MODESTORE

DELIVERABLE D14: FINAL REPORT ON AUSTRIAN FIELD TEST PERIOD (PERFORMANCE AND EVALUATION)

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1 Introduction

The 2nd generation prototype sorption heat storage system that was described in deliverable D6 was installed at the test facility at AEE INTEC in Gleisdorf, Austria. The experimental setup as described in deliverable D9 was designed in order to be able to run various test cycles with specified inlet temperatures and flow rates on both the input and the output side of the store.

The goal of the performed tests was to show the general functioning of the 2nd generation system design and to find a control strategy suitable to work in an application that delivers heat for space heating for a single-family house.

The first part of this report deals with the desorption mode of the system operation. That means charging of the store in summer time or in sunny periods of winter. In this operation mode, the adsorber heat exchanger is heated with solar energy and the condenser heat exchanger has to be cooled to condense the desorbed water vapor.

The following part of the report shows the tests performed in adsorption mode. In this mode, the store is discharged by evaporating water and adsorbing the generated water vapor on the silica gel. Thereby, the adsorber temperature increases and heat can be withdrawn and used in the space-heating loop of the house.

Finally, a summary shows what conclusions can be drawn from the test results for the design of a first pilot plant system that will be built and tested in the framework of a follow-up Austrian national project.

Numerous test cycles have been performed in both modes of operation. Several parameters have been varied throughout the test runs. The following chapters show measurement results that are typical or especially interesting for the further development of the system construction or the development of the control strategy for the pilot system.

An additional experimental study has been carried out to test the influence of the particle size on the adsorption of water vapor on silica gel. Differences regarding the kinetics of the reaction were expected. The results of this study are presented in chapter 5.

2 Desorption

In desorption mode, the energy for charging the store will come from solar thermal collectors. In summer time and in sunny periods in winter, it will be no problem to reach 80 or even 90°C with flat plate collectors. For the system tests described below, the desired temperature at the inlet of the adsorber heat exchanger was generated with an electrical heating element in the circuit marked in red in Fig. 1.

However, the critical factor is the temperature level that is available as a heat sink for condensation. For the tests, the temperature of the heat sink was generated by mixing the temperature available in the buffer store down to the desired value. The buffer store was cooled by a heat pump. The cooling loop for the experiments is marked in blue in Fig. 1.

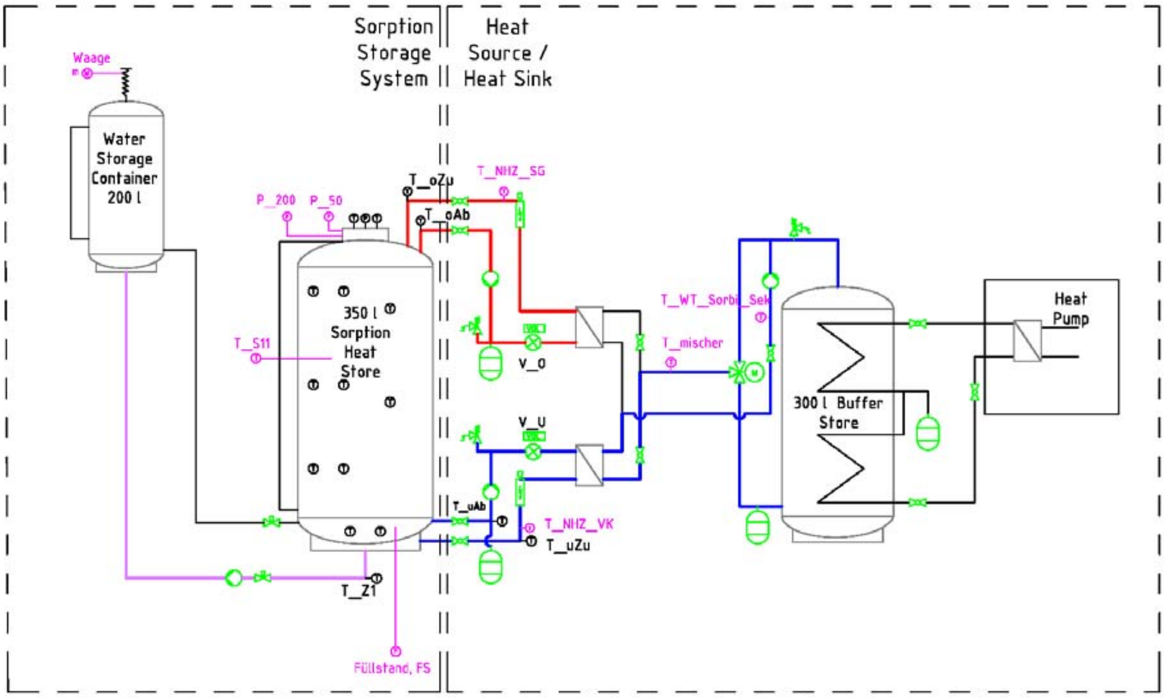

Fig. 1: Setup of the test facility for desorption tests

The desorbed water condenses at the condenser heat exchanger at the bottom of the store and accumulates below the heat exchanger. As soon as a certain amount of accumulated water is detected by the level sensor, the water is pumped into the water storage container using the flexible hose marked in purple in Fig. 1.

2.1 Constant Operation

In the first test runs, constant temperature settings have been used for both the adsorber heat exchanger and the condenser heat exchanger.

2.1.1 Control Strategy

In this test, inlet temperatures to both heat exchangers were kept constant at 88°C and 15°C respectively. The adsorber temperature increases and desorption and condensation starts as soon as the pressure difference between the desorbed vapor and the saturation pressure at the heat exchanger temperature is high enough. The condensed water accumulates below the condenser heat exchanger and is pumped into the storage container as soon as a small amount of water is detected by the level sensor. Desorption continues until the water content of the silica gel is so low that the available temperature difference is not enough to achieve a sufficient pressure difference. The details of the control strategy in the test run shown can be found in Table 1.

Table 1: Control strategy for desorption in constant operation mode

Variable	**Abbr.**	**Value**
Adsorber heat exchanger		
Inlet temperature	T_o_Zu	88°C constant
Flow rate	V_o	250 l/h constant
Evaporator/Condenser		
Inlet temperature	T_u_Zu	15°C constant
Flow rate	V_u	110 l/h constant
Control of Water Level		As soon as 3 l of water have accumulated, turn on pump Turn off pump, when water level is at 0.5 l

2.1.2 Results

Fig. 2 shows the temperatures and the pressure during a constant operation desorption test run. The top two lines are the flow and the return temperature of the adsorber heat exchanger (T_{oZu}, T_{oAb}). There are 11 temperature sensors located at different positions in the store. These 11 sensors are at just above 40°C at the beginning of the test. Then, the temperatures increase at different rates until all of them reach a final temperature around 88°C. The difference between the highest and the lowest temperature in the adsorber during the heating phase is approximately 10K. Just below the adsorber temperatures are the temperatures of the two temperature sensors located in the vapor channel in the middle of the store (T_{D1}, T_{D2}, green and purple lines).

The flow and return temperature of the condenser heat exchanger with the return temperature constant at 15°C, and the temperatures of the two sensors located above and next to the condenser heat exchanger are shown at the bottom of the figure (T_{uZu}, T_{uAb}).

The grey line shows the system pressure throughout the test (P_{200}).

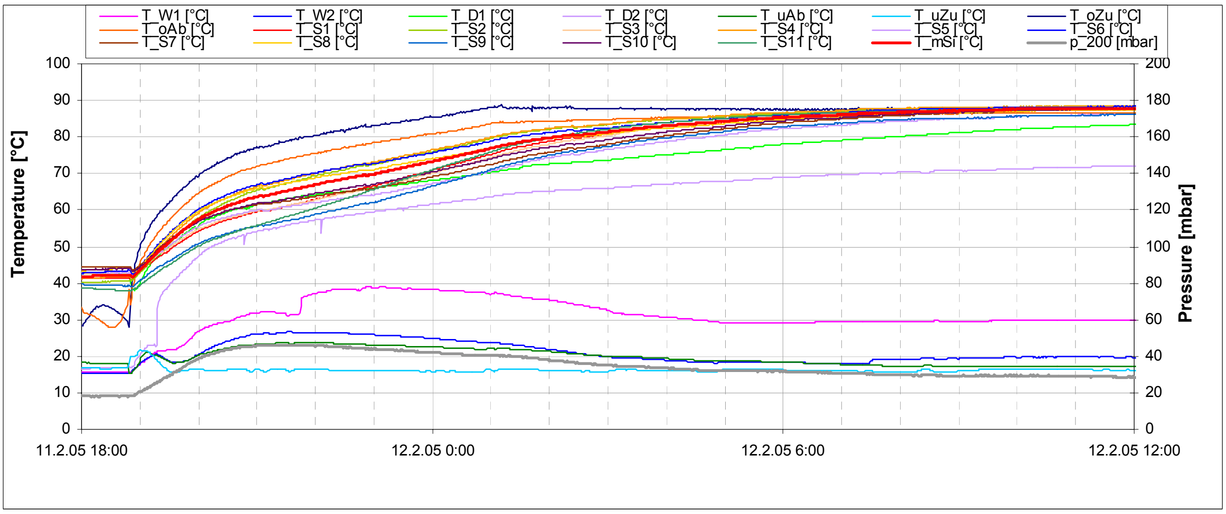

Fig. 2: Temperatures and pressures, desorption in constant operation mode

Fig. 3 shows again the adsorber temperatures, the flow and return temperatures of the adsorber heat exchanger as well as the logarithmic temperature difference between the average of the sensors in the silica gel and the average between the flow and return line (logDeltaTo_zu_ab_mSi). This is the average temperature difference between the store and the heat exchanger fluid. In the beginning of the heating phase, it increases rapidly to approx. 10K and then decreases slowly until all the temperatures have averaged out and the desorption process has almost stopped. This temperature difference is quite high during the active desorption process which shows that the heat conductivity from the heat exchanger to the silica gel and within the silica gel is quite low.

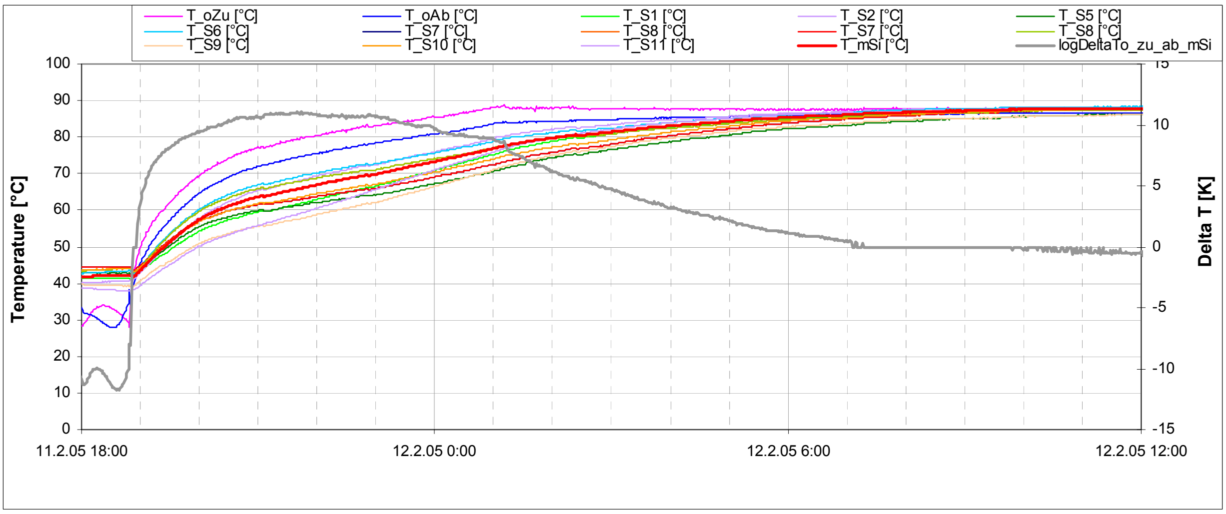

Fig. 3: Temperature difference between silica gel and fluid in adsorber heat exchanger, desorption in constant operation mode

A more detailed analysis of the heat transfer from the adsorber heat exchanger to the silica gel can be found in section 2.6.

Fig. 4 shows the transferred power as well as the flow rates and the flow and return temperatures in both heat exchangers. The adsorber was heated with approx 1.5 kW and the condenser was cooled with approx. 1 kW in this experiment. The transferred power decreases slowly towards the end of the test run. The difference between the heating and the cooling power is used on one hand for sensible heating of the adsorber, and on the other hand lost to the surroundings of the store.

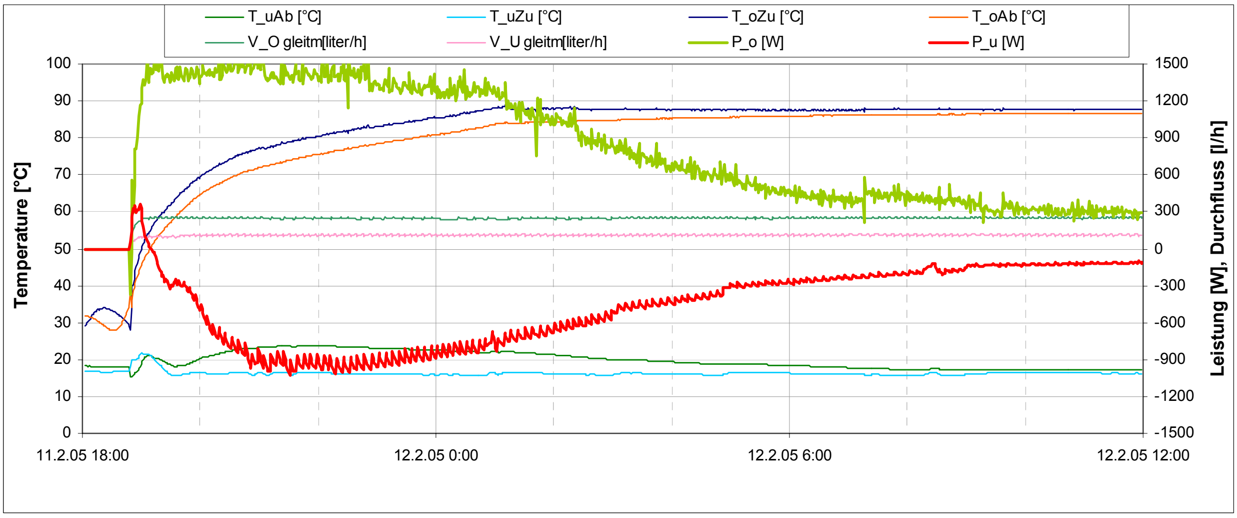

Fig. 4: Transferred power, flow rates and flow and return temperatures, desorption in constant operation mode

Fig. 5 shows the water content of the silica gel (X_{iso}) that was calcualted from measured pressure and temperature in the store. It starts at around 0.1 kg water per kg of dry silica gel (=10%). Then, it decreases rapidly. Most of the water is desorbed in the first half of the experiment. It reaches 2.5% after 18 hours of continuous operation. The blue line shows how the weight of the water storage tank changes throughout the test.

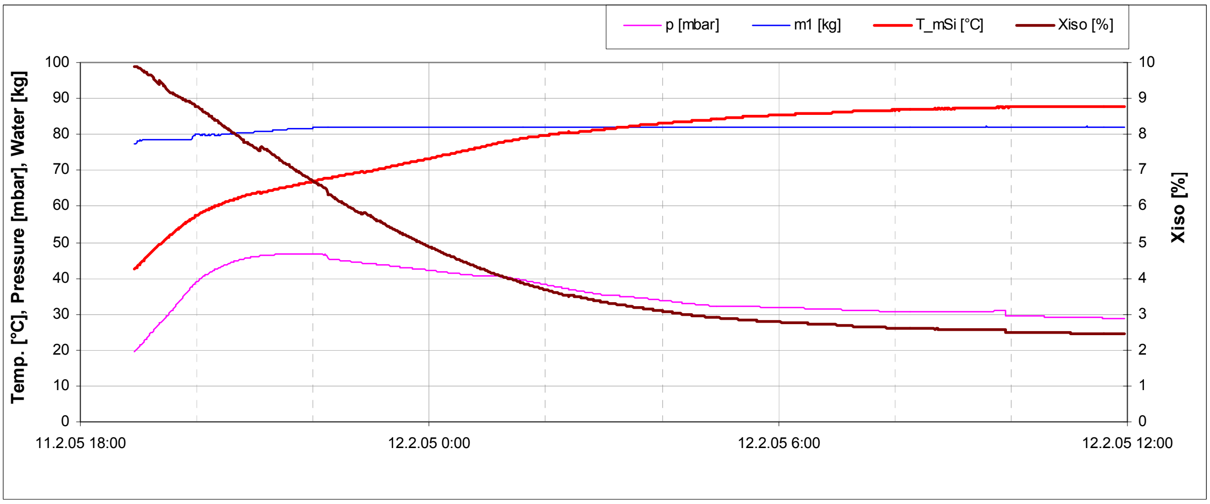

Fig. 5: Water content of silica gel, desorption in constant operation mode

A detailed analysis of the condenser heat exchanger during this test run is shown in Fig. 6. The heat transfer coefficient from the water vapor to the heat exchanger fluid is calculated using the following equation.

$$\dot{Q} = UA \cdot \Delta T_{\ln}$$

with

$$\Delta T_{\ln} = \frac{T_{u,ab} - T_{u,zu}}{\ln \dfrac{T_{u,ab} - T^{sat}(p)}{T_{u,zu} - T^{sat}(p)}}$$

The driving temperature difference in this case is the logarithmic temperature difference between the temperature of the fluid in the heat exchanger and the saturation temperature corresponding to the current pressure in the store. The saturation temperature is the temperature of the condensed water and the water vapor close to the heat exchanger. Here, it is calculated as the saturation temperature corresponding to the measured system pressure.

