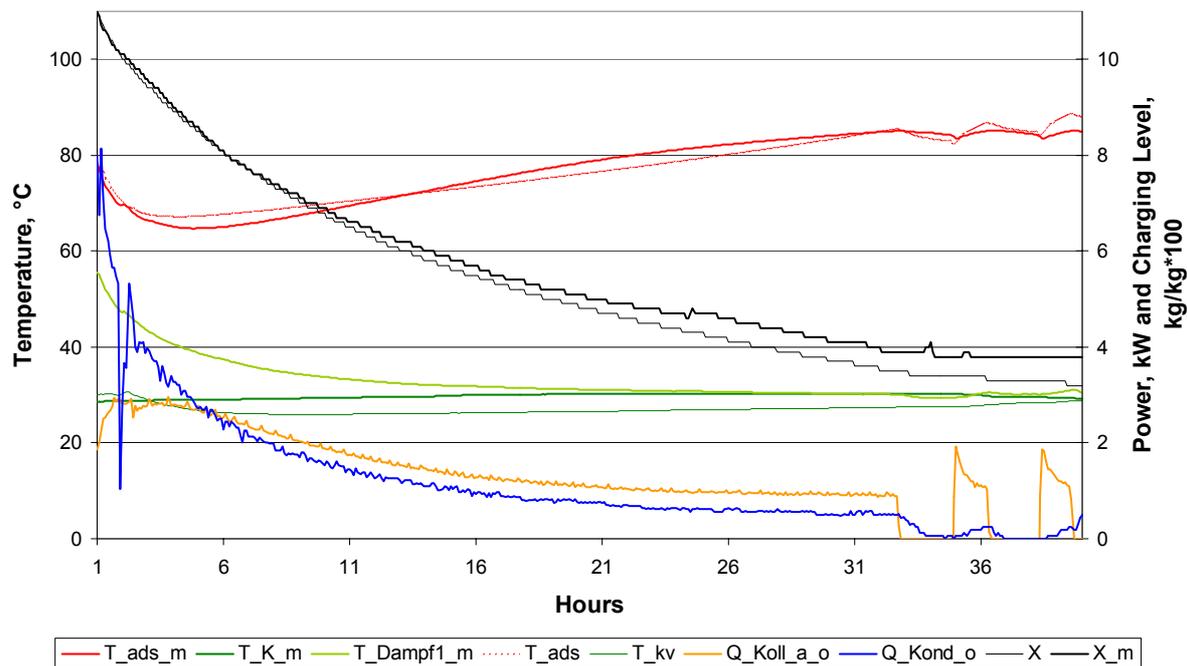
Figure 17: Validation of the simulation model in desorption mode

9 Conclusions

In general, it can be concluded that the underlying system works satisfactorily in praxis. However, theoretically calculated charging levels could not be reached with the theoretical temperature levels. An improved system design is therefore necessary to minimize pressure and heat losses as well as distances that have to be bridged by vapor diffusion in the current system design.

Major problems to accurately measure charging levels in the system occurred. This lead to an improved design of the experimental setup for the 2nd generation system laboratory tests. The water transfer will be determined using scales measuring the weight of the water reservoir.

Experiences made during the 1st generation monitoring phase led to the conclusion that the adsorption mode is the more critical mode of operation because in this mode, it is important to keep the temperature lift as large as possible. Evaporation temperatures that are increased compared to the theoretical values lead to a lower useful temperature lift. It is therefore important to design the 2nd generation system particularly with regard to the adsorption mode. The desorption mode is less critical because it takes place during the summer where high temperatures are available from the solar collectors.

In addition to the measurement of the charging level mentioned above, the experimental setup for the 2nd generation system will be improved in the following ways:

-   In desorption mode, flow temperatures up to 130°C will be feasible.

- A heat pump/chiller will be used as heat sink so that heat sink temperatures as low as 7-8°C will be possible.

The system design of the 2nd generation system including both the evaporator/condenser and the adsorber into a single container is expected to solve most of the problems encountered during the monitoring phase of the 1st generation system. There are going to be very short distances for vapor diffusion and the cross-section open for vapor diffusion is much larger.