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Experimental results of a 3 kWh thermochemical heat storage module for space heating application

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Abstract

A 3 kWh thermochemical heat storage (TCS) module was built as part of an all-in house system implementation focusing on space heating application at a temperature level of 40 °C and a temperature lift of 20 K. It has been tested and measurements showed a maximum water circuit temperature span (released by adsorption) of 20 – 51 K which is by all means suitable for space heating.

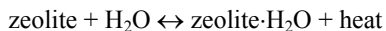
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1. Introduction

Thermochemical heat storage is a promising technology to solve the mismatch between seasonal heat supply and demand as a typical problem for temperate climate zones. Such systems are able to make use of solar irradiation during the summer time to cover the heat demand during the winter time. Storing the energy is based on reversible thermochemical reactions such as:



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Such reactions release heat by ad-/absorption which can be used as input for space heating (SH) and domestic hot water (DHW) applications. The TCS system can be charged by desorption taking the excess solar energy. Usually, water is used as a sorbate. A thermochemical reaction further has a significant advantage over existing long term thermal energy storage (TES) technologies such as sensible heat storage in aquifer (ATES), boreholes (BTES), caverns (CTES), pits and water tanks [1] or latent heat storage (LHTES) using phase change materials (PCM) [2]. Heat can be stored in thermochemical material (TCM) for prolonged periods without heat losses. In addition TCM's allow much higher energy densities, for instance up to 3.2 GJ/m³ [3] or 2.9 GJ/m³ [4] both using Na₂S which can lead to more compact systems.

On the other hand TCS systems also have to sufficiently fulfill heat transfer characteristics in terms of heating power and temperature lift for space heating and/or domestic hot water applications. In this paper we will show the results of a 3 kWh thermochemical heat storage system for SH application.

In recent years investigations into thermochemical heat storage systems and materials have been strongly increased. Thermochemical materials development and characterization is performed in various EU countries. Also focus is set on new TCS components and systems. For recent overview, the interested reader is referred to [5].

2. The 3 kWh thermochemical heat storage module

An all-in house system using a 3 kWh thermochemical heat storage module was designed and built, as has been described by Finck *et al.* [6]. Temperature levels for dehydration and hydration were determined by their heat sources. Regeneration with solar collectors can be performed in a temperature range of 80 – 120 °C using a condensation temperature of 20 – 30 °C. Hydration takes place at 20 °C (return temperature from SH) and has to fulfill a temperature lift of 20 K getting a SH inlet temperature of 40 °C. The hydration process goes along with evaporation that is designed to be functional in a temperature range of 5 – 15 °C. Both, evaporation and condensation are strongly influenced by their external heat source/heat sink which can be ambient air or ground storage [7].

The sorption pair zeolite 5A – water was chosen for its hydrothermal and mechanical stability as well as safety precautions and minimization of corrosion of heat exchanger components. The TCM was placed in a closed system working under sub atmospheric pressure.

Calculations, concerning 3 kWh of heat release during hydration, led to a mass of 41 kg zeolite (hydrated). Zeolite of type 5A, manufactured by Sigma Aldrich (composition: 0.80 CaO : 0.20 Na₂O : 1 Al₂O₃ : 2.0 ± 0.1 SiO₂ : x H₂O), in the form of spheres (diameter 2 – 3mm) was implemented as a packed bed into finned heat exchangers as illustrated in Fig. 1a. Placed in a cylindrical vessel of stainless steel, 8 heat exchanger blocks with sizes of 1000x300x33mm (height x width x depth) were arranged in such a way, that the water flow can be heated in parallel by the adsorption process. Further design specifications resulted in a deliverable hydration heating power of 800 W.