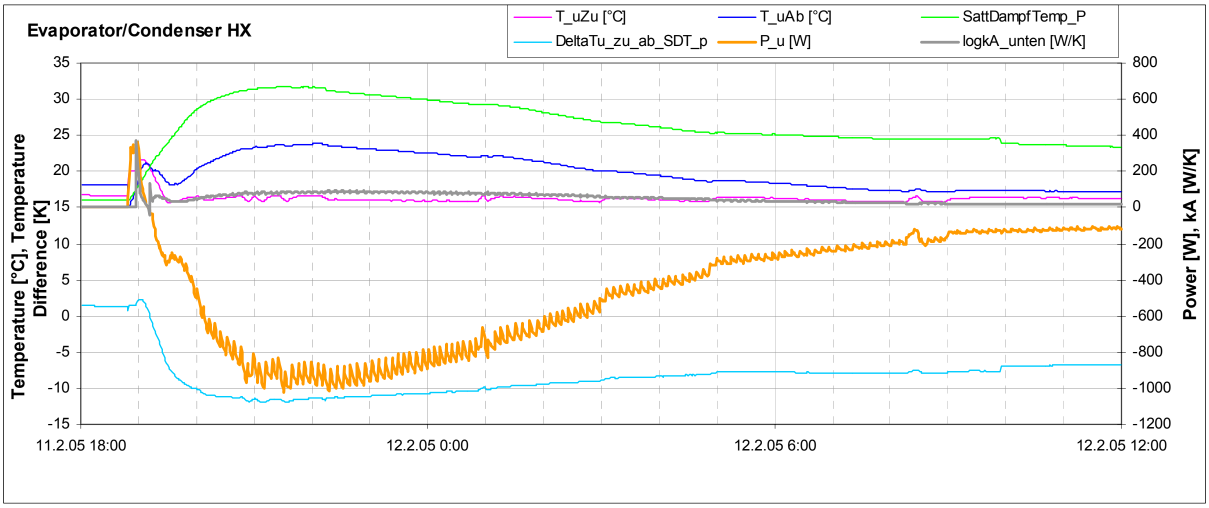

Fig. 6: Temperatures in and around the condenser heat exchanger, desorption in constant operation mode

During the main desorption phase in this test, the UA value was just below 100 W/K at a transferred power of 1 kW. The saturation temperature was 32°C and the temperature difference between the saturated steam and the heat exchanger fluid was around 11K. This value is quite high. Analysis of the flow inside the heat exchanger showed that the flow rate was chosen too low and caused laminar flow in the heat exchanger. However, this is only a relatively small optimization potential.

2.2 Desorption with High Condensing Temperatures

In this section, the results of a desorption test run with much higher condensation temperatures are shown. The goal in this experiment was to see how far the silica gel can be desorbed if only a much smaller temperature difference between silica gel and condenser is available.

2.2.1 Control Strategy

The test was run in constant operation mode again but with 38°C inlet temperature instead of 15°C. The flow rate in the condenser heat exchanger was increased to ensure turbulent flow in the heat exchanger.

Table 2: Control strategy for desorption in constant operation mode (high condensing temperatures)

Variable	**Abbr.**	**Value**
Adsorber heat exchanger		
Inlet temperature	T_o_Zu	88°C constant
Flow rate	V_o	250 l/h constant
Evaporator/Condenser		
Inlet temperature	T_u_Zu	38°C constant
Flow rate	V_u	300 l/h constant
Control of Water Level		As soon as 3 l of water have accumulated, turn on pump Turn off pump, when water level is at 0.5 l

Table 2 shows the control parameters used in this test run.

2.2.2 Results

The increased flow rate in the condenser heat exchanger led to a significantly increased heat transfer coefficient of 130 W/K instead of just below 100 W/K.
Fig. 7 shows the temperatures and pressures during the desorption test with an inlet temperature to the condenser of 38°C. In this experiment, the control for the pump that pumps the water out of the condenser area didn’t work properly in the beginning, so that more than 20 liters of water accumulated before it was pumped into the water storage container. However, this didn’t interrupt the desorption process. The lowest temperature curve in the figure shows the temperature measured in the connecting pipe between the condenser and the water storage container. There are peaks whenever water is pumped.

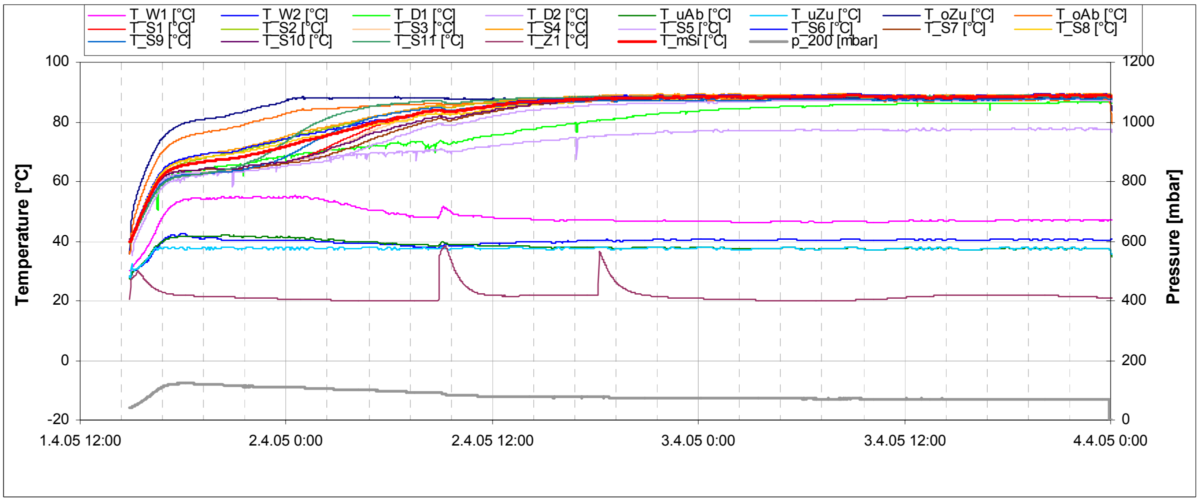

Fig. 7: Temperatures and pressures, desorption in constant operation mode (high condensation temperatures)

The transferred power was the same as what was used in the other desorption experiments shown (1.5 kW heating and 1 kW cooling).

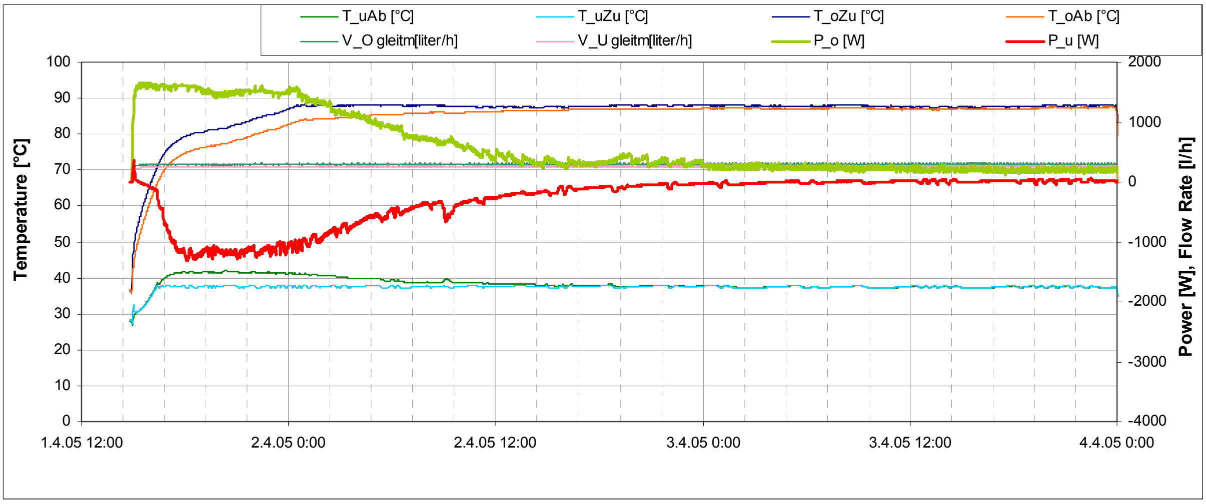

Fig. 8: Transferred power, desorption in constant operation mode (high condensation temperatures)

The initial water content of the silica gel was 24% and decreased to approximately 4% after a little more than 24 hours. Fig. 9 also shows that the pump was only turned on twice as already mentioned.

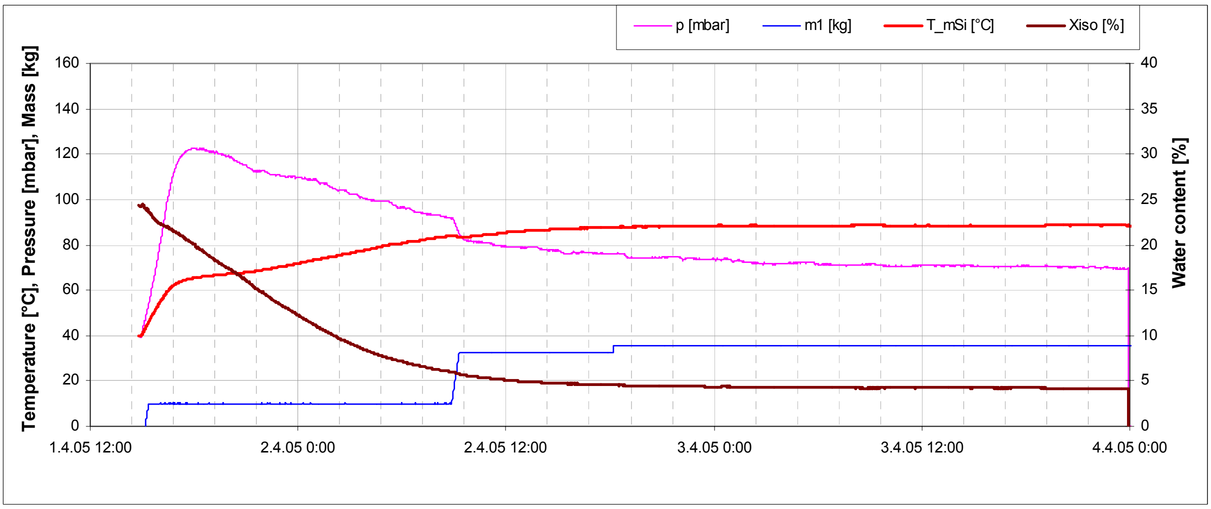

Fig. 9: Water content, desorption in constant operation mode (high condensation temperatures)

In general, one can say that desorption works well also with higher condensation temperatures. A water content of the silica gel of just over 4% was reached with a condensation temperature of 38°C and a temperature difference between adsorber and condenser of 50K. A lower water content can only be reached if higher temperature differences are available. A comparison between the two constant operation desorption test runs is shown in more detail in the following section.

2.3 Comparison of Two Different Condenser Temperatures

The following two figures show a comparison of the two desorption test runs described above. The starting point of the comparison is chosen so that both start at a water content of 9.8%. The same inlet temperature to the adsorber heat exchanger has been used in both cases (88°C). The test run with 15°C inlet temperature to the condenser is indicated with thin lines, the test with 38°C with bold lines. Because the test run with 38°C condenser temperature was started at a much higher water content, the section shown here starts already at higher adsorber temperatures.

Fig. 10 shows that the water content decreases significantly faster with lower condensation temperatures and also reaches a lower minimum. Interestingly enough, in both cases the slope of the curve becomes very small (only very little water is desorbed anymore) approximately at the same time (after about 12 hours of operation).

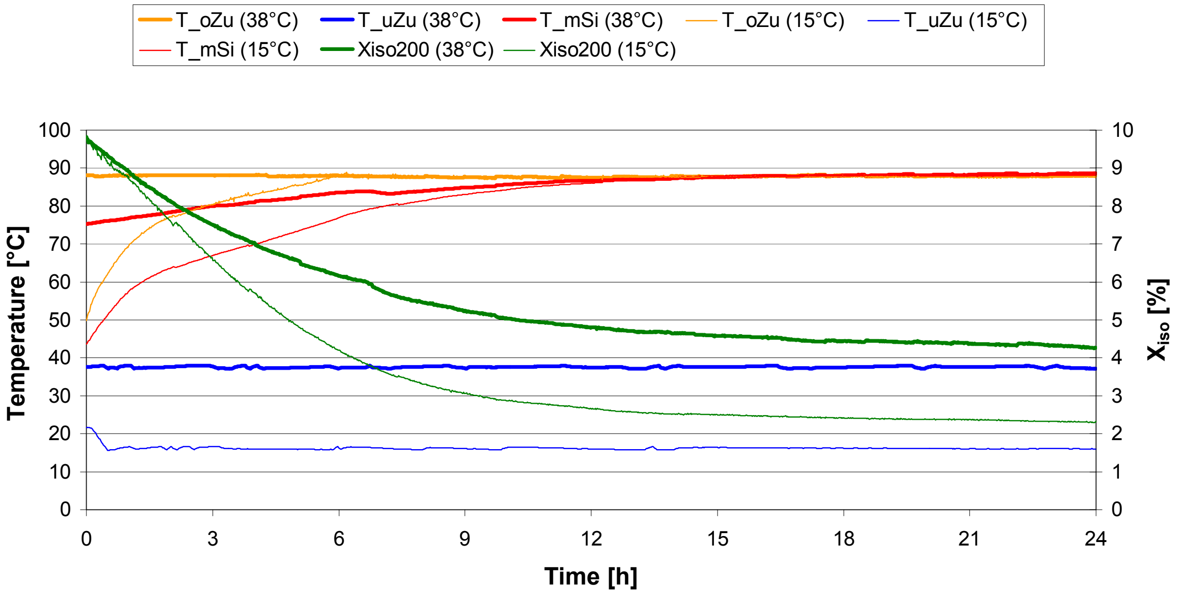

Fig. 10: Desorption with two different condensation temperatures, water content and temperatures

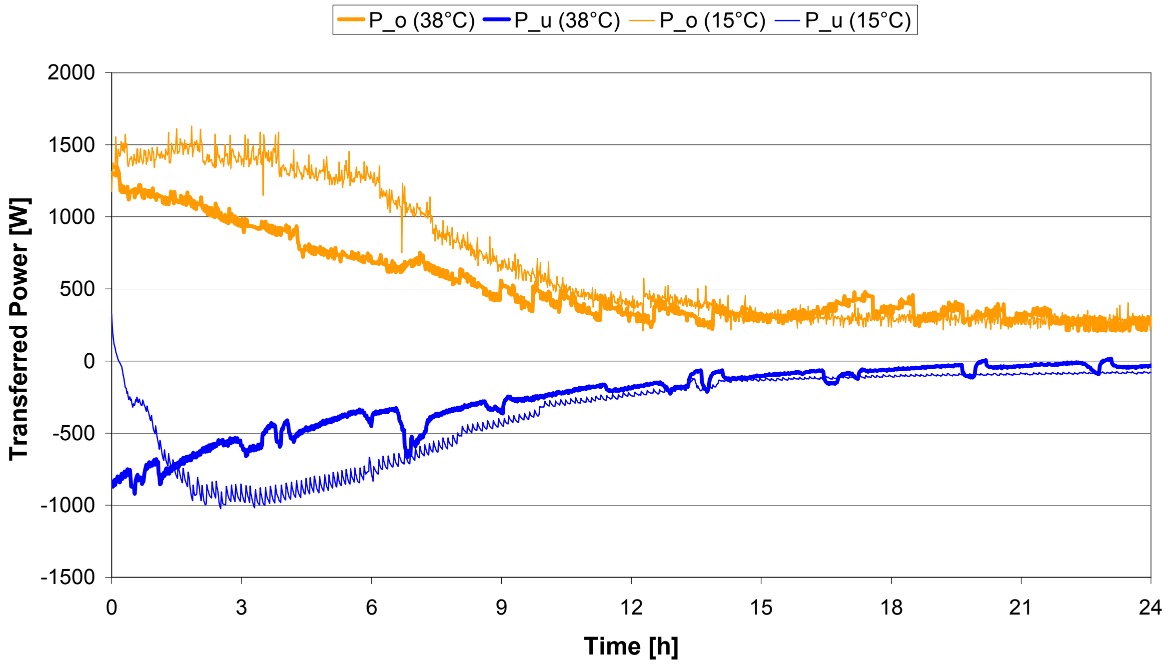

Fig. 11: Desorption with two different condensation temperatures, transferred power

A comparison between the theoretical minimum water contents under the operating conditions of the two test runs described above shows that the theoretical values have almost been reached (see Table 3). The measured values were reached after 2-3 hours of steady state operation after a constant water content was reached. When comparing these figures one has to bear in mind that in a real application there is a pressure drop between the silica gel and the condenser although this pressure drop is very small in the 2nd generation system design. Secondly, there is a temperature loss across the condenser heat exchanger that causes the actual condensation temperatures to be a little higher than the inlet temperatures on the fluid side of the heat exchanger.

