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1. Abstract

The increasing share of renewable energy in the energy supply system requires more balance between energy supply and demand. Research and development activities in the area of smart electricity grids are already a very visible result of that. The balancing of heat supply and demand is of equal importance when the use of solar heat needs to be increased.

The Energy Hub (E-Hub) is a collaborative European project, funded by the EU under the 7th Framework Program. The project aims to demonstrate the full potential of renewable energy by providing 100% on-site renewable energy within an "Energy Hub District". The present work addresses the development of an innovative concept for thermal energy storage as a part of the E-hub system. Because thermal energy cannot be transported over long distances without significant losses, local storage of thermal energy must provide the required flexibility to match the heat demand and supply. Solar heat supply also fluctuates strongly between summer and winter, so to use this source of energy to its maximum, the storage should be capable of long term seasonal storage. Heat storage technology based on reversible sorption reactions offers the opportunity to store heat in a compact way and with limited heat losses over a long period of time.

A laboratory prototype of a heat storage system is developed and its performance is tested. The concept of the heat storage system is based on an atmospheric open sorption system that contains 150 kg of zeolite sorbent, divided in two batches. Ambient air, containing a controlled amount of water vapour is blown through the bed of sorbent material. The air is used both as the heat transfer medium and to transport the water vapour to react with the solid sorbent. The test results show that this concept can provide a solution for long term thermal energy storage. It is capable of delivery of thermal energy at temperature levels useful for domestic applications. The aspects of this system concept that need further improvement in order to become a viable technology for seasonal heat storage are: the system thermal storage cycle efficiency, the air tightness of the open sorption concept, the stability of salt hydrates for increased energy storage density and the reduction of auxiliary electric consumption.

Keywords: thermal energy storage; sorption reaction; prototype system; energy-hub

2. Introduction

The bulk of the solar radiation is received in the summer months while radiation is relatively low during the winter months. The ability to effectively store solar thermal energy for a period of months provides an opportunity to substantially increase the use of solar energy. Although seasonal storage is already successful (UTES, Underground Thermal Energy Storage), to date, these demonstration projects appear to have limited application in retrofitting the existing building stock. Other, more compact solutions are needed to address the challenges of increasing solar energy use in the built environment.

The Energy Hub (E-Hub) is a collaborative European project, funded by the EU under the 7th Framework Program. The project aims to demonstrate the full potential of renewable energy by providing 100% on-site renewable energy within an "Energy Hub District". The present work addresses the development of an innovative concept for long term thermal energy storage as a part of the E-hub system.

To reach high solar fractions, it is necessary to store heat (or cold) efficiently for longer periods of time. Hot water storages require very large volumes and become expensive. They also have significant heat losses when used for long term storages. An alternative storage technology is based on the use of thermo-chemical materials (TCMs). TCM can store thermal energy in the reversible breaking and restoring of the chemical bond between two molecules. This chemical bond has a higher energy density than heat stored as sensible heat (e.g. hot water storage) or heat stored in a phase change (e.g. ice storage). In addition, the energy can be stored in a TCM for a very long time without any loss of the stored energy of the chemical bonds.

The basic principle for compact thermal storage based on TCM is simple: a suitable chemical compound is heated to the point where the compound dissociates into two (or more) other compounds, which can be stored separately. When these compounds are recombined, the original compound is formed again and the stored heat is released, see Figure 1.

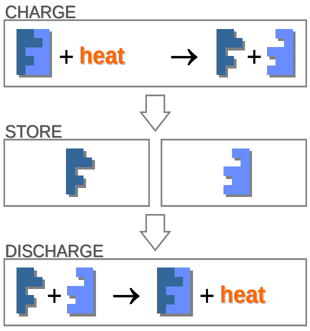

Figure 1: Concept of thermochemical heat storage.

This concept is also referred to as ‘sorption systems’ and is successfully applied in thermally driven heat pumps for heating and cooling purposes. Sorption systems can be operated as ‘closed’ systems and as ‘open’ systems. In closed systems, both compounds are kept within the storage and hermetically sealed and evacuated vessels are applied. In open sorption systems a connection to the ambient is present and water vapour is used as reacting compound [1]. The concept of ‘open sorption’ system seems economically more attractive for seasonal heat storage [2], as it requires far lower investment in the storage container system in comparison to closed sorption systems.

