Investigation of the charge boost technology for the efficiency increase of closed sorption thermal energy storage systems

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Abstract. The inclusion of solar thermal energy into energy systems requires storage possibilities to overcome the gap between supply and demand. Storage of thermal energy with closed sorption thermal energy systems has the advantage of low thermal losses and high energy density. However, the efficiency of these systems needs yet to be increased to become competitive on the market. In this paper, the so-called “charge boost technology” is developed and tested via experiments as a new concept for the efficiency increase of compact thermal energy storages. The main benefit of the charge boost technology is that it can reach a defined state of charge for sorption thermal energy storages at lower temperature levels than classic pure desorption processes. Experiments are conducted to provide a proof of principle for this concept. The results show that the charge boost technology does function as predicted and is a viable option for further improvement of sorption thermal energy storages. Subsequently, a new process application is developed by the author with strong focus on the utilization of the advantages of the charge boost technology over conventional desorption processes. After completion of the conceptual design, the theoretical calculations are validated via experiments.

1. Introduction

The upcoming shortage of fossil fuels as well as the already occurring climate change lead to a growing interest in the usage of renewable energies [1], [2]. The main problem with energy sources like solar thermal energy is the discrepancy between supply and demand which occurs in two ways [3]. Firstly, the majority of the radiation is received during the day when the sun provides its energy to the collector. However, the peak in energy demand usually occurs in the evening. Although this is problematic, it is not the main issue of solar energy. The greatest obstacle to overcome is the gap between summer and winter. In summer, when solar energy is abundant, no space heating is needed. During the heating period in winter when heat is very much required, the lowered solar radiation cannot supply enough energy to cover that demand.

This means that the currently biggest challenge for solar energy implementation in housing is the long term storage of the excess energy in summer for the use during the high energy demand periods in winter [4]. Already existing sorption thermal energy storages need to be improved in size and cost in order to be competitive in the storage market. The Austrian flagship project Tes4seT investigates the possibilities of efficiency increase of these systems. The project is funded by the Austrian FFG programme Energieforschung under grant agreement no. 845020.
2. Theoretical foundations and system design

2.1. Closed sorption thermal energy storage systems

The physical principle used to store the heat is physical adsorption. Adsorption processes are always exothermal. They can be described as a function of three parameters; temperature, pressure and moisture load \(X\) of the system. Several approaches have been made to find suitable functions for this purpose. The one that is used throughout this work is the Dubinin-Astakhov approach \([5]\) as stated in Eq. (1).

\[
X(T,p) = X_{\text{max}}(T) \times \exp \left[ \left( -\frac{RT}{EM} \times \ln \left( \frac{p_s(T)}{p} \right) \right) ^n \right]
\]

As adsorption is always exothermal, a dry adsorbent holds a thermo-physical potential to release energy in the form of heat as soon as it comes in contact with a suitable adsorbate, in this case water. This effect can be used to store thermal energy as depicted in Fig. 1.

![Diagram of the coupling of adsorption and desorption](image)

**Figure 1.** Schematic of the coupling of adsorption and desorption for the storage of thermal energy.

As the adsorbent is at ambient temperature when not used, the thermal energy can be stored with virtually no losses for long periods of time. This predestines the adsorption energy storage system for long term storage applications. A closed sorption energy storage system essentially consists of two main parts. These two components are the water storage and the material storage (in this case zeolite 13 XBF) which are separated with a valve. Closed systems usually operate under vacuum, which means that only water vapour is present as gas phase.

In order to generate or move water vapour in the system, energy sources and sinks are necessary in the system. For the theoretical considerations in this work, solar radiation is considered as single high temperature energy source. The required low temperature energy source for evaporating the water content as well as the heat sink for the condensation would be provided by a ground heat exchanger which can supply constant power throughout the winter. The classic process operation is depicted in the isosteric diagram (a plot of the three-dimensional Dubinin-Astakhov equation) for the zeolite/water pair in Fig. 2.
The system can store more energy if the available pressure and moisture load gradient for step three is larger. This means that the efficiency is limited by the two system temperatures, the low temperature level of the heat sink and the high temperature level of the thermal energy provided by solar radiation. In the works of Georg Engel [6] a new mode of operation is suggested which would further improve the energy storage capabilities and reduce the material requirements of the system without the need for a change of the system temperatures.