Table 3: Comparison between desorption with different condensing temperatures

$T_{u,zu}$	$\Delta T=T_{m,Si}-T_{u,zu}$	$x_{theoretical}$	$x_{measured}$
[°C]	[K]	[%]	[%]
15	72	1.85	2.04
38	51	3.85	4.13

2.4 Alternating Operation

A possible heat sink in a real application is to use the solar thermal collectors to dissipate heat at night when the ambient temperature is below the desired cooling temperature. That means that the adsorber is heated during the day. During the night the condenser is cooled by pumping water through the collectors. Desorption will take place only during the cooling phase and will continue until the adsorber temperature has decreased and there is not enough pressure difference between the silica gel and the saturation conditions at the condenser anymore.

To simulate this alternating operation, a 4-phase cyclic operation has been used:

1) Heating of the adsorber heat exchanger with a constant flow temperature and constant flow rate
2) Rest period
3) Cooling of the condenser with a constant flow temperature and constant flow rate
4) Rest period

The rest periods have been introduced because in a real application there is always going to be a period in the afternoon when the collectors cannot deliver heat anymore to the store but the ambient temperature is still higher than the necessary cooling temperature. Also in the morning, there will be a gap between the end of the cooling phase and the start of the heating phase.

2.4.1 Control Strategy

In a real application, the 4 phases will last in total 24 hours. In the laboratory setup with a relatively small store, the duration of the four phases has been shortened according to the store size. The test run shown below was operated in the following time schedule: phase 1: 3 hours, phase 2: 2.5 hours, phase 3: 1.5 hours, phase 4: 2.5 hours.

Table 4: Control strategy for desorption in alternating operation mode

Variable	**Abbr.**	**Value**
Adsorber heat exchanger		
Inlet temperature	T_o_Zu	92°C constant
Flow rate	V_o	280 l/h constant in phase 1, otherwise 0
Evaporator/Condenser		
Inlet temperature	T_u_Zu	12°C constant
Flow rate	V_u	170 l/h constant in phase 3 otherwise 0
Control of Water Level		As soon as 3 l of water have accumulated, turn on pump Turn off pump, when water level is at 0.5 l

Table 4 shows the control parameters used in the test run. At the end of the test run, the controller was set to constant operation mode to desorb any remaining water from the silica gel.

2.4.2 Results

The following figures show six heating and five cooling phases as well as the simultaneous heating and cooling phase at the end.

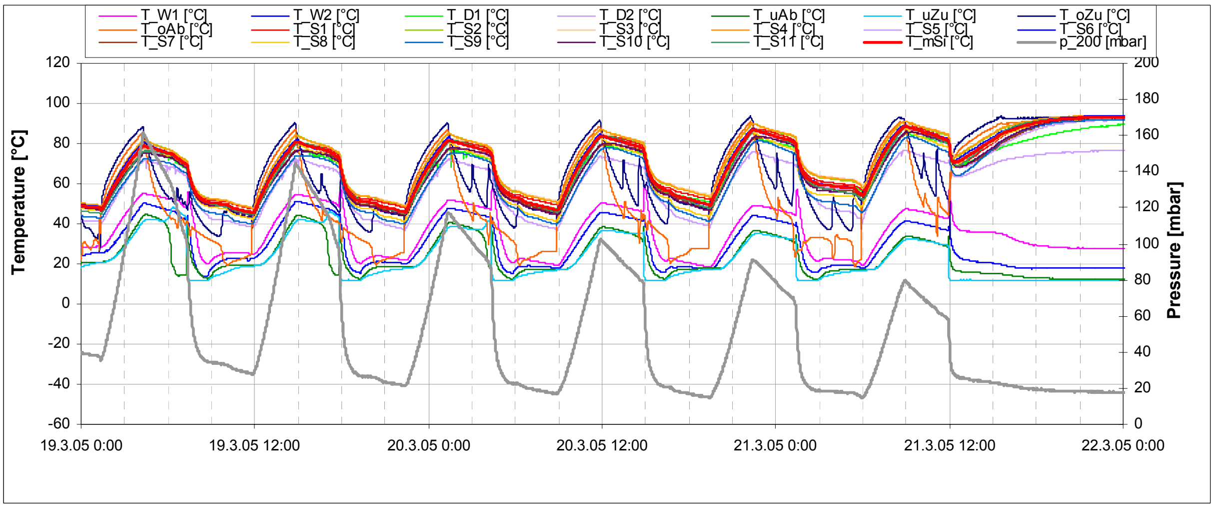

Fig. 12: Temperatures and pressures, desorption in alternating operation mode

Fig. 12 shows that the adsorber temperature increases to about 80°C in the first heating phase and is cooled to about 50°C in the cooling phase. As the desorption proceeds the temperatures that are reached during the heating phase increase to about 90°C. The pressure in the system increases rapidly during the heating phase and decreases rapidly during the cooling phase. The top pressures reached in a heating phase decreases as the desorption process advances due to the decreasing water content of the silica gel.

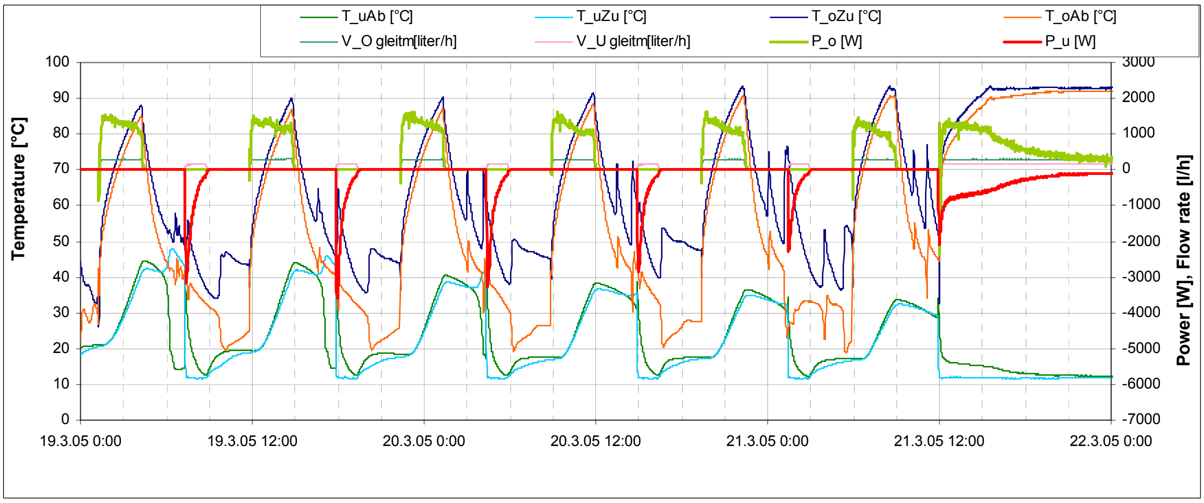

Fig. 13: Transferred power, flow rates and flow and return temperatures, desorption in alternating operation mode

The transferred heating power was again around 1.5 kW as shown in Fig. 13. The cooling power is as high as 3-4 kW at the beginning of the cooling phase and decreases to zero towards the end of the cooling phase. The decrease of the water content of the silica gel is shown in Fig. 14. The curve fluctuates somewhat. The reason for that is that because of the alternating operation there are no quasi steady-state conditions in the store in terms of temperature and pressure. The water content has been calculated based on these values. However, the decrease of the water content throughout the test is still evident. The water content decreases from 15% to 2% in 72 hours. The blue curve in the figure shows the step change in the water mass in the water storage container whenever water is pumped out of the condenser area.

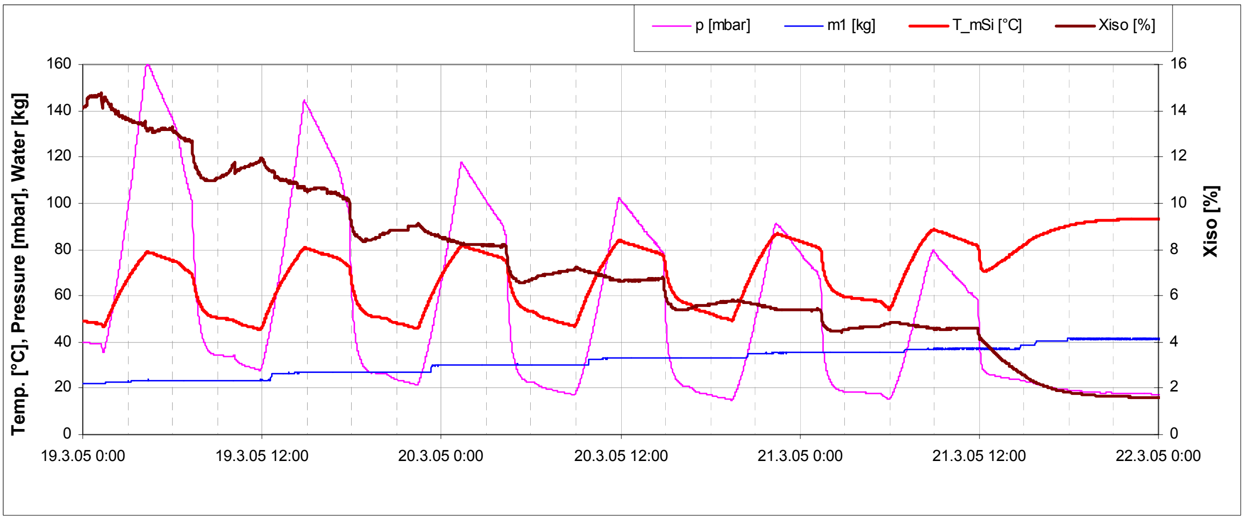

Fig. 14: Water content of silica gel, desorption in alternating operation mode

The desorption process in the alternating mode takes obviously much longer than in constant operation mode. But the feasibility of alternating heating and cooling phases could be shown and the result is quite satisfactory.

2.5 Desorption with Inert Gases in the Store

Desorption test runs were performed also with some inert gas (air) in the store. It turns out that the air accumulates at the bottom of the store because it is heavier than water vapor and therefore prevents condensation of water vapor on the condenser heat exchanger. In addition, vapor diffusion is inhibited by inert gases.

2.6 Heat Transfer from the Adsorber Heat Exchanger to the Silica Gel

The adsorber heat exchanger consists of a spiral perforated sheet copper with copper pipes soldered to it. Heat conduction in the sheet copper was calculated analogous to the calculation of heat conduction in a flat plate solar thermal collector. Starting from the desired power to be transferred across the heat exchanger, the necessary sheet copper thickness and distance between pipes were calculated. Based on these calculations a sheet copper of 0.5 mm thickness and a distance between pipes of 10 cm were chosen.

For manufacturing reasons, the pipes were not soldered on the entire length of the pipe to the sheet copper but in sections of 3-4 cm alternating with sections of the same length that are not soldered.

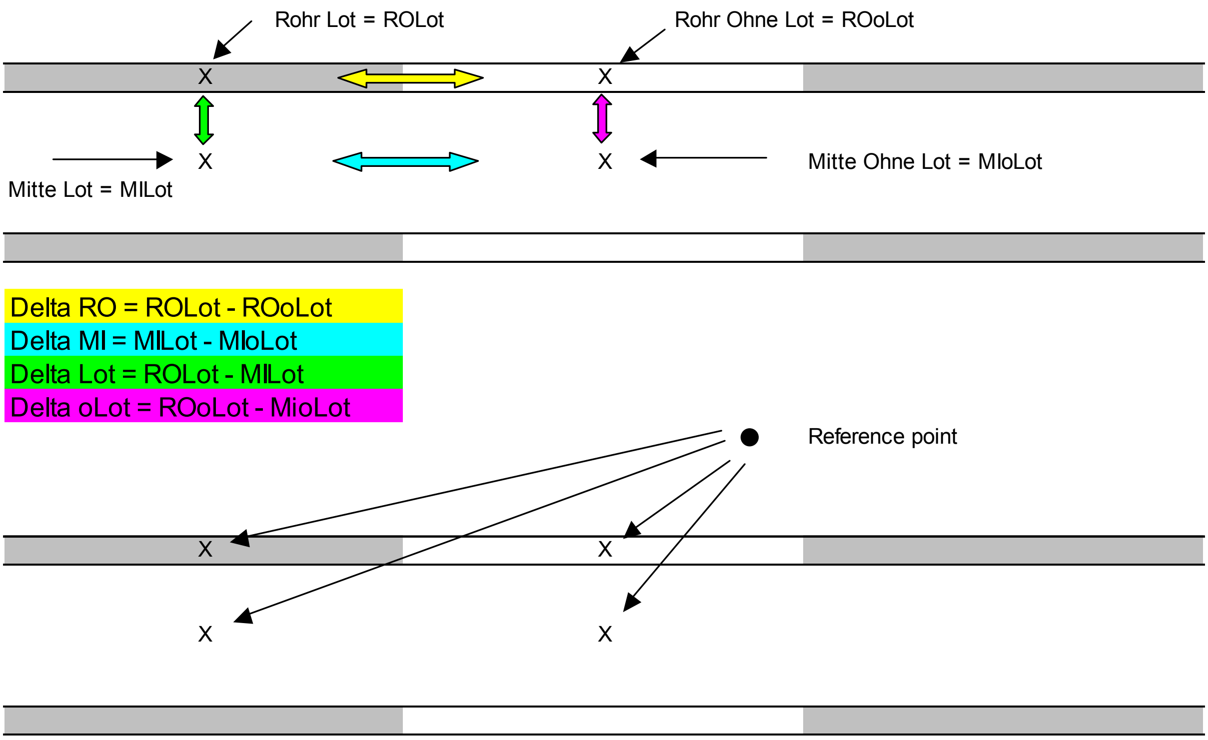

Fig. 15: The thermocouples measurement points in relation to each other on the adsorber heat exchanger

4 thermocouples have been soldered to the sheet copper at different locations to check whether the heat transfer from the pipe to the sheet copper is much inferior in areas where the connection was not soldered (see Fig. 15). The figure shows the plane of the sheet copper with the horizontal bars representing the pipes. The grey areas are where the connection was soldered, the white parts where it was not soldered. The crosses show the positions of the thermocouples. The thermocouples consist of constantan (copper-nickel) wire soldered to the sheet copper. The sheet copper itself acts as the other thermocouple material. That means that the thermocouples measured the temperature difference to a reference point. Therefore no absolute temperatures could be measured but only temperature differences between the four sensors. These temperature differences are shown with the colored arrows.

Fig. 16 shows these temperature differences during a heating phase of a desorption test run as well as the average adsorber temperature and the inlet temperature to the adsorber heat exchanger. The diagram shows that the highest temperature is recorded at the location where the pipe is soldered to the sheet metal. This had to be expected. The other three sensors show very small temperature differences between eachother (0.5-1 K). However, the temperature difference between the part where the pipe is soldered to and the other three sensors is around 4-5 K in the heating phase. It is interesting that the non-soldered part by the pipe has almost the same temperature as the sensors located between pipes. That shows that there is very bad heat transfer between the pipe and the sheet copper if it is not soldered. At the end of the heating phase, the adsorber temperatures reach the inlet temperature of the heat exchanger and all temperatures even out. In this stage, the temperature differences between the thermocouple sensors become small.

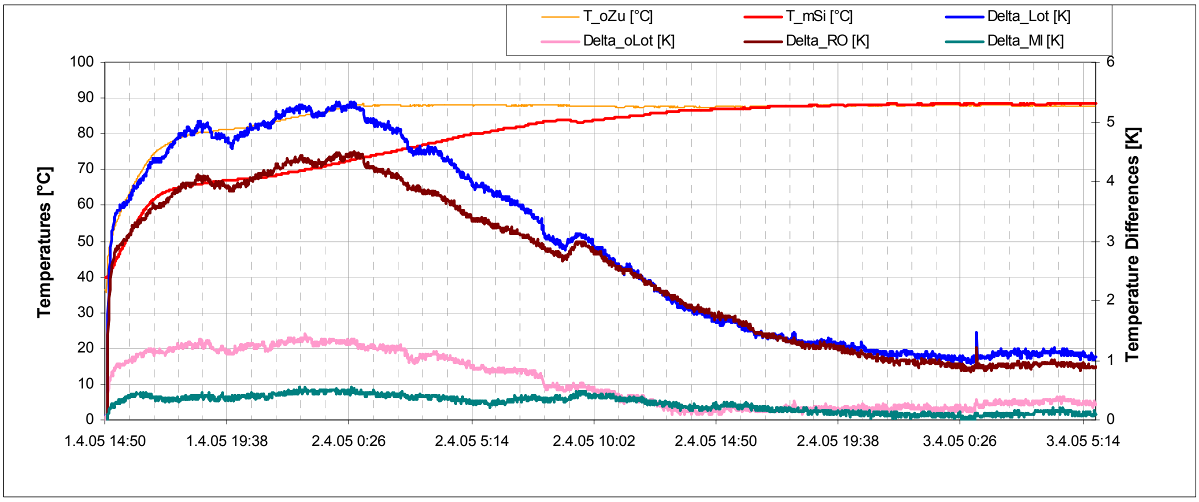

Fig. 16: Temperature differences between different positions on the adsorber heat exchanger

The results show that the UA values is reduced significantly where the pipes are not soldered to the sheet copper. The cross section that is used to transfer heat from the pipes to the rest of the heat exchanger much smaller because of this. In the design of the next prototype system, the pipes should be soldered to the sheet copper on their entire length.