The open sorption concept for heat storage was tested using the $MgCl_2$-H_2O reacting system in a previous prototype. [3,[4] It gave a good perspective for the thermal performance and the energy storage density, however the chemical stability of the salt appeared insufficient to be applied in a scaled-up prototype. During the dehydration reaction, a trace of HCl was found, arising from irreversible decomposition of the $MgCl_2$-H_2O system at elevated temperature. This phenomenon is currently being studied [5]. The new open sorption prototype system therefore uses zeolite 13X as a stable replacement for the $MgCl_2$. The sorption properties of zeolite 13X are well known [6,[7[8[9], and its range of operating temperatures is comparable to that of $MgCl_2$. Although the energy storage density for zeolite is lower than for $MgCl_2$, it allows to study the system performance characteristics of the open sorption concept for practical use in long term heat storage applications.

3. Prototype design and construction

The intended use of a compact long term heat storage solution as presented here is as decentralized seasonal solar heat storage system for low-energy single family houses. The global system specifications for this heat storage system are derived for the operating temperatures, thermal power levels, storage capacity and efficiency, see Table 1.

Table 1 General design values for a domestic seasonal heat storage system

Property	Value
Charge temperature solar vacuum tube collector	130°C
Discharge temperature	60°C
Average air humidity level	12 mbar H_2O pressure
Charging thermal power	3 kW
Discharging power	1.5 kW
Storage capacity	6 GJ (delivered)
Thermal storage efficiency	>60%
Auxiliary electric energy	<5% of thermal energy delivered

The values given in **Error! Reference source not found.** are considered to be the target values to reach in the seasonal heat storage application for a single family house. For the lab-scale prototype 'derived' specifications were used. The characteristics of the prototype system are given in Table 2.

Table 2 Characteristics of the prototype open sorption system

Property	Value
Storage container volume, dimensions	112dm^3, 70x40x40 cm (h x w x d)
Number of storage containers	2
Storage capacity	50 MJ
Sorption material, Shape, Weight	Zeolite 13X BF, binderfree, Chemiewerk Bad Koestritz, beads of 2.5-3.5 mm. 150 kg
Air flow rate	Max 80 m^3/hr
Maximum heat input:	200°C, 2 kW

The design of the prototype system is schematically depicted in Figure 2. The section on the right shows the 2 storage containers with thermocouples inserted in the zeolite bed. The one-way airflow through the bed is from bottom to top for charging and discharging.. Each container has an electric valve at the inlet to control the airflow through the bed. In the outlet a non-return valve is placed to prevent natural convection. The air temperature and humidity level entering the bed are partly controlled by the arrangement of heat exchangers in the left part of the system, the air handling unit. The ambient air enters the system from the bottom, below the H_2O-air heat exchanger. The humidity level of the incoming air is controlled by this first heat exchanger and humidification system. Next, the airflow is preheated in the air-to-air heat exchanger and then flows to an oil-to-air heat exchanger. Here the air temperature can be further increased by simulated heat of a (vacuum tube) solar collector. During the sorption phase no additional heating takes place. The air passes through the zeolite bed, exchanges water vapour with the zeolite, and its temperature is changed. At the exit of the bed it passes through an oil to air heat exchanger that extracts heat from the air (heat release in winter conditions). The heat from the outgoing air is exchanged with the incoming air in the air-to-air heat exchanger. The air flow is controlled by a fan at the inlet at the bottom of the air handling unit. Two thermostatic baths are connected to the system. One to deliver or extract the heat to the oil-to-air heat exchangers at the high temperature and one to keep the temperature of the water-to-air heat exchanger at a constant value.