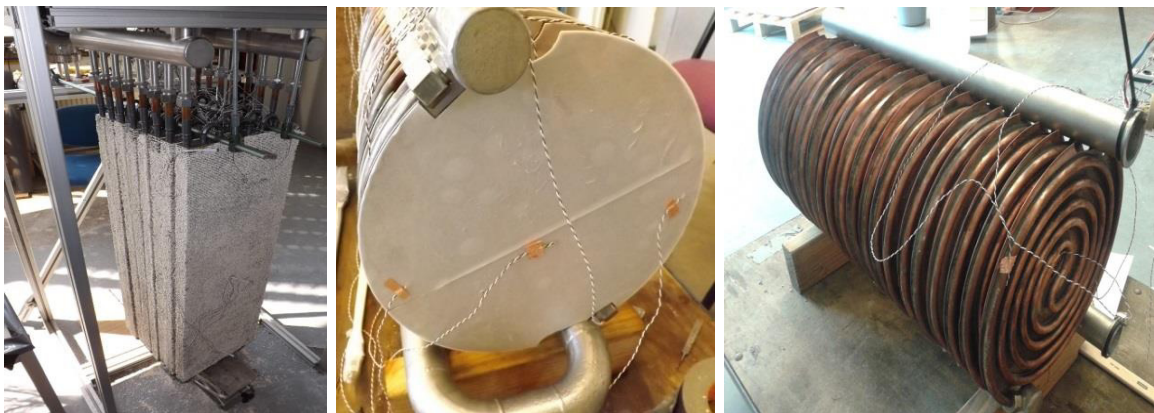


Fig. 1. (a) adsorber/desorber unit; (b) evaporator/condenser unit front view; (c) evaporator/condenser unit back view.

For evaporation and condensation a single unit was developed. It consists of a combination of a copper fin connected on one side to a copper spiral and a capillary working material on the other side (Fig. 1b & 1c), so that the heat exchanger can serve both processes, of evaporation and condensation. The unit contains a heat exchange surface of 1.4 m², resulting from 20 spirals with a diameter of 0.3 m, delivering a theoretical power peak of 3000 W.

3. Experimental aspects

A test rig was constructed containing the heat storage module, consisting of one adsorber/desorber unit and one evaporator/condenser unit. As heat sources were chosen a 12 kW electrical heater feeding the desorption process and individual, thermostatic water baths for evaporation, condensation and adsorption.

In order to obtain accurate test results in terms of power and energy content calculations, Pt100 of type IEC 751 class A (variance < 0.1 K between 0 °C and 100 °C) and electromagnetic flow meters of type Promag H (manufactured by Endress + Hauser) for low flow rates up to 4700 dm³/min (including temperature compensation for proper density values) were used in all water circuits. In order to gain insight in heat transfer values and water vapor flow behavior to and from the adsorber/desorber unit, thermocouples of type T class 1 (variance < 0.5 K between -40 °C and 350 °C) were placed at the outer surface of the heat exchanger, at the outer surface of the zeolite bed and in the center of the heat exchanger (center of zeolite bed).

4. Experimental results

Experimental results of a hydration process using 20 °C of adsorber inlet temperature and 15 °C of evaporation temperature are shown in Fig.2. Prior to this experiment the zeolite was dehydrated at 103 °C (desorption) and 20 °C condensation and afterwards cooled down to the mentioned adsorption and evaporation temperature conditions.