The measurements described above dealt with the heat transfer within the adsorber heat exchanger itself. However, another important issue is the heat transfer from the heat exchanger to the silica gel and within the silica gel itself.

A total of 11 temperatures sensors have been mounted at different location in the silica gel to analyze this. The positions of these sensors are shown in detail in deliverable D9. 6 of these sensors were mounted at the same height of the store but in an arrangement between the layers of the heat exchanger as depicted in Fig. 17. The vertical lines are the sheet copper layers of the heat exchangers. The circles show schematically the horizontal pipes of the heat exchanger. The vertical line on the left hand side is the innermost layer of the sheet copper. The positions of the sensors is shown schematically with the blue rectangles in the middle. There are two sets of three sensors where two sensors are located very close to the sheet copper and one exactly in the middle between the layers.

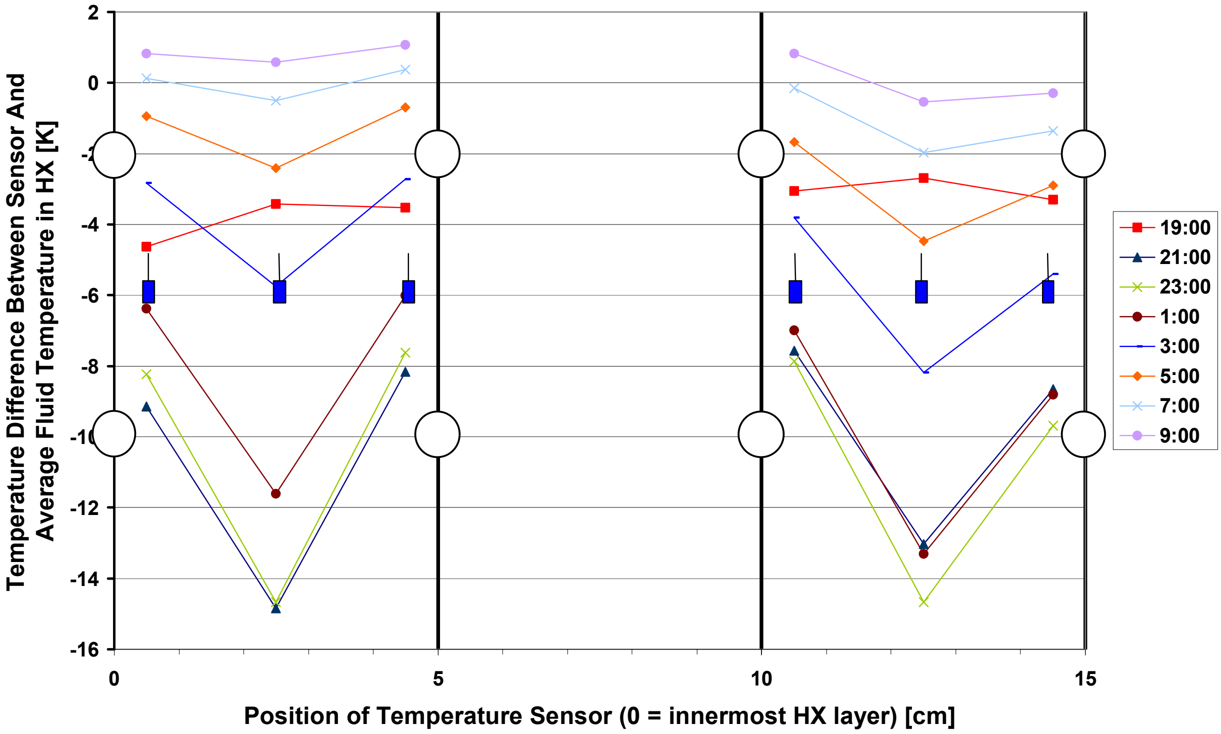

Fig. 17: Development of the temperature distribution within the silica gel packing during a heating phase in a desorption process

The diagram shows the temperature distribution within the silica gel packing as snapshots in 2-hour time intervals during a heating phase in a desorption process. The temperatures are shown not as absolute temperatures but as temperature differences to the average temperature between inlet and outlet of the heat exchanger according to the following equation:

$$\Delta T_x = T_{S,x} - \frac{T_{o,zu} + T_{o,ab}}{2}$$

The silica gel is heated through the adsorber heat exchanger and at the same time it is cooled due to the desorption process taking place. At the beginning of the heating phase at 19:00 h the temperature differences are still quite small, but two hours later there are significant temperatures differences both between the pipe and the sensors right next to the heat exchanger layer in the silica gel (8-10 K) and between the sensors next to the heat exchanger and the one in the middle (~ 6 K). As the heating continues the temperature differences become smaller and smaller until all temperatures are more or less equal.

These results show that the heat transfer both from the heat exchanger to the silica gel and within the silica gel is not very good and should be improved for the next prototype design.

Using the same calculation method as for the heat conduction in the sheet copper heat exchanger, the heat conductivity within the silica gel was deducted from the measurements to be approximately 0.11 W/(m K). The heat transfer coefficient from the heat exchanger to the silica gel is around 35 W/(m² K).

2.7 Conclusions for Desorption in a Single-Family House Application

First desorption tests when the storage tank was not fully evacuated showed that inert gases in the store prevent the water vapor from condensing because the inert gases block the condenser heat exchanger. Therefore, good evacuation of the store is necessary for a correct functioning of the system. Not knowing the exact vacuum pressure that is necessary, just a rough estimation of about 1 mbar absolute pressure can be given when there is no water vapor present.

Desorption test runs at steady-state operating conditions showed that desorption operation works well with the new system design. Very low water contents can be reached if a large temperature difference between heating and cooling side of the system is available.

Desorption with higher condensation temperatures (38°C) showed that even with quite high condensation temperatures water contents as low as 4% can be reached. This is especially interesting considering that the return from the space-heating loop which is even lower than 38°C in a low-temperature heat distribution system, could be used as heat sink.

Alternating operation (sensible heating of silica gel during the day and cooling of the condenser during the night) is a viable solution if no suitable low temperature is available in the system.

The detailed analysis of the heat exchangers used in the 2nd generation prototype design lead to the following conclusions:

- Condenser: In some experiments the volumetric flow rate through the heat exchanger was too low to ensure turbulent flow in the heat exchanger. When designing the condenser heat exchanger for the next prototype system, it is important to make sure that not too many strands are connected in parallel depending on the desired flow rates.

- Adsorber heat exchanger: In general, the heat exchanger works well. However, the heat transfer from the pipes to the sheet copper of the heat exchanger can be improved significantly by soldering the pipes on their entire length to the sheet copper. The distance between the spiral layers of the heat exchangers should be reduced to decrease the temperature differences that were identified within the spacing between two sheet copper layers. The ratio between thickness of the sheet copper and distance between the pipes is an important parameter. The parameters that were chosen for this prototype turned out to be reasonable values.

In a single-family house application the critical question in desorption mode is to find a suitable heat sink. The solar thermal collectors will deliver high enough temperatures to heat the store to at least 90°C in summer and in sunny periods in winter. However, as a low temperature heat sink there are several possible solutions:

- The bottom part of a domestic hot water store, a standard (water-filled) energy store or combistore can be used. However, to rely on the domestic hot water consumption as the heat sink is problematic if there is very little hot water consumption in general or if the house is unoccupied during sunny periods for example during vacations.

- The solar collectors can be used as a heat sink at night.
- The low-temperature heating system can be used as a heat sink if the system is completely discharged and a conventional burner has to be turned on for auxiliary heating. In this case, the conventional burner would heat the adsorber and the heat of condensation is used for space heating.

3 Adsorption

Adsorption is the operation mode used for discharging the store. Water is led into the bottom of the storage tank through the flexible hose marked in purple in Fig. 18 and evaporated by heating the evaporator/condenser heat exchanger. The evaporated water is adsorbed on the silica gel and generates heat that can be removed into the space-heating loop through the adsorber heat exchanger.

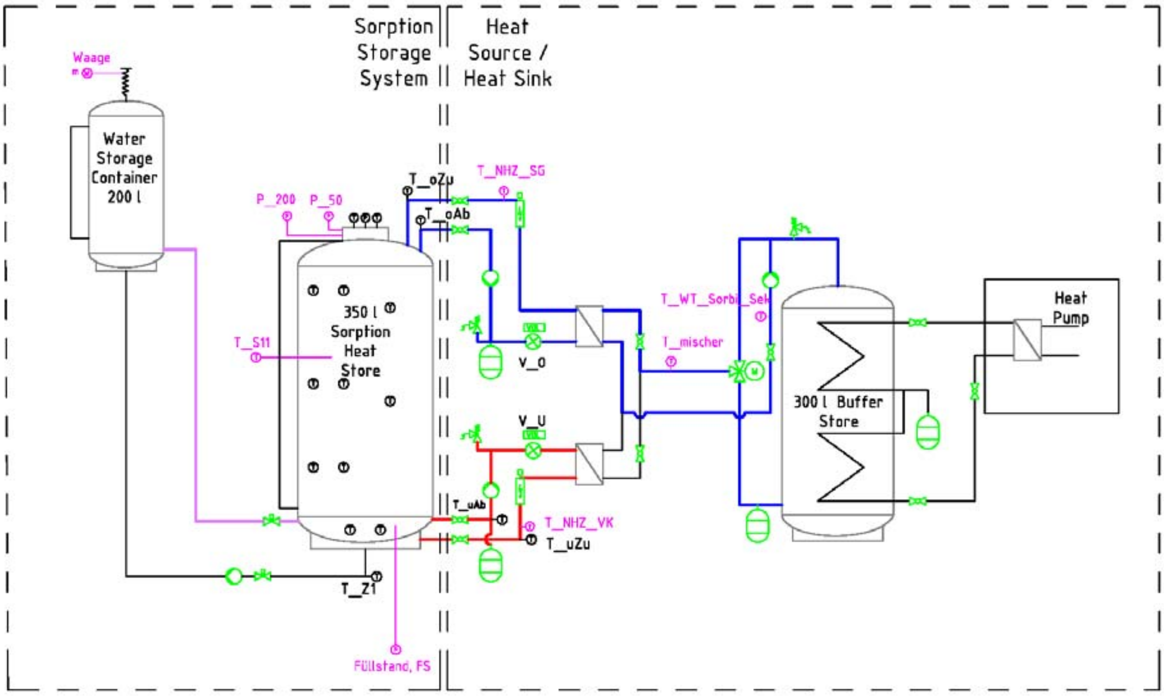

Fig. 18: Setup of the test facility for adsorption tests

To test adsorption operation at the test facility, the desired temperature and energy at the inlet of the evaporator heat exchanger was set by the second electrical heating element located in that circuit. Two manual valves were switched over so that the buffer store could be used as a heat sink for the upper circuit simulating the space-heating loop. The return temperature of the simulated space-heating loop was generated by mixing the flow temperature down to the desired value using the temperature available in the buffer store. Again, the buffer store was cooled by a heat pump. Fig. 18 shows the heating and the cooling loops for the adsorption test runs marked in red and blue respectively.

3.1 Influence of Water Level

In the course of the experiments, it turned out that the water level in the evaporator has a significant influence on the performance of the system. This becomes apparent in the test run described below.

3.1.1 Control Strategy

The control strategy for an adsorption test run includes 3 aspects. The first aspect is to simulate a space heating load. The second one is to control the water level in the evaporator area and the third one is to control the inlet temperature to the evaporator heat exchanger.

In this test, the space heating load was simulated by providing a constant return temperature and a constant flow rate through the space-heating loop.

To reach the desired store temperature, water must be led into the evaporator/condenser area up to a certain specified water level. The water level is detected using a level sensor. The water is led into the store simply by opening the valve between the water storage container and the sorption store. For that reason the water storage container is positioned at a higher level than the sorption store.

The water was meant to just cover the entire evaporator heat exchanger. Therefore, the control was set according to the values obtained when the evaporator was gauged by liters for calibrating the level sensor. According to this, about 32 liters of water should just cover the heat exchanger. To keep the valve from opening and closing too often, a hysteresis of a few liters was used.

Table 5: Control strategy for adsorption in constant store temperature mode

Variable	**Abbr.**	**Value**
Desired adsorber temperature	T_si_set	40°C
Adsorber heat exchanger		
Inlet temperature	T_o_Zu	T_o_zu = 32-33°C
Flow rate	V_o	475 l/h
Evaporator/Condenser		
Inlet temperature	T_u_Zu	Inlet temperature started at 20°C but was increased throughout the test (see text below for more details)
Flow rate	V_u	110 l/h
Control of Water Level	FS	Keep water level just above the upper edge of the evaporator heat exchanger.

When the adsorption process was started, water was led into the evaporator area and the evaporator inlet temperature was set to 20°C. The adsorber temperature was then controlled manually. When the adsorber temperature dropped somewhat below 40°C, the evaporator inlet temperature was increased by 2K. The maximum evaporator inlet temperature was 27°C. After reaching that value, it was kept constant until the end of the test.

3.1.2 Results

The test was started at an average adsorber temperature of 32°C. Then, water was led into the evaporator and the adsorber temperature increased rapidly. It was held at around 40°C for approximately 20 hours but still stayed above 35°C for more than 24 hours afterwards.

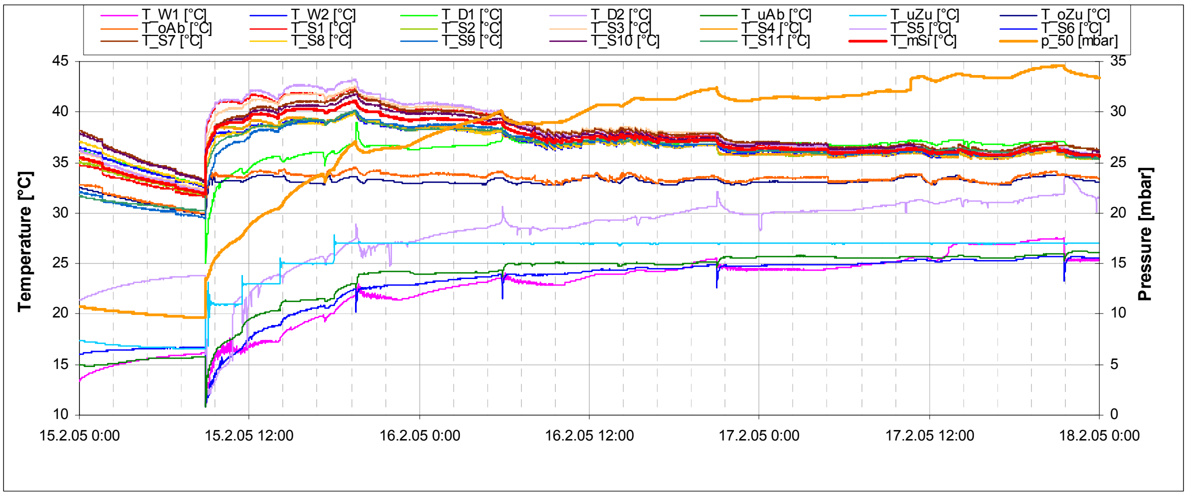

Fig. 19: Temperatures and pressures, influence of water level test

The inlet temperature to the space-heating loop was kept fairly constant at 31-32°C but due to varying store temperatures the transferred power ranged between 0 and 500 W. The evaporation power always increased rapidly when the inlet temperature is increased and then decreased continuously afterwards.

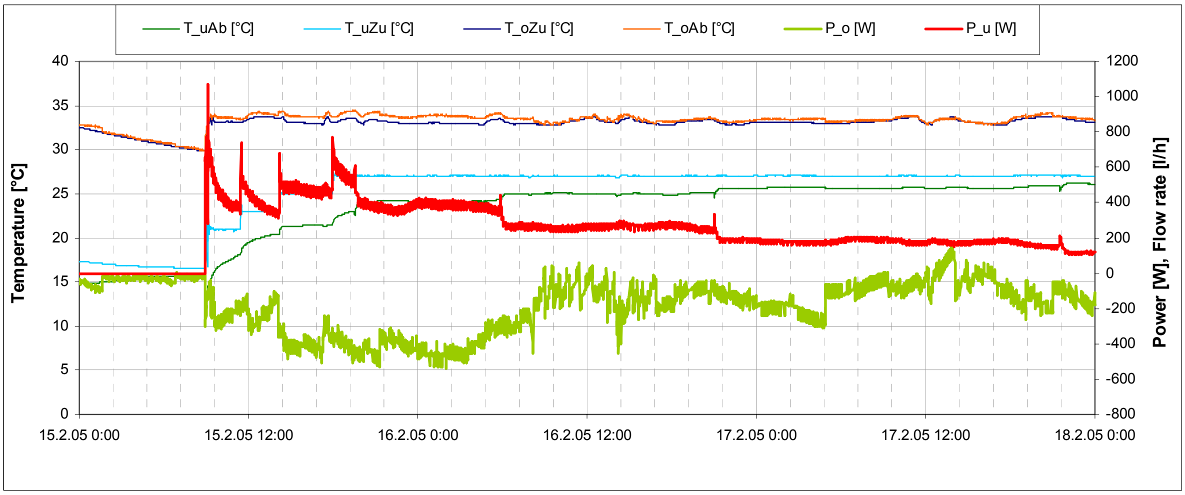

Fig. 20: Power and temperatures, influence of water level test

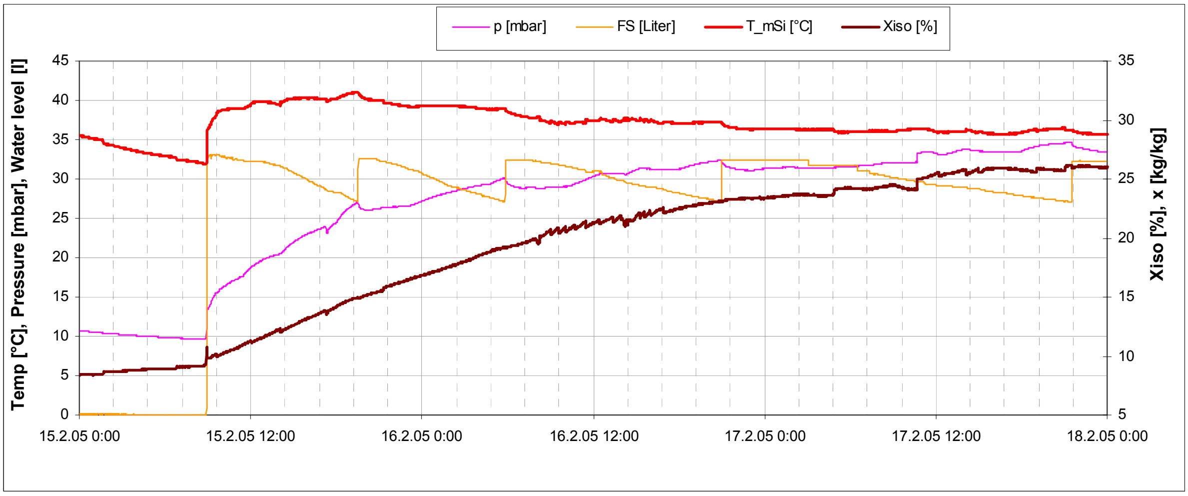

Fig. 21: Water content, influence of water level test

The water content of the silica gel increased almost linearly from a value of 10% to almost 20%. After that, the slope of the curve became smaller. The water level in the evaporator went up to 33 liters at the beginning of the test and then decreased until it reached 27 liters. Then, more water was led into the evaporator.