2.2. The charge boost technology

The charge boost technology uses the effect that a vessel filled with adsorbent reduces its pressure if it is cooled down in an isosteric way. When integrating two sorption vessels in a system, the cooled one can be connected to the hot one and steam will be transported from higher to lower pressure. This way the moisture load of the hot storage is decreased further and more energy is stored within, whereas the moisture load of the colder storage is increased again. As suggested by Müller [7], the system is designed with a smaller “recharge unit” and a bigger “main storage unit”. The reason for the recharge unit being smaller is that it should be possible to completely regenerate the used recharge unit during one day using solar radiation energy. By using this setup, the bigger main storage unit can be charged using the smaller recharge unit to directly desorb both units in addition. The routine for the charge boost process is described in Fig. 3.
This operating mode shows several advantages over pure desorption. The main storage unit can be charged further with charge boost than by normal desorption at the same temperatures. In return, this indicates that the lower temperatures are needed to reach a desired energy density in the material. Combined with the fact that the solar-thermal collectors show better efficiency at low temperatures [8], this increases the efficiency of the whole process. Furthermore, less material is required in the system as the main storage can reach higher energy densities than with pure desorption. This reduces the cost and the space requirement of the system.

3. Development of a new application
The main benefit of the charge boost technology is the possibility to use comparably low temperatures to further charge a unit that has already been charged by normal desorption. Therefore, a new application for the use of the charge boost technology during winter is developed. During this season, partially charged main storages are present along with large quantities of solar radiation energy at low temperature levels. Recharging these units in winter would be beneficial to the process by reducing the amount of adsorption material needed to operate a seasonal thermal energy storage system, thereby reducing the cost and also the space demand of the whole apparatus. For the theoretical design, a fictional house is simulated, both as consumer and producer of thermal energy [9], [10]. The system properties are listed in Table 1 along with the chosen temperature levels for the storage system.

Figure 3. Schematic of the ideal charge boost process with descriptions for each step in the order of 1): Heating period during the day using pure adsorption. 2): Isosteric cooling of the recharge unit during the night. 3): Connection of the two units with steam exchange. 4): Regeneration of the recharge unit. Letters represent the main storage while numbers represent the recharge unit.
A material screening is performed to identify new materials which show good performance in the desired operating range [11]. Theoretical investigations indicate that silica gels may show better behaviour at the operating range of the recharge unit, whereas zeolite remains the best choice for long term storage options. This lead to the decision that the main storage will stay zeolite filled while the theoretical calculations will be performed for six different materials in the recharge unit in order to identify which works best. The actual design of the units was done by calculation using the Dubinin-Astakhov approach and a calculation tool. The design of the respective recharge units was performed by calculating their masses from the daily available solar radiation. The goal was to be able to desorb the recharge unit to the same benchmark at 25 per cent of the winter days (winter was defined as 01.12 to 28.02). Subsequently, the masses of the main storages are calculated based on the results for the recharge units. After the system masses have been determined, the amount of energy that can be fed to the respective main storages with three consecutive charge boost steps is calculated. The results for the six different materials are depicted in Fig. 4.

Regarding these results, the system with Sorbead R in the recharge unit is chosen as the most promising candidate. It shows the highest energy increase in the main storage unit per kg material in the recharge unit (benefit per effort).

### Table 1

(a) Characteristics of the simulated house for the development of the new charge boost application for winter.

| (a) single family house in Graz | (b) Temperature levels T [°C] |
|-------------------------------|-------------------------------|
| surface area                  | Desorption recharge unit 40   |
| space heating demand          | Desorption main storage 40    |
| domestic hot water demand     | Regeneration recharge unit 5   |
| collector type                | Charge boost recharge unit 5   |
| collector area                | Charge boost main storage 40  |
|                               | Condenser 5                   |

Temperature levels for the development of the new charge boost application for winter.