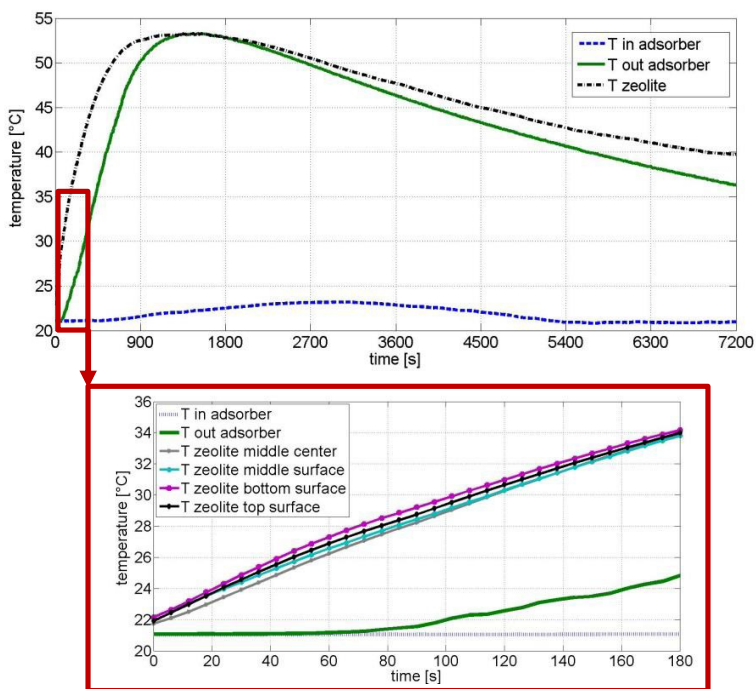


Fig. 2. (a) top diagram – results adsorption, horizontal axis in the graph displays time [s], vertical axis displays temperatures [°C], (b) bottom diagram – results adsorption for the initial 180 s, horizontal axis in the graph displays time [s], vertical axis displays temp. [°C].

The zeolite temperature increases gradually and peaks after 1500 s (25 minutes). The maximum temperature lift during hydration (adsorption) is 31.2 K. This is the result from the difference between outlet and inlet of water circuit temperatures as can be seen in Fig 2a. Within a period of 1 hour and 18 minutes the adsorber delivers a temperature lift higher than 20 K. In this period, the average temperature lift was 25.5 K. Looking at a deliverable, average temperature span of 20 K a time frame of 2 hours and 42 minutes can be noticed.

Fig. 2a shows a temperature change of 2.5 K for the adsorption inlet temperature. This is because the thermostatic water bath, used as heat sink for adsorption, could not fully dissipate the power peak delivered by the adsorption process.

Looking at the zeolite temperatures in the initial phase of hydration, placed on different spots of the heat exchanger, they should give an indication of water vapor flow from evaporator to adsorber. In Fig.2b three different spots, distributed over the height of the heat exchanger, at the outer surface, were chosen (zeolite top surface, zeolite middle surface, zeolite bottom surface). As the water vapor inlet is at the top of the adsorber vessel, the homogeneous temperature increase in Fig. 2b shows that the water vapor is evenly adsorbed over the reactor, indicating that there is no substantial pressure drop of water vapor along the zeolite bed and between the heat exchanger blocks. The same approach of looking at the temperature slope was taken for the pressure drop through the zeolite bed. The measured temperatures at “zeolite middle surface” and “zeolite middle center” do not show any difference, pointing out that there is no significant restriction of water vapor transport through the zeolite bed.

The temperature profiles as indication for a proper vapor flow can only be taken if enough water vapor is provided by the evaporator. Fig. 3 depicts that even after 40 s of hydration process the evaporation power has already reached a value of 1700 W and after a period of 180 s a value of 2060 W.

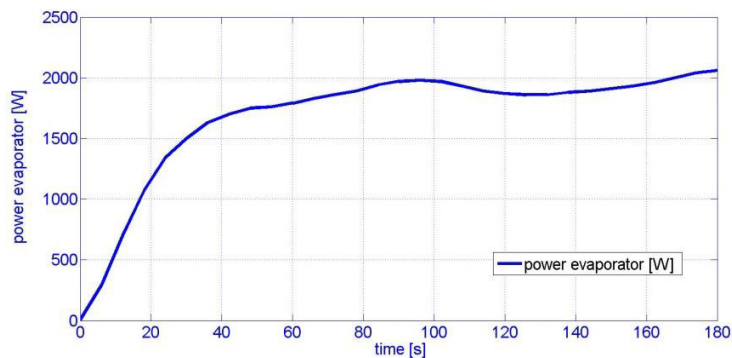


Fig. 3. results evaporation for the initial 180 s, horizontal axis in the graph displays time [s], primary vertical axis displays evap. power [W].

The maximum evaporation power reached for this particular experiment is 2300 W and an average maximum power of 2900 W is achieved in different experiments. Differences in maximum power values for evaporation between the experiments have to do with the change of flow of the evaporation water circuit which strongly influences the heat exchange.

The power and cumulative heat released by the adsorber were derived from temperature and flow measurements of the adsorber water circuit. This is illustrated in Figure 4.