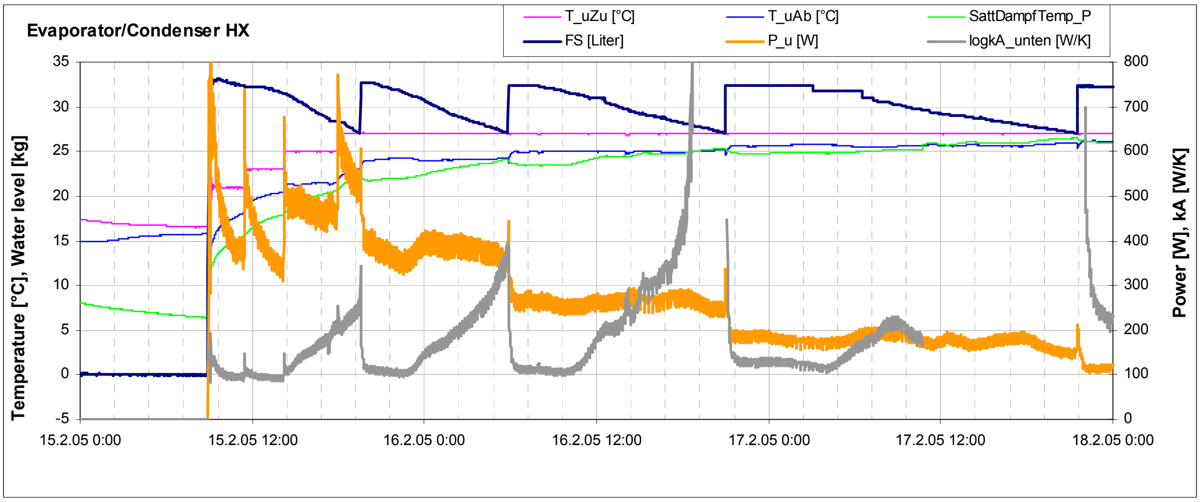

Fig. 22: Influence of the water level on the UA-value of the evaporator heat exchanger

From the measured power transferred across the heat exchanger and temperature differences, the UA-value is calculated according to the logarithmic temperature difference method. The UA-value varied from 100 W/K to up to 700 W/K. A strong dependency on the water level in the evaporator area can be noticed. When the water level is low, the UA-value is much higher than when it is above approximately 32 liters. These findings match the fact that the heat exchanger was just covered with water at 32 liters when the level sensor was gauged by liters.

As soon as there is some water above the heat exchanger, the heat transfer is not as good anymore. Evaporation takes place mainly at the water surface at not at the heat exchanger surface. Apparently, a layer of water above the heat exchanger inhibits the heat transfer from the heating surface to the evaporating surface of the water.

These experiences show that when designing the heat exchanger as much as possible of the heat transfer area should be placed in contact with or very near the water surface. That means a wide and flat heat exchanger is better than a narrow and high one.

The results also show that the arrangement used for the evaporator in the HYDES project was not very advantageous because the entire water reservoir was above the heat exchanger. This led to a very low UA-value.

3.2 UA-value Adsorber Heat Exchanger

The next test run shows an adsorption process starting with very dry silica gel and a high initial temperature of the store. The operation of the adsorber heat exchanger in an adsorption situation is shown.

3.2.1 Control Strategy

Just like for the test before, the return temperature of the simulated space hating loop was kept constant at 32 to 33°C.

The water level in the evaporator area was kept a little bit lower than in the previously described test. The maximum water level was about 30 liters.

Table 6: Control strategy for adsorption in constant store temperature mode

Variable	**Abbr.**	**Value**
Desired adsorber temperature	T_si_set	40°C
Adsorber heat exchanger		
Inlet temperature	T_o_Zu	T_o_zu = 32-33°C
Flow rate	V_o	480 l/h
Evaporator/Condenser		
Inlet temperature	T_u_Zu	Inlet temperature calculated as a function of system pressure and store set temperature (see text below for more details)
Flow rate	V_u	180 l/h
Control of Water Level	FS	Keep water level just below the upper edge of the evaporator heat exchanger.

The temperature needed to evaporate water depends on the current water content of the silica gel and the adsorber temperature. More precisely, the evaporation temperature needed to reach the desired store temperature depends on the store set temperature and the water content of the silica gel at the time when the desired temperature will be reached.

Unfortunately, only the currently measured variables can be used for control purposes. Therefore, the water content of the store was estimated from the measured system pressure and the store set temperature. With this value, the necessary evaporator temperature was calculated. Fig. 23 shows the correlation of system pressure, store set temperature and evaporator temperature.

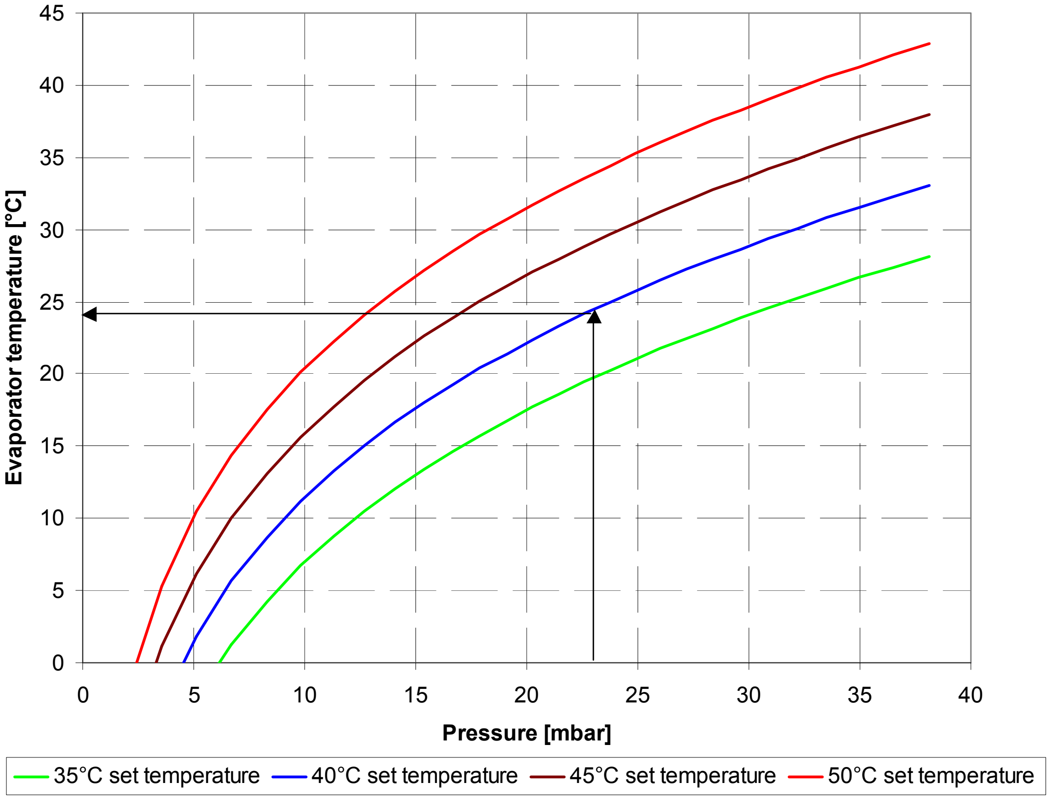

Fig. 23: Control strategy for the evaporator inlet temperature in adsorption mode

3.2.2 Results

The adsorption started at an adsorber temperature of 55°C. Water was led into the evaporator area and evaporation started right away although the evaporator was not heated. The temperatures measured in the water surrounding the heat exchanger and in the evaporator loop decreased below 10°C. On the other hand, the adsorber temperature increased rapidly to almost 70°C. Then, it decreased again because the store was discharged into the space-heating loop.

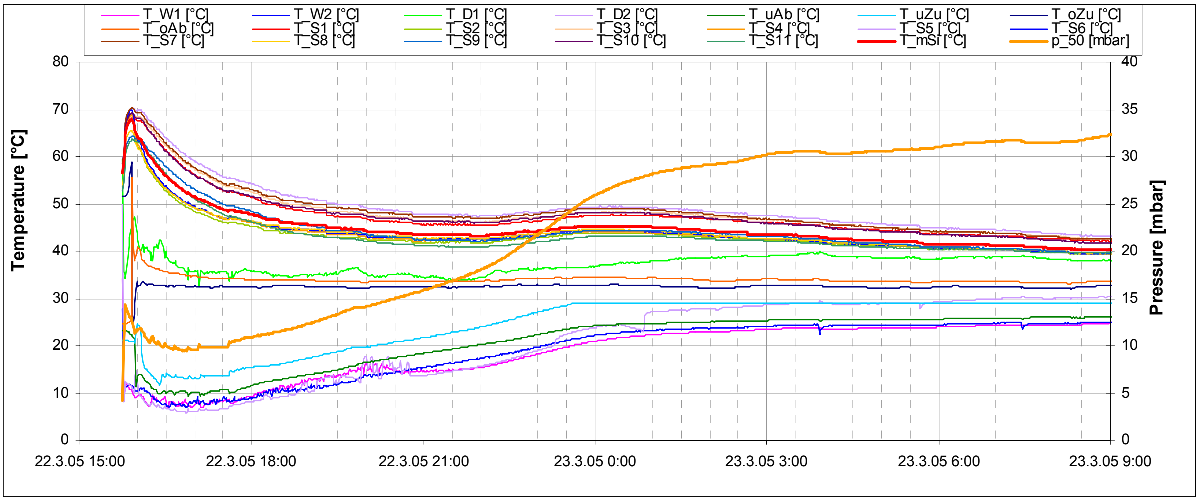

Fig. 24: Temperatures and pressure, adsorption test

The evaporator inlet temperature was calculated according to the algorithm described above. Unfortunately, this algorithm only works if the adsorber temperature is below the set value. In this experiment, the evaporator inlet temperature was increased although the temperature in the store was high enough anyway and evaporation was not necessary. Therefore, the algorithm had to be improved for the following tests.

The results show that high temperatures can easily be reached in the adsorber if it is still very dry.

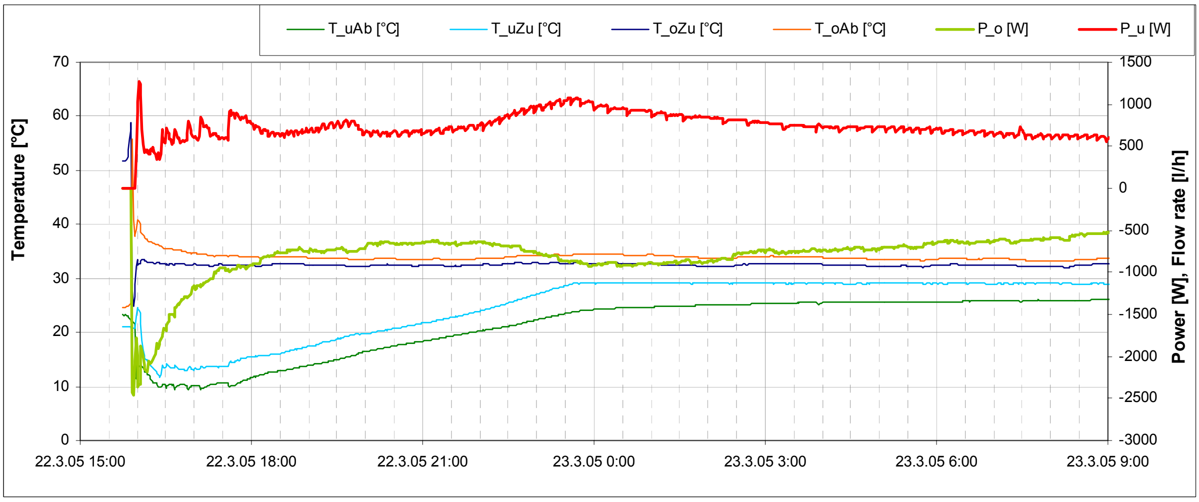

Fig. 25: Power and temperatures, adsorption test

The power withdrawn to the space-heating loop was not very constant again but depended on the current store temperature because inlet temperature and flow rate were kept constant. In the beginning of the test with store temperatures of almost 70°C, the power withdrawn reached almost 2500 W. Then it decreased to between 500 and 1000 W. Of course, this is not a realistic situation for a space-heating loop. If the temperatures available in the store are higher than needed, the mixing valve in the space-heating loop will decrease the flow rate and the power discharged from the store will stay the same.

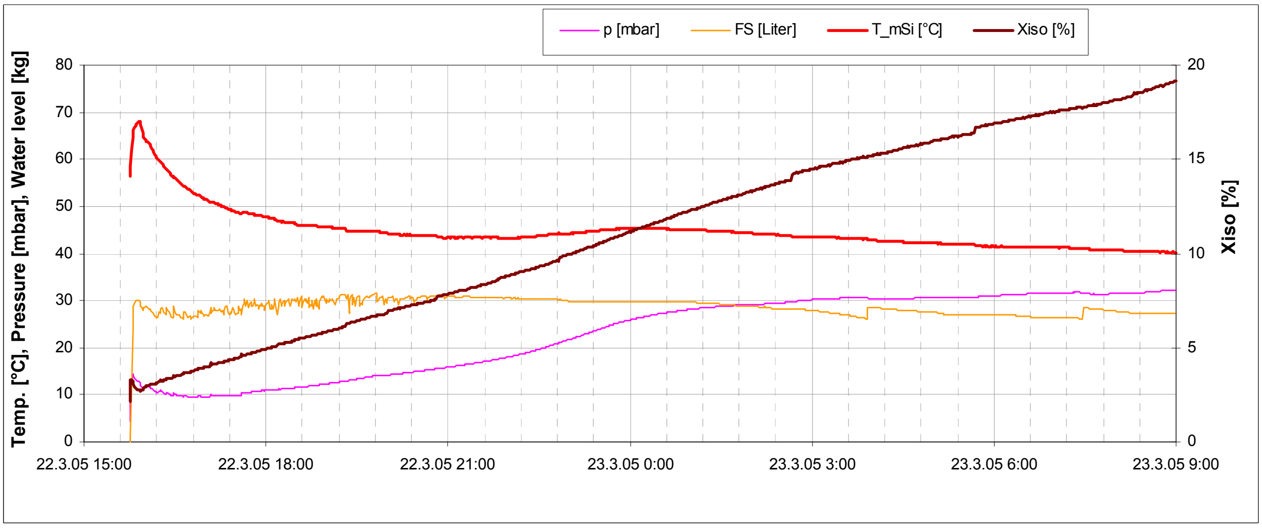

Fig. 26: Water level, water content of silica gel, temperature and pressure, adsorption test

The water content of the silica gel increased from 2.7% to 19% during 17 hours of operation.