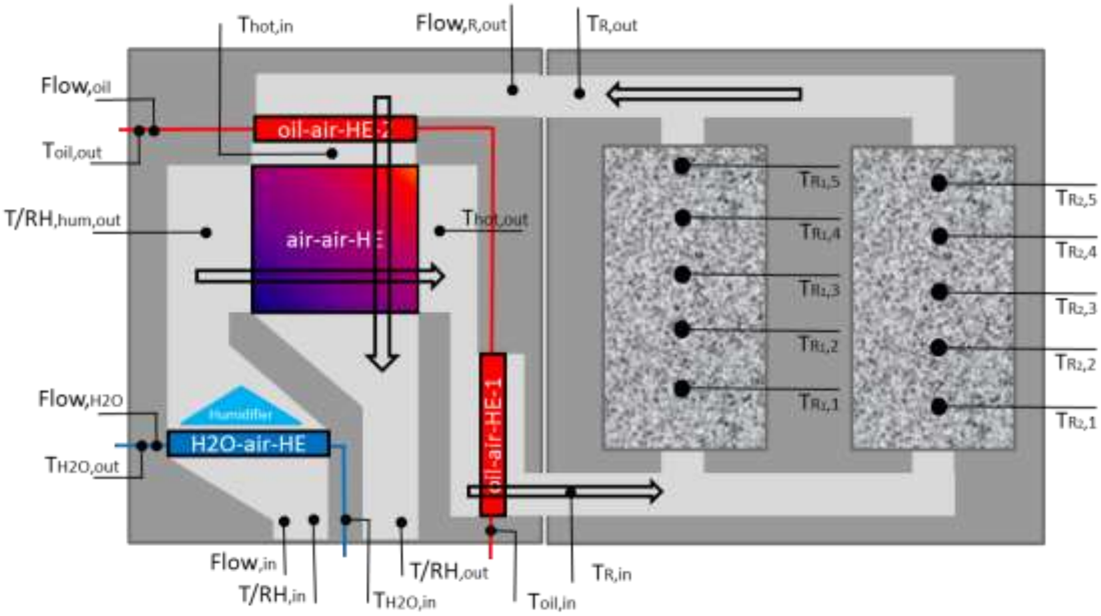

Figure 2: Process flow diagram and instrumentation for the open sorption prototype system.

The prototype is equipped with temperature sensors, humidity sensors, air velocity measurement devices and pressure difference sensors, to monitor the system performance. Pictures of the system under construction are shown in Figure 3. Special attention was paid to obtain a compact construction and to have a good thermal insulation, in order to reach low thermal losses. The air channels in the system were constructed from insulating board with a mineral wool core and sealed with aluminium tape and high temperature silicon flexible sealant.

Figure 3: Pictures of the open sorption prototype system under construction. Left: the air handling section, right: the storage containers section

4. Results and Discussion

The temperature program used for a charge discharge cycle for reactor 1 and 2 is schematically shown in Figure 4. The storage system is charged during 4 days (2 days per reactor). Charging occurs by heating the inlet air to the reactors to 185°C, using oil-air HE-1. The beds are charged sequentially. The reactors are then allowed to cool down during 5 days to reach ambient temperatures. In discharging mode, the air flow to the zeolite bed is humidified to 12 mbar of water vapour. This water vapour pressure is derived from humidifaction of air at 10°C, representing the use of a borehole as winter heat source. The zeolite adsorbs the water vapour and the heat of adsorption is released. The zeolite and the air flow heat up and the hot air leaves the zeolite bed and transfers its excess heat to the oil-air HE-2 in the system. The air flow applied during all measurements was 80 m^3/hr.

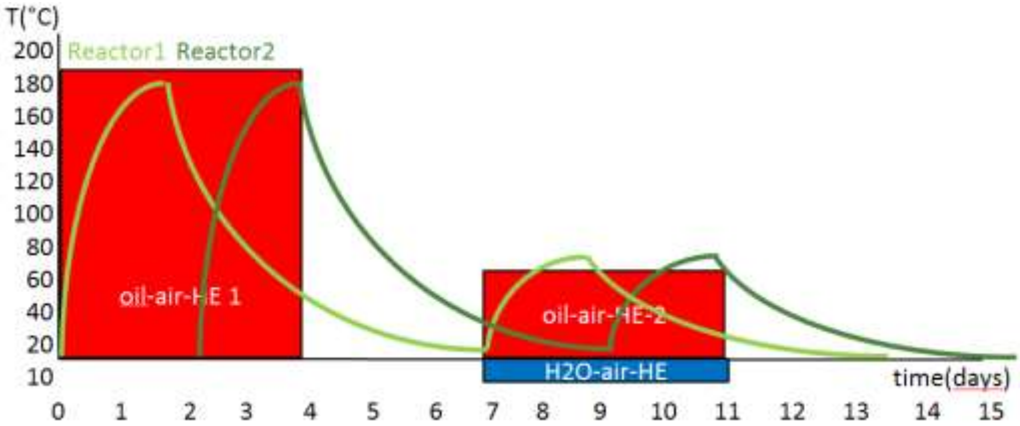

Figure 4: Simplified temperature profiles for the zeolite reactors during the charge and discharge measurement. The green lines indicate the evolution of the reactor temperatures

Charging of the zeolite reactor

The measured temperature change in one of the zeolite beds (reactor 2) during the charging phase is shown in Figure 5.