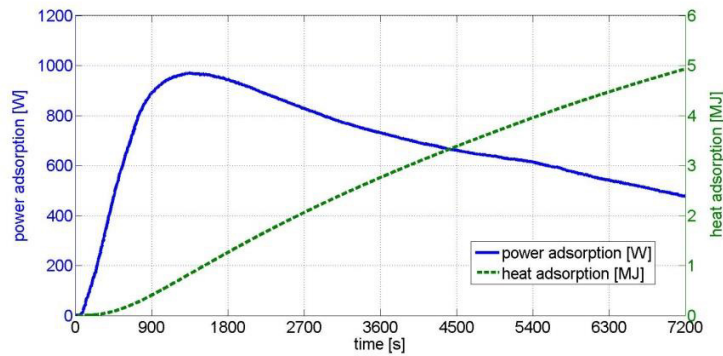


Fig. 4. results adsorption, horizontal axis in the graph displays time [s], primary vertical axis displays released adsorption power (P) [W], secondary vertical axis represents cumulative released adsorption heat [MJ].

A maximum adsorption power released of 971 W could be realized at the particular conditions of this experiment (103 °C for desorption, 20 °C for condensation, 20 °C for adsorption and 15 °C for evaporation), (Fig. 4). Thus, 41 kg zeolite gives a maximum specific power of 24 W/kg. When related to the period of 1 hour and 14 minutes during which an average temperature lift higher than 20 K was obtained, an average heating power of 800 W was found, giving an average specific power of 20 W/kg.

After 2 h (7200 s) an amount of heat equal to 4.9 MJ (1.4 kWh) was transferred to the water circuit. At this time the temperature span in the water circuit had dropped to 15.4 K. After 50000 s (about 14 hours) the total heat extracted from the adsorption process is 9.3 MJ (2.6 kWh). This comes to 226 J/g zeolite 5A. At that time, the temperature lift in the water circuit had dropped to less than 0.5 K.

Taking the 41 kg zeolite and a materials density of 750 kg/m³, a material energy density of 0.17 GJ/m³ can be calculated. As the zeolite makes up only about 27% (by volume) of the current total reactor system, overall energy density in this particular experiment was 0.045 GJ/m³.

Additional experiments were carried out to calculate the heat losses from the reactor vessel during adsorption and desorption. In one experiment, hydrated zeolite was exposed continuously for 2 days to a heating flow of 40 °C at ambient temperatures varying between 21.5 and 23.3 °C. Assuming quasi-stationary conditions, the difference of inlet and outlet water circuit temperature is a measure of the heat losses of the heat storage module. Taking the geometry of the reactor vessel led to an average heat resistance of 5.8 K/W. Applying the heat resistance value to the temperature integral of adsorption and desorption experiments allowed calculation of heat losses during the experiment. In the experiment described above, the heat released increased from 9.3 to 9.38 MJ.

Taking the temperatures for desorption, condensation, adsorption and evaporation and using the corresponding loading states from Clausius-Clapeyron curves for thermodynamic equilibriums of the sorption pair zeolite 5A – water from Wang et.al [8], can give a theoretical comparison to experimental results.

An average adsorption enthalpy of 54.5 kJ/mole water on zeolite could be derived [7] that is approximately 20 % higher than the evaporation enthalpy of water with 44 kJ/mole. Using the molar mass results in a value of 3 MJ/kg of adsorption enthalpy per kg of water. The theoretical difference of loading states between adsorption and desorption, for the above mentioned temperatures, is 0.11 g/g [8]. Thus, an amount of 41 kg zeolite results in a theoretical adsorption heat of 14 MJ (3.9 kWh). This is 50 % higher than our experimental result. At this point it has to be concluded that the zeolite 5A used for the 3 kWh reactor must be different from the zeolite 5A mentioned in Wang et.al [8] (zeolite 5A of type MS522 used, manufactured by Grace Davison [8]), so that a comparison to the theoretical results, that includes all loading states at all pressure temperature relations, cannot be accurately determined. Additional effects that can influence the experimental results could be excluded. The maximum saturation of zeolite with water, which means a maximal, possible loading of mass water per mass zeolite, at the end of all experiments could be assessed.