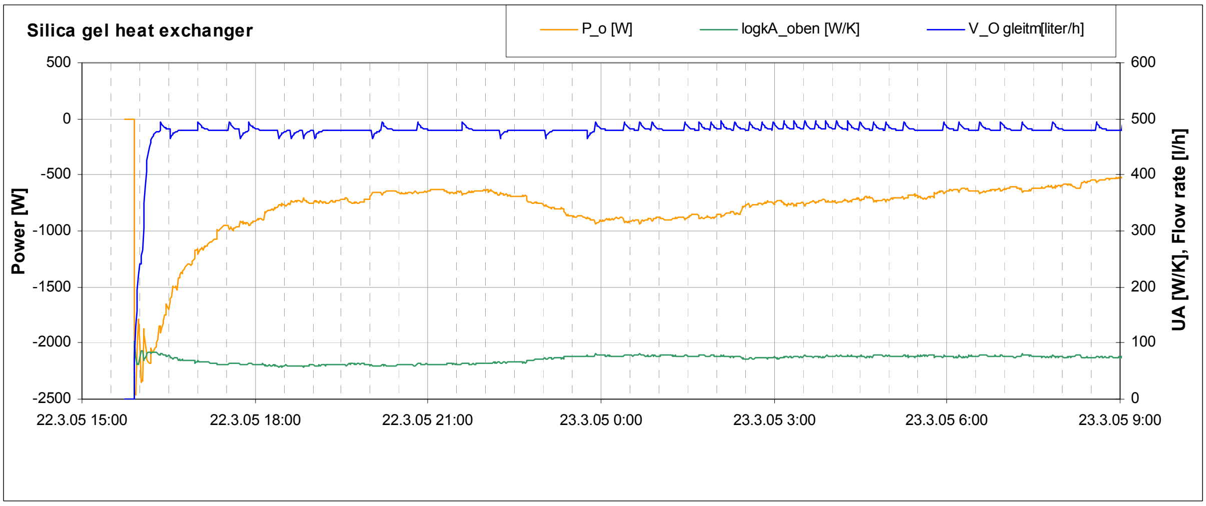

Fig. 27: Power, flow rate and UA-value adsorber heat exchanger, adsorption test

Fig. 27 shows an analysis of the adsorber heat exchanger during this adsorption test. The transferred power was between 500 and 1000 W for most of the test and the corresponding UA-value was only 60 – 80 W/K. This value is quite low and, again, shows the bad heat transport characteristics of the silica gel.

For future applications, the heat exchanger should be improved to ensure smaller temperature differences across the heat exchanger. The same conclusion was drawn from the analysis of the adsorber heat exchanger during desorption testing.

3.3 Constant Store Temperature

When space heating is required, the sorption store has to be heated to a certain temperature depending on the desired flow temperature in the heating loop and then kept at that temperature until the space-heating loop is shut off. For the test run described below, a constant set temperature of the store of 40°C was assumed which is likely to be the maximum required for a low-temperature heat distribution system.

3.3.1 Control Strategy

In this test, a different control strategy was used to generate a more realistic space heating load. This is done by controlling the space heating return temperature (=inlet temperature to the adsorber heat exchanger) and the flow rate through the heat exchanger so that the heating power withdrawn to the heat sink has a realistic value. For most of the experiments a value of a few hundred watts was chosen. The reason for choosing a value as small as that is that the store is much smaller than it will be in a real single-family house application and therefore the heating power has to be chosen accordingly.

For controlling the evaporator inlet temperature, the same strategy as in the previous test was used calculating the needed evaporator temperature from the current system pressure and the desired store temperature.

But in contrast to the previous test, the evaporator inlet was only heated when the store temperature was below the desired value.

As soon as the store temperature drops below the desired value, the evaporator inlet temperature is heated to the calculated value. However, this initial value will still be too low to reach the set temperature. But as the evaporator temperature goes up and some water evaporates, the pressure will increase and a new (higher) value for the evaporator inlet temperature is calculated. Using this iterative method, the desired store temperature will be reached.

Table 7: Control strategy for adsorption in constant store temperature mode

Variable	**Abbr.**	**Value**
Set temperature adsorber	T_si_set	40°C
Both circuits are turned on if T_silicagel < T_si_set:		
Adsorber heat exchanger		
Inlet temperature	T_o_Zu	T_o_zu = T_silicagel – 4, on 30/07/05 at 17:00 changed to -7 (hysteresis 1 K)
Flow rate	V_o	280 l/h
Evaporator/Condenser		
Inlet temperature	T_u_Zu	Inlet temperature depending on the current water content of the silica gel (see text above for more details)
Flow rate	V_u	250 l/h
Control of Water Level	FS	Keep water level just below the upper edge of the evaporator heat exchanger.

The most important control variables are summarized in Table 7.

3.3.2 Results

The adsorption test was started when the adsorber part of the store was still at a high temperature from the previous desorption test. Therefore, water was led into the store, the pump for the evaporator heat exchanger was turned on but heating of the evaporator started only when the adsorber temperature dropped below the set temperature.

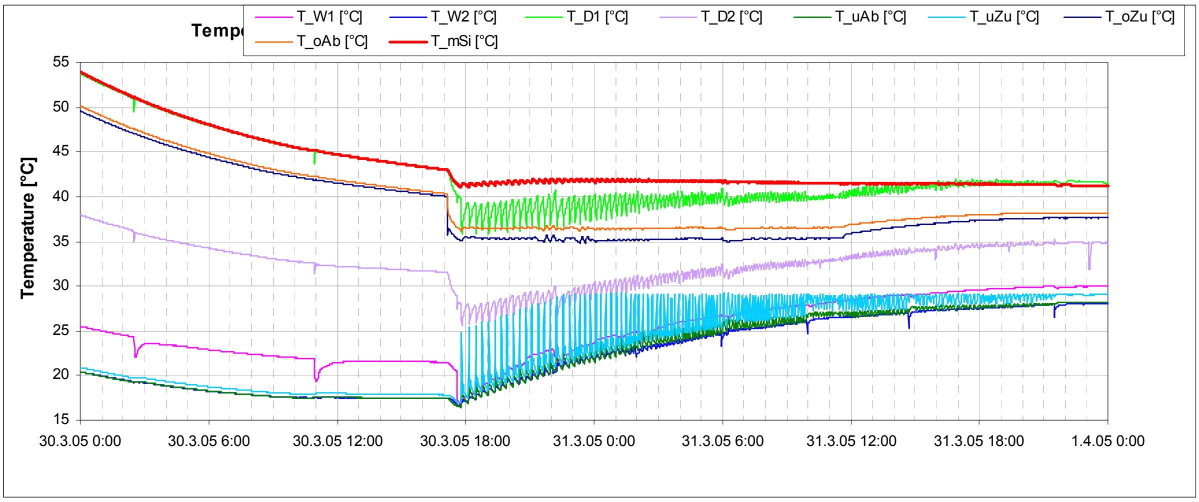

Fig. 28: Temperatures, adsorption with constant store temperature

In the beginning of the test run, the heat withdrawn to the simulated space-heating loop was far too low (100-200 W). Therefore, the space heating load was increased to around 400 W on March 30, 2005 at 17:00 h. In Fig. 28 one can see the significant drop in temperature at that time. Shortly after increasing the space heating load, the store temperature fell below 40°C and the system started to cycle. The average adsorber temperature is kept at around 42°C. Only one temperature sensor was used for the control and this one is obviously a couple of degrees below the average.

When cycling started the evaporator inlet temperature calculated with the algorithm described above was about 22°C at a water content of the silica gel of about 10%, at the end of the shown period the evaporator temperature has reached 28°C at a water content of 22%. The evaporator inlet temperature was limited to that value because of a temperature higher than that is available from the solar thermal collectors it would be more efficient to use that temperature directly in the space-heating loop than to go through the sorption heat store.

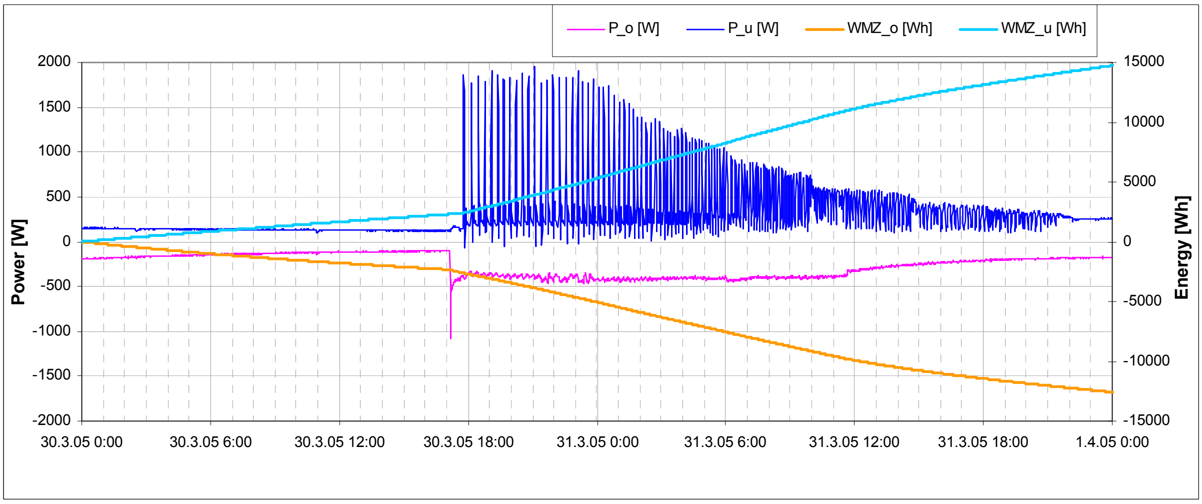

Fig. 29: Power and cumulated energy, adsorption with constant store temperature

The simulated space heating load stays at 400 W. Only at the end of the test run the heat pump that was meant to cool the buffer store had failed. Therefore, the temperature in the buffer store increased slowly and the desired return temperature in the space-heating loop could not be reached anymore (see Fig. 28).The power used for evaporation oscillates between 1800 W and 0 due to the cyclic operation.

The other two curves in Fig. 29 show the cumulated energy on the heating and the cooling side of the store. The energy transferred in 30 hours of operation (counting from the start of the cycling) are 12.2 kWh at the evaporator and 9.9 kWh into the space-heating loop. That means that there were store losses of approximately 2.3 kWh knowing that the additional adsorption energy is very small.

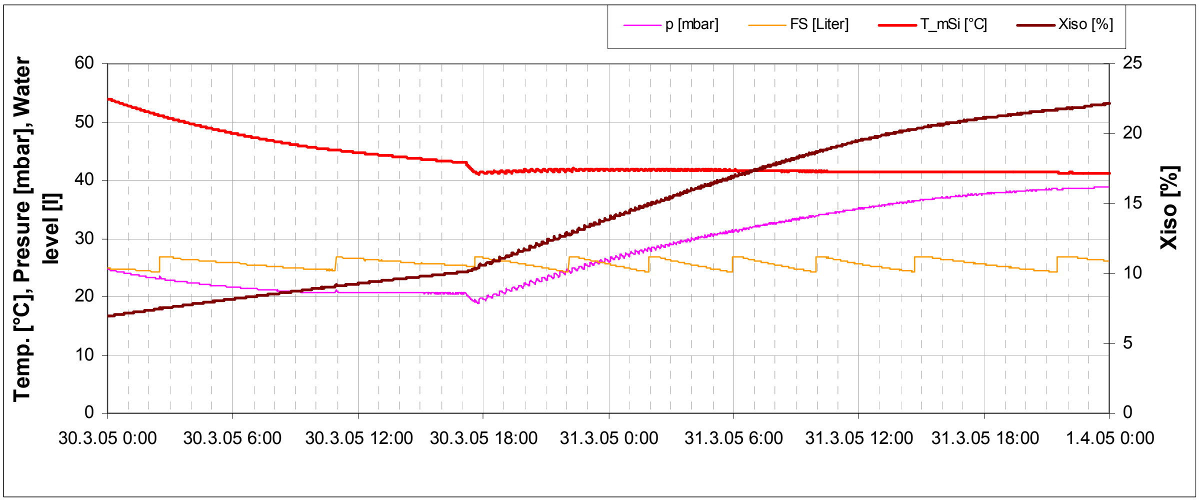

Fig. 30: Water content of silica gel and water level in evaporator area, adsorption with constant store temperature

The water content of the silica gel was 7% at the beginning of the test. During the first 18 hours of the test, no energy was put into the evaporator but nevertheless some water evaporated due to heat transfer from the outside into the evaporator area. The water content of the silica gel increased to 10%. When the cycling starts the evaporator is heated and the water content of the silica gel increases more rapidly. After 30 hours of cyclic operation the water content has increased to 22%. Fig. 30 shows the development of the water content as well as the average adsorber temperature, the system pressure and the water level in the evaporator area measured in liters of water. The water level was controlled to be between 25 and 27 liters which is just about around the upper edge of the heat exchanger.

3.4 Adsorption with Very Dry Silica Gel

This test is very similar to the one described in section 3.3. The only difference is that the adsorption process was started after cooling the store rapidly below 40°C. The reason for that was that in a real application the store will be cold when adsorption starts because there is heat demand in the space-heating loop.

3.4.1 Control Strategy

Before the test started, the store was very hot from the last desorption test (90°C). After the desorption test had ended, the water was pumped out of the bottom of the store controlled by the level sensor just like in every desorption test run.

Before starting the adsorption test, the store was then cooled by circulating cold water from the buffer store through the adsorber heat exchanger. There was no flow in the evaporator heat exchanger.

When the adsorber temperature had decreased to about 35°C, the adsorption was started by letting water into the evaporator area and turning on the pumps for both the evaporator and the adsorber heat exchanger. The cooling phase between the desorption and adsorption test took approximately 1.5 hours.

3.4.2 Results

The development of the system pressure and temperatures are shown in Fig. 31. The temperature sensors T_{W1} and T_{W2} are the ones located above and next to the evaporator heat exchanger. That means they are in the water vapor throughout the cooling phase. At 10:45 h one of the sensors goes below 0°C. When the adsorption was started, there was no flow through the evaporator heat exchanger and the water led into the evaporator surroundings froze instantly. After some time it became obvious that the heat exchanger pipes had burst due to ice formation inside the pipes.

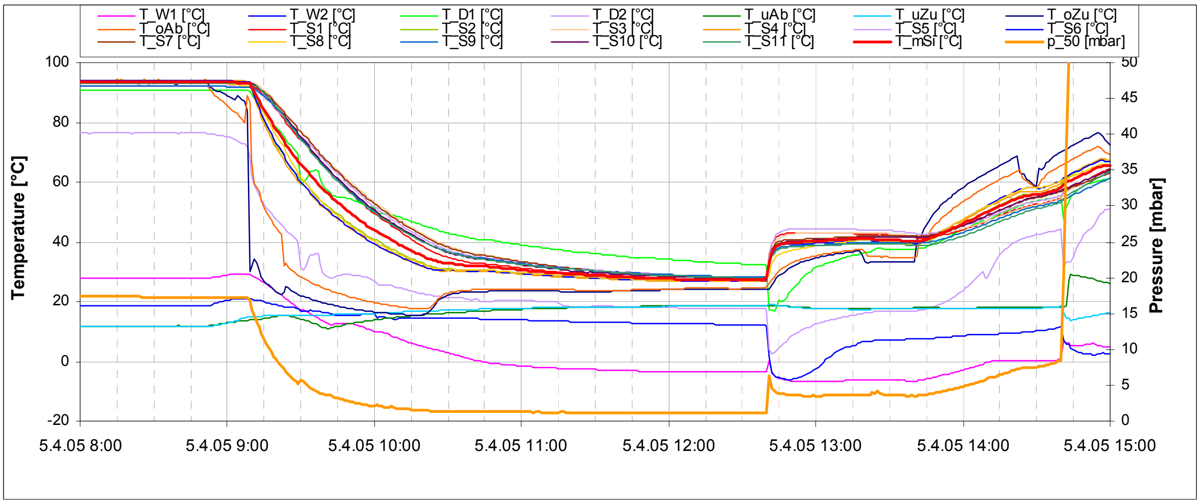

Fig. 31: Pressure and temperatures, adsorption test with very dry silica gel

An explanation for this gives Fig. 32. If the water content of the silica gel is very low, the theoretical available temperature lift can be as high as 70 K or even more. As long as there is no liquid water present, nothing happens. If there is some leftover water in the bottom of the store, it evaporates and cools the remaining water. The temperature of the water vapor is the adsorber temperature minus the temperature lift. This can easily be below 0°C.

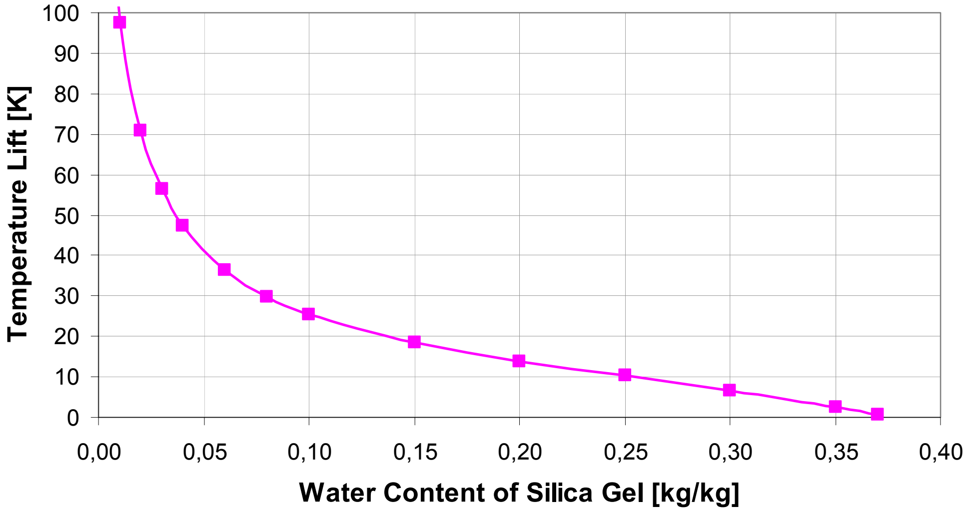

Fig. 32: Available temperature lift as a function of water content of the silica gel at an evaporator/condenser temperature of 20°C

3.4.3 Ice Formation in the Evaporator

In the case of the underlying experiment, this is the only logical explanation of what happened. There was some water (probably 0.5 liters or so) left in the bottom of the store. When it evaporated, sub-zero steam passed the evaporator pipes and the water inside the pipes froze.