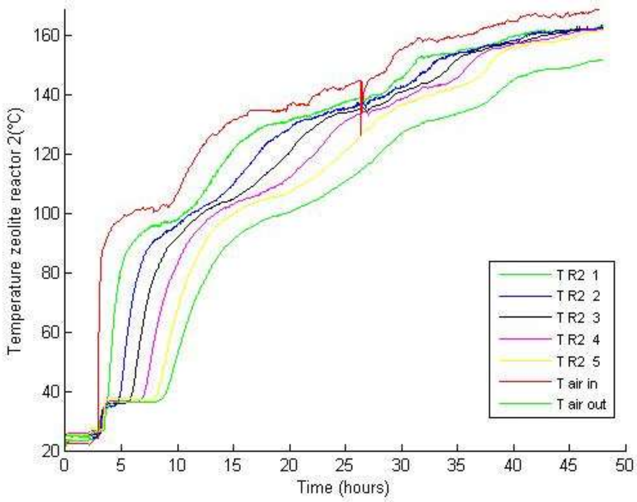

Figure 5: Temperature over time of the air and the zeolite bed of reactor 2 during charge process

The temperature of the zeolite follows the air supply temperature (brown top line in the figure above) with a delay. The temperature in the bed rises from bottom to top and follows the air supply direction. The temperature gradient in the bed can be seen as a moving reaction zone of desorption. The stepwise increase of the air supply is due to thermal power limitations in the oil to air heat exchanger. It takes about two days to fully charge a single reactor.

Discharging of the zeolite reactor

Cool and humidified air (12 mbar water vapour pressure) is blown through the dried zeolite reactor to release the stored heat. The water vapour present in the air is adsorbed by the zeolite. The air-to-air heat recovery unit makes the inlet air to the bed rise slowly to 40°C. The heat of sorption is released and over time the zeolite and the air increase in temperature up to 70°C, see Figure 6. After 25 hours of discharge the zeolite has reached its equilibrium sorption capacity and heat release stops rapidly. It is clearly seen from the steep drop in temperature through the bed, that the adsorption process shows a distinct reaction zone inside the bed that gradually shifts from bottom to the top. The thermal energy output of the zeolite remains at its useful temperature level until the system is completely discharged.

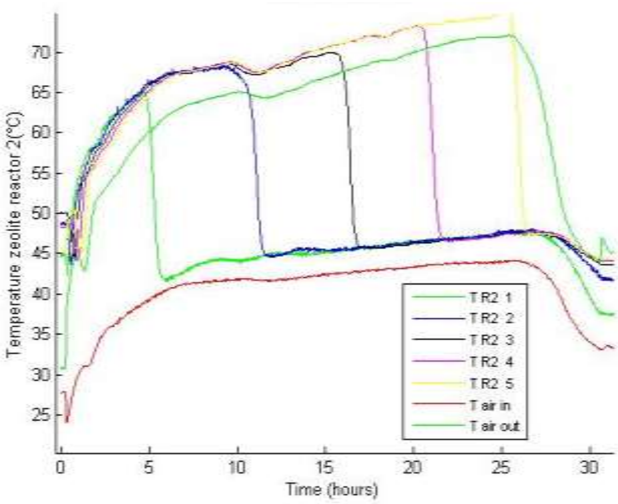

Figure 6: Temperature over time of the air and the zeolite bed of reactor 2 during the discharge process

Thermal storage efficiency analysis

The heat storage cycle efficiency for reactor 2 was analysed based on the measurements performed and shown above. From the changes in temperature and humidity between the air entering the zeolite bed and exiting the bed, calculations were made to determine the thermal powers transferred and to determine the total amount of energy stored and released again by the zeolite. The result of the analysis is shown in the graph of Figure 7. A distinction is made between the amount of heat that is stored in the zeolite as sorption reaction heat, and the amount that is ‘stored’ as sensible heat. The sorption heat is derived from the change in water uptake of the zeolite, and the associated enthalpy of reaction [9]. The sensible heat is based on the temperature and heat capacity of the zeolite bed and its containment.