During the adsorption process a quasi-stationary state of over 2300 s was achieved. Thermocouples were used to measure a number of relevant zeolite temperatures in order to calculate the overall heat transfer between zeolite and water circuit. Within the quasi-stationary time frame a mean temperature lift between 13.1 and 15.2 K was measured. Using integral inlet and outlet water circuit temperatures, along with a measured water flow, a power transfer of 740 – 971 W from the zeolite bed to the water circuit was calculated. Thus, knowing that the heat exchange surface area amounts to 2.1 m² and considering power and mean temperature lift a heat transfer coefficient in a range of 25 – 31 W/(m²K) was found.

The thermochemical heat storage module was designed to operate in dehydration mode with temperatures ranging between 80 – 120 °C for desorption and 20 – 30 °C for condensation. These temperature levels were set in ranges because of varying weather conditions during use. Investigations have been done to show the influence on the maximum heat stored in the heat storage module. Fig. 5 gives an overview of experiments in which temperatures for desorption and condensation were varied and in which adsorption and evaporation temperature were held constant at 20 °C and 15 °C, respectively.

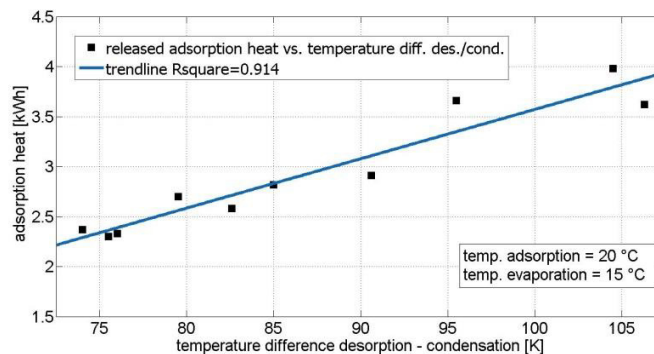


Fig. 5. horizontal axis displays the temperature difference between desorption and condensation [K], vertical axis displays the experimental adsorption heat [kWh], T adsorption = 20 °C, T evaporation = 15 °C.

What can be clearly seen in Fig. 5 is the strong influence of the temperature difference between desorption and condensation. A decrease of 20 K from 100 K to 80 K can reduce heat released by adsorption from 3.5 kWh to 2.5 kWh. This is almost 30 % less.

Further experiments have been performed to investigate the change of total adsorption heat by changing the evaporation temperature within the range of 5 – 15 °C and similarly by changing the adsorption temperature within the range of 20 – 30 °C. For both cases residual temperatures had to be held constant, to be able to compare these to the reference experiment at 103 °C desorption, 20 °C condensation, 20 °C adsorption and 15 °C evaporation. Decreasing the evaporation temperature to 5 °C results to a total adsorption heat of 7.8 MJ (2.2 kWh) which is almost 16 % lower than from the value of the reference experiment with 9.3 MJ (2.6 kWh).

Increasing the adsorption temperature to 30 °C results in a total adsorption heat of 7.4 MJ (2.1 kWh) which is 20 % lower than from the value of the reference experiment.

5. Conclusion

All test results are in agreement with the design and simulations of the 3 kWh heat storage module [6]. A SH temperature span of 20 – 51 K, a heating power range of 730 – 1600 W and a maximum energy content of 14.3 MJ

(4 kWh) could be realized. This leads to a maximum material energy density of 0.3 GJ/m³ and a current system energy density of 0.08 GJ/m³ whereby the latter one can be expected to be increased to 0.13 GJ/m³ by optimizing the system. Further investigations on variations of process temperatures showed clearly a strong influence of desorption and condensation temperature change on the performance of the heat storage module. Decreasing the temperature difference between desorption and condensation from 100 K to 80 K resulted in a 30 % lower energy content. This is a feature that should be kept in mind for future thermochemical storage system designs. In addition, storage materials properties proved to be constant throughout the measurements performed.

Future work involves system optimization and scale-up, demonstration system implementation, and active material enhancement by encapsulation of which the results will be discussed in forthcoming papers.

Acknowledgements

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