Then, water was let into the evaporator area and froze instantly at the water surface. At some point the evaporator pipes burst and there was no pressure on the evaporator loop anymore.

Fig. 33: Burst evaporator pipe

After disassembling of the system, it became visible that many of the bent pipe connections in the evaporator had burst as shown in Fig. 33.

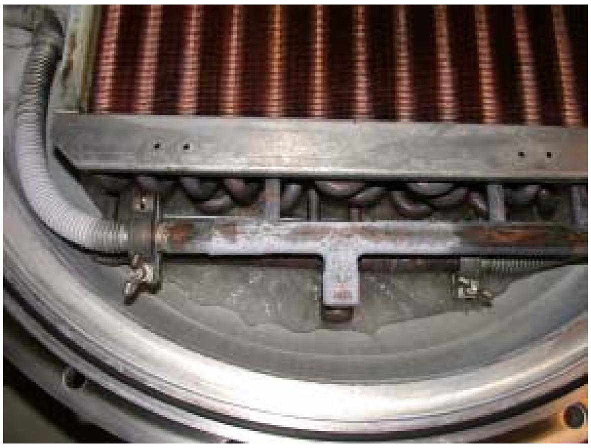

Fig. 34: View inside the evaporator area after freezing occurred

Below the heat exchanger was a sheet of ice where used to be the water surface. Fig. 34 shows the ice sheet still inside the store, and Fig. 35 shows a view from the bottom of the heat exchanger after taking it out of the store. The ice sheet is very flat which shows that freezing has occurred at the water surface.

Fig. 35: Evaporator with frozen ice sheet which used to be the water surface

The freezing of the inside of the evaporator heat exchanger happened under very extreme operating conditions:

- The silica gel was very dry
- The store had been cooled very quickly
- There was some water left at the bottom of the container
- There was no flow through the evaporator heat exchanger

These type of operating conditions are not that likely to occur in a real application. The reason for that is that very dry silica gel is reached at the end of summer or during extended sunny periods in winter. In most cases, the store will cool down after desorption without heat being removed and even if the store is discharged to the space-heating loop the heating load will be rather small. In those cases, even if there is some water left in the store, there will be enough time to add the required heat of evaporation either by operating the evaporator loop without load or by heat transfer from the surroundings. After the leftover water has been evaporated, there is no danger of freezing inside the pipes anymore.

3.5 Adsorption with Inert Gases in the Store

Adsorption operation was also tested with inert gas in the store. For this purpose, the store was not fully evacuated but only to a system pressure of 60 mbars.

The adsorber was cold at the beginning of the test. When water was led into the evaporator area and heated, the temperature of the adsorber increased by a few degrees but not further than that. This shows that some water vapor was adsorbed. But the effect is too slow and too small to be technically useful.

The goal of the test was to be able to reduce the vacuum significantly. It was shown that this is not possible as a vacuum pressure of 60 mbar already prevents proper adsorption operation

3.6 Conclusions for Adsorption in a Single-Family House Application

A detailed analysis of the heat exchanger used in the 2nd generation prototype design lead to the following conclusions:

- Evaporator: Measurements of the UA-value of the heat exchanger showed that the UA-value depends strongly on the water level outside of the heat exchanger. The best UA-values are reached if the water level is just below the upper edge of the heat exchanger. If the heat exchanger is covered by a layer of water, the UA-value goes down significantly. When designing the heat exchanger for the next prototype system, it should be as wide and flat as possible.

- Adsorber heat exchanger: Also in adsorption mode, the heat exchanger works well in general. A sensible ratio between the thickness of the sheet copper and the distance between heat exchanger pipes is necessary. The values chosen for this prototype were a good compromise. However, the UA-value is quite low and should be improved by soldering the pipes on the entire length to the sheet copper and reduce the distance between the spiral layers as already mentioned in the desorption section.

The control of the adsorption operation is much more difficult for the 2nd generation system than it was for the 1st generation system. The reason for that is that there is no valve between the evaporator and the silica gel. That means that the amount of water vapor absorbed can only be controlled by letting more or less water into the evaporator area and/or by heating the evaporator more or less.

In a real space-heating application, the temperature at the inlet of the evaporator cannot be chosen freely but depends on whatever is available from the solar thermal collectors or in a buffer store. Control of the adsorber temperature worked well with cyclic operation of the evaporator. When the water content of the silica gel is low, freezing at the outside of the heat exchanger occurred during most test runs. This could be noticed by noise inside the store generated by ice crystals touching the heat exchanger fins. Except for the noise, this kind of ice formation didn’t cause any problems in the operation of the system. The ice melted again during the further operation.

The biggest freezing problem occurred during very extreme operating conditions. But until a safe and reliable control strategy is found, it would not be wise to use the system design as it is in a real-application pilot plant. A possible solution of this problem is presented in the following chapter.

4 Redesign of Prototype for Pilot Plant

The results of the laboratory tests of the 2nd generation system led to some changes in the design of the system for the pilot plant system planned to be installed in a single-family house in Austria in the framework of a follow-up Austrian national project. A sketch of the new system design is shown in Fig. 36.

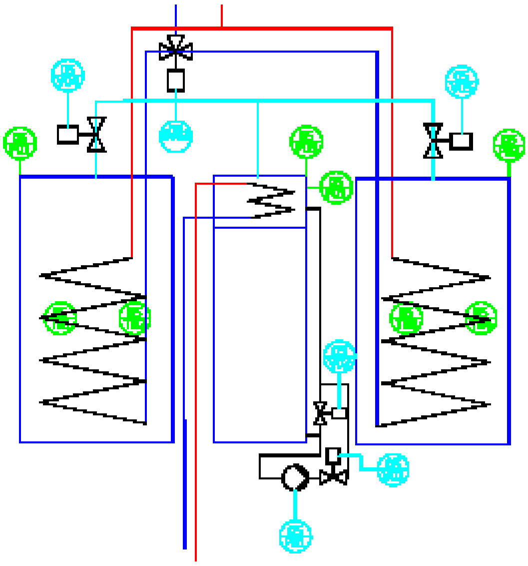

Fig. 36: Setup of the pilot plant system

The following changes are planned:

- Separation of evaporator/condenser and adsorber by a valve. This way freezing of the evaporator/condenser heat exchanger can be prevented simply by closing the valve. The system will be modular with two adsorbers. The new design means that only one evaporator/condenser is necessary. With the 2nd generation design two heat exchangers would have been necessary. The evaporator/condenser is integrated into the top of the water storage container. When adsorption is needed, water is pumped from the water storage to the evaporator and the valve to one of the adsorbers is opened only when there is enough steam available in the evaporator.

- The evaporator/condenser heat exchanger will be designed so that the flow regime will be turbulent at all times. In addition, the evaporator will be wide and flat to ensure good heat transfer to the water surface.

- The adsorber heat exchangers will be improved by soldering the pipes to the sheet copper on their entire length. This will be done in a soldering oven just like absorbers for solar thermal flat plate collectors are produced. In addition, the distance of the sheet copper layers will be decreased from 5 to 4 cm whereas the sheet copper material itself and the distance between the pipes will remain the same.

5 Experimental Study of Adsorption of Water Vapor on Silica Gel Particles of Different Particle Size

5.1 Introduction and Goals

The goal of this study was to test the influence of the particle size on the adsorption of water vapor on silica gel. Differences regarding the kinetics of the reaction as well as the final water content of the silica gel are possible. To eliminate differences due to different manufacturing processes or the chemical composition of the silica gel, different particle sizes were obtained by crushing of the same silica gel sample.

5.2 Experimental Details

Silica gel (LON 51939), in three different particle sizes („original size", Ø = approx. 2.6-5 mm (A); Ø = 0.5-1 mm (B); Ø = 0.063-0.1 mm (C)), is weighed out in cylindrical borosilicate glass containers (Ø = 3 cm) („initial weight"). In addition, sample C is covered with a glass frit (porosity G2) for the desorption process (Fig. 37), because the desorption process led to powerful mass transport (convection) as determined in preliminary tests (see below for more details).

The silica gel samples were evacuated simultaneously to a pressure of 1 mbar in a vacuum drying chamber by the company Heräus using a rotating vane oil pump (Edwards RV 8; capacity: 8 m^3/h; final vacuum: 10^{-3} mbar). Afterwards, they were heated for 2 hours at a temperature of 250°C. Then, they were cooled under vacuum to room temperature and the drying chamber was brought to ambient pressure with argon. (pureness > 99,999 %; H_2O < 3,0 vpm). After further cooling of the samples under argon atmosphere, the samples were weighed again. (= „starting weight"; sample C without glass frit and adherent silica gel particles). The samples were then placed in a glass dehydrator (Fig. 38) that contained liquid water instead of the drying agent. In a water vapor saturated atmosphere, the increase in weight based on the starting weight was recorded in irregular intervals until saturation of the silica gel was reached. Saturation was reached after approximately 51,330 minutes (partial pressure (H_2O) approx. 17 Torr). The key figures of the experiment are summarized in Table 8.

Fig. 37: glass frit (similar)

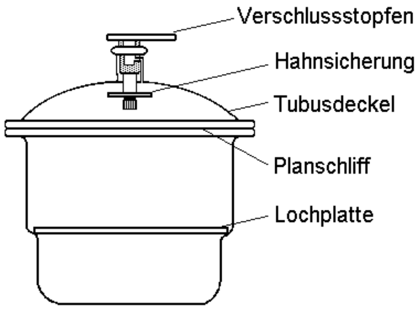

Fig. 38: dehydrator

Table 8: Key figures of the experiment

Sample	Particle size [mm]	Initial weight [g]	Fill level [cm]	Starting weight [g]	Saturation weight [g]	Saturation (relative) [%]
A	2.6-5	25.223	4.3	22.848	30.753	34.60
B	0.5-1	27.472	5.0	25.084	32.894	31.14
C	0.063-0.1	24.991	4.9	23.329	30.469	30.61

5.3 Results and Discussion

Already during the desorption process, significant differences occurred depending on the particle size. The mass of the single particles in sample C is so small that they are dispersed during desorption. The glass container of sample C was therefore closed with a glass frit that is gas permeable but keeps the particles inside the container. Samples A and B did not show such behavior. For the adsorption of water at the dehydrated samples, the glass frit was removed again because a deceleration of the adsorption process due to the glass frit would be likely.

Water adsorption showed a continuous weight gain of all three samples during the time period that they were exposed to the water atmosphere. The increase continued until saturation was reached. In the case of the tested samples and under the given conditions, this was the case after approx. 40,000 minutes. Apart from the development of the weight gain over time, the maximum final water content for the different particle sizes is of interest. An increase of surface area per gram of adsorbent is expected to result in a higher maximum water content if the boundary conditions are the same.

5.3.1 Time Dependent Behavior

The relative adsorption (gram adsorbate/gram adsorbent, Fig. 42), the adsorption rate ($\Delta m/\Delta t_{rel}$ (weight increase per gram adsorbent and time), Fig. 40) and the adsorption progress ($\Sigma ads(t)/\Sigma ads_{max}$, Fig. 39) were determined as characteristic values based on the absolute weight increase of the samples (Fig. 41). The rate of adsorption decreases continuously towards the end of the adsorption period for all particle sizes. It can be noticed that initially the rate of adsorption for particle size C is higher that that of sample size A or B (Fig. 40). That means that particle size C needs less time to reach the same adsorption progress than the other samples (Fig. 39). The smaller particles have a higher adsorption rate in the beginning, but it decreases after some time, goes below that of the larger particle sizes and approaches zero. The development of the relative adsorption shows only small differences between the samples. The smallest particle size (sample C) has the highest relative adsorption, but it is olny 0.5 percentage points better than for the lowest value of sample A or B. The bigger particle sizes show an unexpected trend: The biggest particle size A has the smallest relative adsorption in the beginning, but already at around 7% the values are similar to sample B and from around 15% the values are close to those of sample C. The reason for this could be the transition from surface to pore coverage.

5.3.2 Water Content at Saturation

All three samples adsorb more water than was removed during the preceding desorption process. Obviously, the samples were not saturated at the beginning of the experiment. The water content of the samples before desorption was also not identical because during the crushing process to obtain the smaller particle sizes "bulk"-areas with high water content were transformed into surface that was not saturated. To eliminate these different initial conditions from the analysis, the water content under saturated conditions (Σads_{max}) was used to calculate the adsorption progress. The saturation is reached earlier for the smallest particle size (see Fig. 39). However, the difference in time necessary to reach saturation is very small compared to the total time needed to reach saturation.

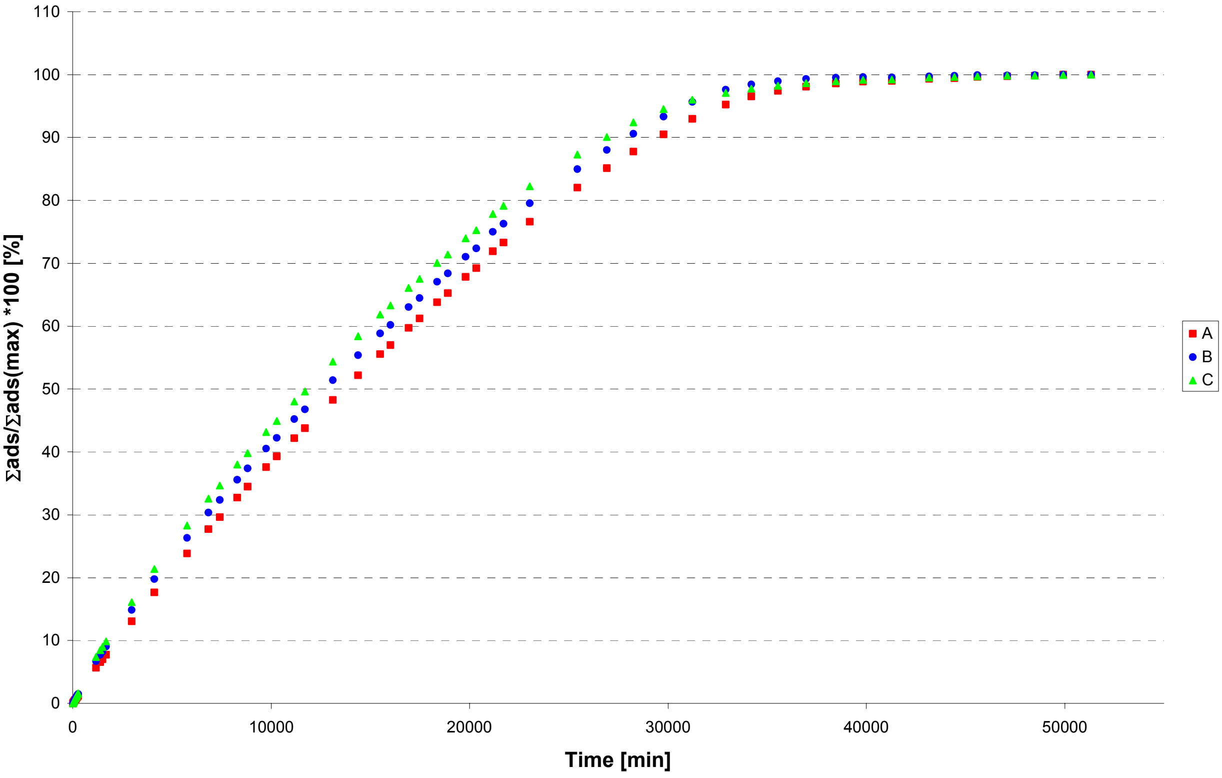

Fig. 39: Adsorption progress during adsorption

5.3.3 Limitations

The conclusions that can be drawn from the results is limited by the fact that the particle size of the samples is not uniform. Each sample represents a distribution of particle sizes within the given range. The exact distribution is not known.

Another limitation is that particle size A is the result of the chemical production process, while the smaller particles sizes were obtained by mechanical crushing of sample A. This could have damaged the microporous structure of the original material. Some pores might be plugged. This could be verified by measurement of the surface and pore distribution of the samples. Another possibility are samples where all particle sizes were obtained by the chemical production process e.g. AEROSIL®. This last approach makes more sense because in a real storage application a commercial product like this would be used.

During the adsorption phase, it was observed that the weight increase during day and night time was not identical. This can be seen best in the diagram with the adsorption rate (Fig. 40). The reasons for this are probably the non-isothermal conditions. Changes in ambient temperature and therefore dehydrator temperature influence the partial pressure of water vapor during the adsorption. For the analysis of the weight increase, this factor is not relevant. However, the absolute values of the adsorption rate are not meaningful without isothermal conditions.