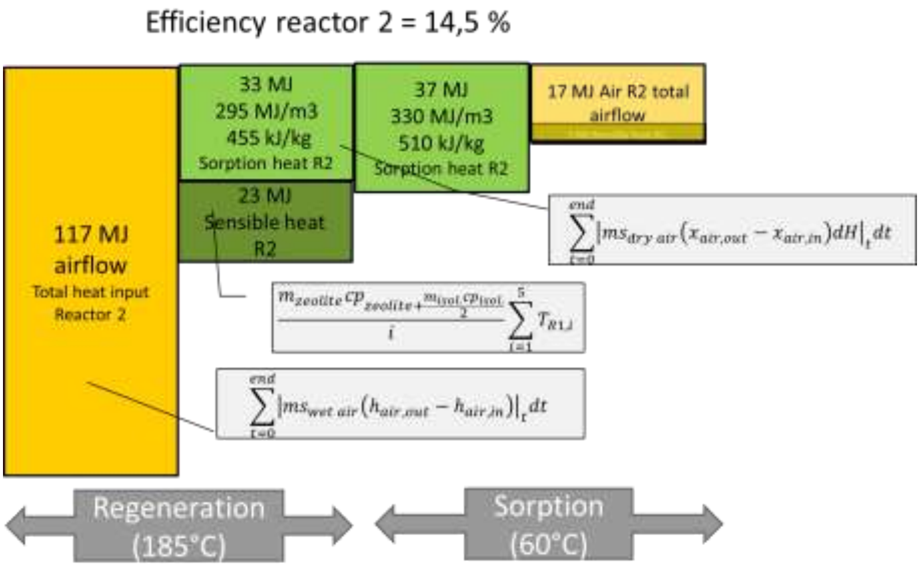

Figure 7 Analysis of the overall storage cycle efficiency for reactor 2.

The net result of the thermal storage efficiency is only 15% for the current measurement. Of the 117 MJ of heat added to the reactor, around 56 MJ is stored in the zeolite reactor, partially as sorption heat and partially as sensible heat. The sensible heat is largely lost to the ambient on cooling down of the reactor during the storage period of 5 days. The sorption heat is released again in the discharge mode. A part of this heat is again needed to heat up the zeolite bed and its containment, part of the heat is lost by conduction, and 17 MJ is delivered to the air.
The loss factors strongly influencing the efficiency of the system, are the thermal losses due to convection, conduction and due to air leakages and the low efficiency of the air-to-air heat recovery unit, which is around 80%. Especially in the charging phase these losses are significant due to the high temperatures of 185°C applied during that stage. A further improvement of the air tightness and the thermal insulation of the system is required to increase the overall storage cycle efficiency. Another factor is the duration of the charging process, because in the end stage of the charging the heat losses are larger than the heat being stored in the reactor. An optimization of the duration of the charge process will further enhance the efficiency.
Another aspect of efficiency holds for the sensible heat that is charged to the system and later on completely lost, when the system has cooled to ambient conditions. In the case of zeolite the ratio of sensible heat over sorption heat is less favourable than for salt hydrates. But in all cases improvement can be obtained when also the sensible part can be kept in the storage and be used again during the discharge, or can be recovered in another way.

The overall energy balance of a sorption heat storage system is an important aspect in the further development of this technology. This includes the thermal energy in the system as well as the auxiliary electric energy. In the current system an electric fan of 51 W is applied to create the necessary air flow in the system, and this is the largest electricity consumer of the system. The energy consumption of this fan over a storage cycle should preferably be less than 5% of the total thermal energy released. In the current system this ratio was around 85%.This ratio will improve significant when the heat losses will be minimized, but it is still a challenge to reach the target of 5%, knowing that in the current prototype, already consideration was given to obtain a low pressure drop in the system. The reduction of electricity consumption should be addressed in further development work on the open sorption heat storage concept.

5. Conclusions

A prototype heat storage system based on the open sorption concept was designed, built and tested. The system contained 150 kg of zeolite 13X as the active sorption materials divided in two separate reactors. The test results have shown that this concept can provide a solution for long term thermal energy storage. It is capable of delivery of thermal energy at temperature levels useful for domestic applications. The test results also revealed a few critical aspects of this system concept, which need careful attention during the next development stages of the technology, being

- Improvement of the system thermal storage efficiency, by improving air tightness to reduce the thermal losses
- Using the sensible heat of the storage system as much as possible
- Increasing the ratio of thermal power over auxiliary electric power

The thermal efficiency of the system can be further improved when sorption materials (salt hydrates, e.g. $MgCl_2$-H_2O) with higher sorption reaction heat, a lower charging temperature and higher energy storage density can be applied.

The open sorption heat storage system concept, using modular storage containers and a separate air handling unit, can provide the flexibility to match the storage system design to the local long term heat storage requirements for storage capacity, charge-discharge powers and timing. Sizing of the individual storage modules, the number of modules to be applied, and the sizing of the thermal power in the air handling unit provide this flexibility.

6. Acknowledgement

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