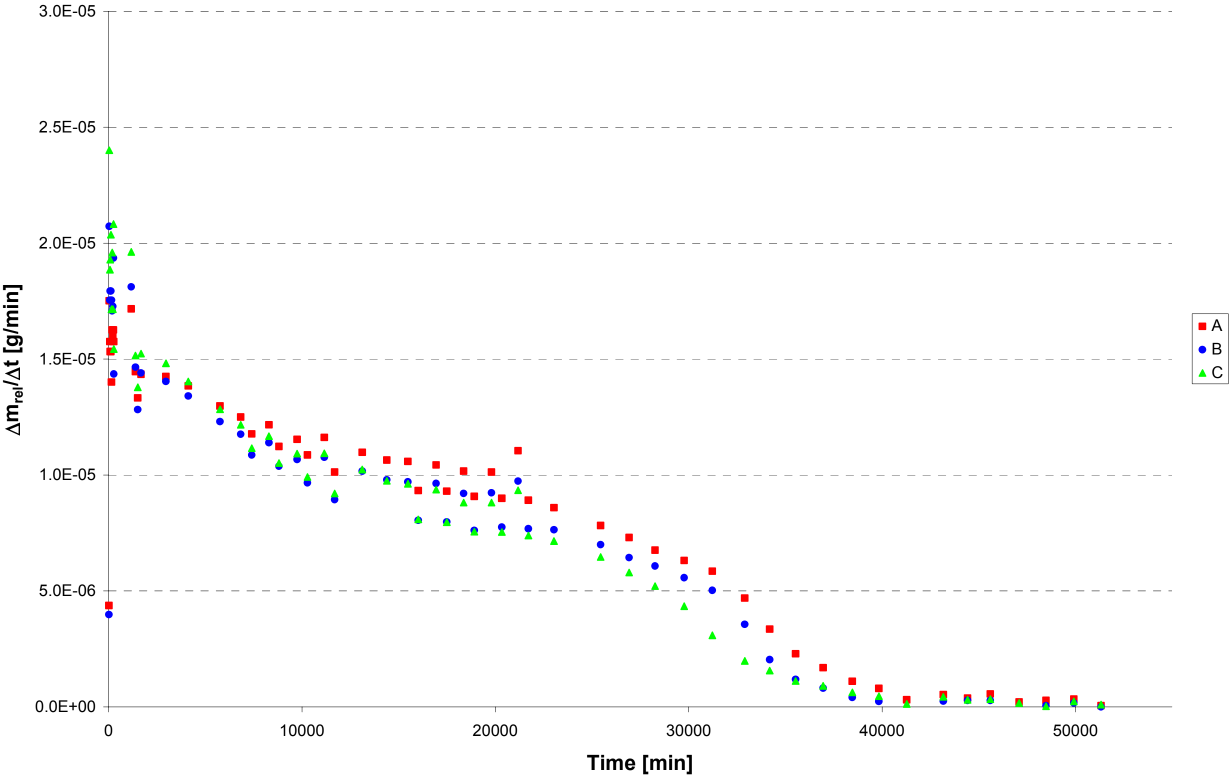

Fig. 40: Adsorption rate during adsorption

5.4 Conclusion

A priori, an acceleration of the adsorption process had been expected when the particle size is decreased. However, the experiments showed that this is not significant. On the contrary, the larger particle sizes have a higher maximum water content even though the adsorption takes place at a slightly slower rate. The reason for the smaller maximum water content of the smaller particle sizes could be the different manufacturing processes and due to this different microporous structure.

The small absolute mass of a single particle in the smallest particle size leads to dispersion during desorption. This mixing of the particles within a heat store might be able to partly compensate for a low thermal conductivity of silica gel. This would enhance heat transfer and is an advantage for storage applications. It would be interesting to analyze other macroscopic material characteristics like thermal conductivity and bulk density to see how they depend on the particle size.

Overall, the effect of the particle size seems to be insignificant based on the underlying results. The faster adsorption process of the smaller particles is overcompensated by the higher maximum water content of the bigger particles. This would mean that larger particles are advantageous for the energy balance of sorption heat stores. It has to be noted that the conclusion is limited by the fact that the reduced maximum water content can be due to the different production process of the samples. A doubtless comparison can be done only with samples that have undergone the same pretreatment.

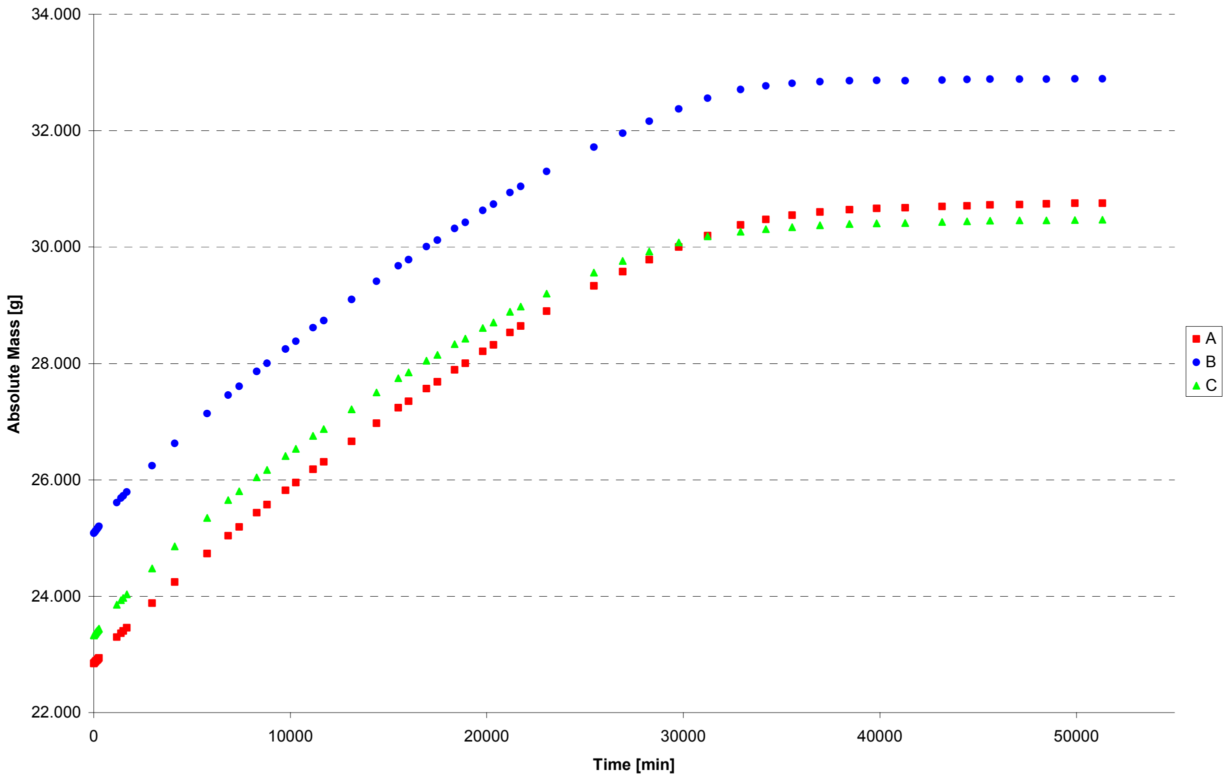

Fig. 41: Absolute weight increase during adsorption

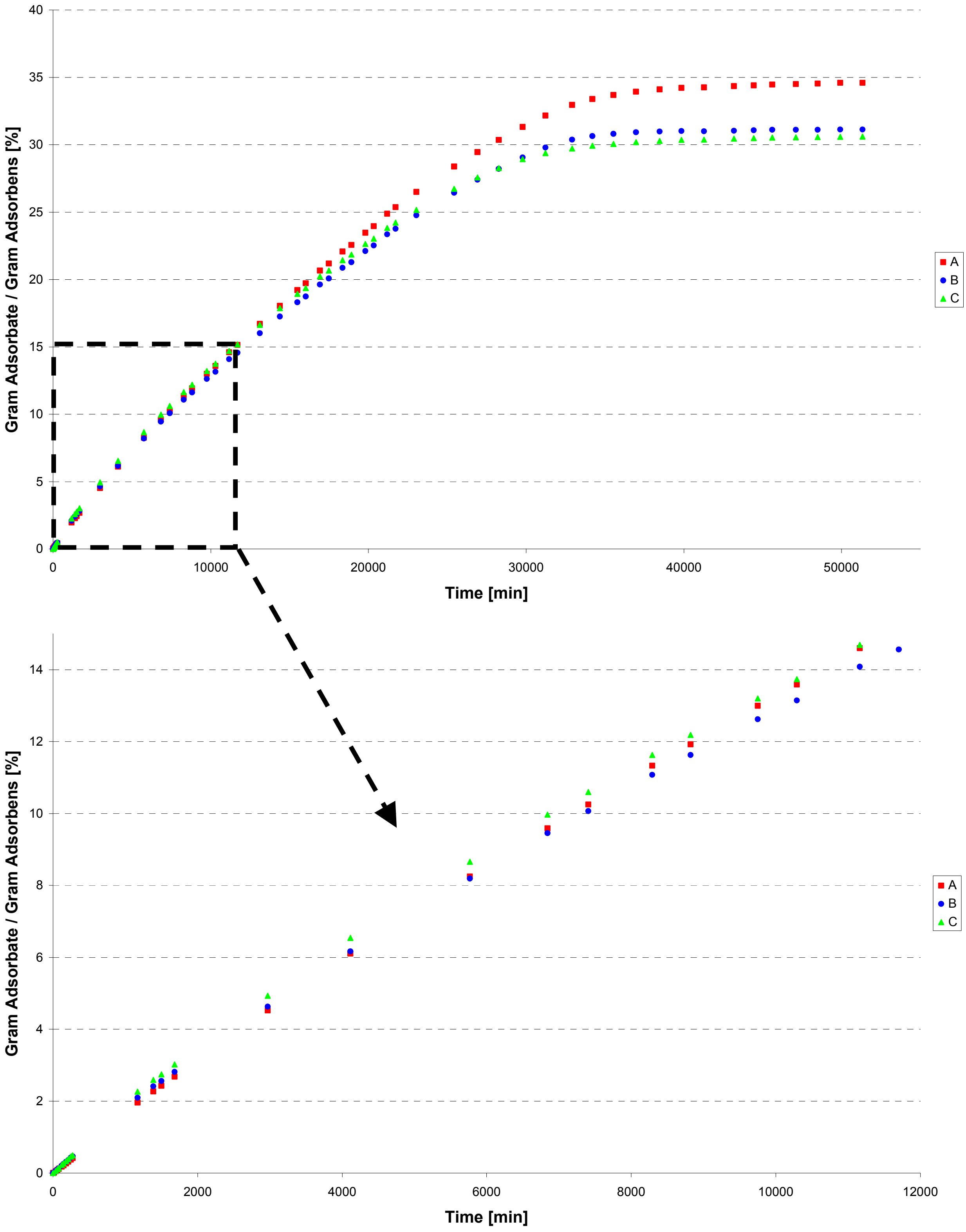

Fig. 42: Relative weight increase during adsorption (with zoom on the first part of the adsorption process)

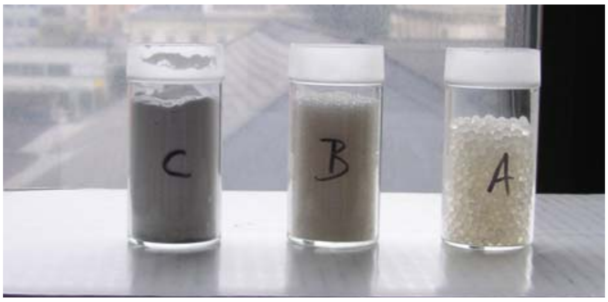

Fig. 43: Samples after saturation

Fig. 44: Vacuum oven with pump and pressure sensor

Fig. 45: Dehydrator with samples during adsorption and scales

6 Conclusions and Outlook

It has been shown that the operation of a sorption storage system under operating conditions that are necessary for space heating in a single-family house is technically feasible.

The 2nd generation system design brought significant improvements compared to the 1st generation system built and tested within the earlier EU project HYDES.

- The heat transfer across the evaporator heat exchanger was analyzed in detail. The result is that the surface of the water body around the heat exchanger should be as close as possible to the heat exchanger surface. Therefore the new design with only little water in the evaporator area is significantly better than the old design with the evaporator heat exchanger located at the bottom of the water storage container.

- The new design and manufacturing process of the adsorber heat exchanger have several advantages compared to the heat exchangers used in HYDES: The pressure drop on the water side is much lower, water vapor can pass through the perforated sheet copper which facilitates vapor transport within the store significantly, less material is used (lower cost, less space lost for sorption material) and the production is cheaper. The available heat transfer area is also larger with the new design while the costs are lower.

- All components are included in a single container: The performance of the 2nd generation system with all components in a single container has been shown to be better than the 1st generation setup. One reason for this is that there is very little pressure drop between the evaporator/condenser and the adsorber. But due to the freezing problems described above it was decided that for the first pilot plant system a valve will be put in between the components. However, it might still be possible to use the design with a clever control strategy and an improved construction that avoids that water stays in the tank after pumping the water into the storage container. More research is needed in this area.

It was shown that it is not possible to utilize the entire theoretical adsorption capacity of about 30 kg per 100 kg of dry silica gel because at higher water contents the available temperature lift is too small to be useful. A water content range from 3 to 13% is the part that can be used technically.

Assuming a storage tank with 1500 kg of dry silica gel, this would mean that 150 kg of water can be adsorbed. The evaporation enthalpy of 150 kg of water is approximately 100 kWh, the additional adsorption energy would be around 4 kWh. That means that a store of this size would be much too small to cover the space heating demand of a single-family house for the heating season, even if it is a low-energy building. Thus, the store would be far from being a seasonal store but would have to be recharged during sunny periods in winter.

For reaching the goal of a seasonal storage, very large storage volumes would be necessary. While this might be technically feasible it does not make a lot of sense because the system is going to be very expensive and the main problem remains, that almost all of the energy (for evaporation) has to be delivered in winter by the solar thermal system even if at a lower temperature.

More materials research will be needed to identify a different sorption material and working fluid combination where the fraction of the binding energy is higher compared to the evaporation enthalpy. Another possibility would be a materials combination with lower evaporation temperatures.

Finally, an important aspect is that the process has to take place under vacuum conditions. The vacuum technology makes the system and its installation more complex.

7 Nomenclature

Symbol	Unit	
Delta_Lot	K	Temperature difference between the location on the pipe and between pipes where the pipes are soldered to the sheet copper
Delta_MI	K	Temperature difference between the two locations between pipes (soldered and not soldered)
Delta_oLot	K	Temperature difference between the location on the pipe and between pipes where the pipes are not soldered to the sheet copper
Delta_RO	K	Temperature difference between the two locations on the pipe (soldered and not soldered)
DeltaTu_zu_ab_SDT_p	K	Temperature difference between the saturated steam temperature at the pressure p and the average of the inlet and the outlet temperature of the evaporator/condenser heat exchanger
FS	l	Water level in the evaporator/condenser area measured in liters
HX		Heat exchanger
logDeltaTo_zu_ab_mSi	K	Logarithmic temperature difference between the average store temperature and the average of the inlet and outlet temperature of the adsorber heat exchanger
logkA_oben	W/K	UA-value of the adsorber heat exchanger calculated using the logarithmic temperature difference
logkA_unten	W/K	UA-value of the evaporator/condenser heat exchanger calculated using the logarithmic temperature difference
MILot	-	Measurement location between pipes where the pipe is soldered to the sheet copper
MIoLot	-	Measurement location between pipes where the pipe is not soldered to the sheet copper
m1	kg	Mass of water in water storage container
P_o	W	Power transferred across the adsorber heat exchanger
P_u	W	Power transferred across the evaporator/condenser heat exchanger
p_{50}	mbar	Pressure sensor located at the top of the store
p_{200}	mbar	Pressure sensor located at the top of the store
ROLot	-	Measurement location where the pipe is soldered to the sheet copper
ROoLot	-	Measurement location where the pipe is not soldered to the sheet copper
SattDampfTemp_P	°C	Saturated steam temperature calculated as a function of system pressure
T_{D1}	°C	Temperature in the steam channel in the middle of the store

T_{D2}	°C	Temperature in the steam channel in the middle of the store
$T_{mischer}$	°C	Temperature behind the mixing valve
T_{mSi}	°C	Average adsorber temperature
$T_{NHZ,SG}$	°C	Temperature behind the electrical heating element in the adsorber heat exchanger circuit
$T_{NHZ,VK}$	°C	Temperature behind the electrical heating element in the evaporator/condeser heat exchanger circuit
T_{oAb}	°C	Outlet temperature of the adsorber heat exchanger
T_{oZu}	°C	Inlet temperature to the adsorber heat exchanger
$T^{sat}(p)$	°C	Saturation temperature at pressure p
$T_{si,set}$	°C	Adsorber set temperature
T_{S1}-T_{S11}	°C	11 temperature sensors located at different positions of the silica gel
T_{uAb}	°C	Outlet temperature of the evaporator/condenser heat exchanger
T_{uZu}	°C	Inlet temperature to the evaporator/condenser heat exchanger
$T_{WT,Sorbi,Sek}$	°C	Temperature on the secondary side going into the buffer store
T_{W1}	°C	Temperature in the evaporator/condenser area
T_{W2}	°C	Temperature in the evaporator/condenser area
V_o	l/h	Flow rate through the adsorber heat exchanger
$V_{o,gleitm}$	l/h	Flow rate through the adsorber heat exchanger (moving average)
V_u	l/h	Flow rate through the evaporator/condenser heat exchanger
$V_{u,gleitm}$	l/h	Flow rate through the evaporator/condenser heat exchanger (moving average)
WMZ_o	kWh	Cumulated energy at the adsorber heat exchanger
WMZ_u	kWh	Cumulated energy at the evaporator/condenser heat exchanger
X_{iso}	kg/kg	Water content of silica gel calculated as a function of T_{mSi} and system pressure

ΔT_{ln}	K	Logarithmic temperature difference