- Desorption recharge unit: 40°C
- Desorption main storage: 40°C
- Regeneration recharge unit: 5°C
- Charge boost recharge unit: 5°C
- Charge boost main storage: 40°C
- Condenser: 5°C

![Figure 4](image_url)

**Figure 4.** Amount of energy that can be fed to the respective main storages with three consecutive charge boost steps for six different materials in the recharge unit.
4. Experiments

Based on the ideas of Engel [6], experiments are conducted to verify the theoretical predictions. Engel suggests the use of the charge boost technology to further charge a main storage unit which was already pre-charged during the summer period using pure desorption. Additionally, a new application for the use of the charge boost technology during the winter months is developed by the author and then verified via further experiments. In order to perform these two experimental investigations, a testing plant built by Müller [7] at AEE INTEC is used.

4.1. Proof of principle for the charge boost technology

The mass of materials in the test rig as well as the temperature levels for the experiments are depicted in Table 2 with reference to Fig. 3.

| Table 2. (a) Mass of materials in the test rig. (b, c) Temperature levels for the experiments with indices referring to figure 3. |
| --- |
| (a) Materials | (b) Temperature level | T [°C] | (c) Temperature level | T [°C] |
| Material main storage unit | 13,1 kg zeolite 13XBF | Desorption recharge unit (2) | 140 | Desorption | 60 |
| Material recharge unit | 1,3 kg zeolite 13XBF | Charge boost recharge unit (3) | 16 | Charge boost | 60 |
| | | Regeneration recharge unit (2) | 140 | Condenser (1) | 16 |

In total, ten experiments have been conducted. The results of one are depicted in Fig. 5.

![Figure 5. Comparison of the moisture load X in the main storage unit for experiment and theoretical calculation over the course of sixteen consecutive charge boost steps.](image)

The results show good agreement with the theoretical predictions at first but then drift away. This trend could be observed for all respective experiments and is most likely caused by inert gases in the system. Since the vacuum components are not completely tight, air from the ambient changes the absolute pressure within the test rig. As the theoretical calculations have been performed under the assumption that only water vapour is present in the gas phase, the results differ from the experimental values. A possible reason for the values falling below the theoretical predictions in the beginning might be measurement inaccuracies as the moisture content was determined via a calculation from the system temperature and pressure.
4.2. **Proof of principle for the newly developed application**

In order to provide a proof of principle for the newly developed application from Section 3, experiments are conducted. The second cycle of experiments is performed with an adapted test rig and new temperature levels listed in Table 3 with reference to Fig. 3.

**Table 3.** (a) Masses of material in the adapted test rig. (b) Temperature levels for the second set of experiments with indices referring to figure 3.

| (a) Materials | (b) Temperature level | T [°C] | (c) Temperature level | T [°C] |
|---------------|-----------------------|-------|-----------------------|-------|
| Material      |                       |       |                       |       |
| main storage  | Desorption            | 40    | Desorption            | 40    |
| unit zeolite  | recharge unit (2)     |       | main storage (B)      |       |
| 13XBF         |                       |       |                       |       |
| Material      | Charge boost          | 10    | Charge boost          | 40    |
| recharge unit | recharge unit (3)     |       | main storage (B)      |       |
| 0,655 kg      |                       |       |                       |       |
| Sorbead R     | Regeneration          | 40    | Condenser (1)         | 10    |
| recharge unit | unit (2)              |       |                       |       |
| 40            |                       |       |                       |       |

The goal was to investigate three consecutive charge boost steps in order to compare the theoretical concept with the experimental results. The low temperature level in the experimental setup is higher than the one suggested in the theoretical concept. This is due to the fact that the lab environment could provide only a minimum temperature of 10 °C. Also, the preconditioning of the main storage was carried out at a moisture load of X = 24 % rather than X = 30 %. In order to be able to compare the theoretical concept to the experiments anyway, the model was recalculated with the new boundary conditions. The results of the experiments are depicted in Fig. 6.

![Figure 6. Absolute moisture content values X in the main storage unit for one experiment (dots) as well as the values for the adapted theoretical model (dashed line) with the same starting point as the experiment.](image)

The experimental results show good agreement with the theoretical model. However, also in this system, inert gases from the ambient changed the characteristics of the process. Again, this resulted in a higher moisture content than the anticipated one over the course of the experiment. Nonetheless, it could be proven that the charge boost technology is also working for the low temperatures in winter despite the non-optimal process conditions.
5. Conclusion
In this work, the use of the charge boost technology for summer and winter applications was investigated via experiments. In summer, this technology can be used to further charge a main storage unit which has already reached its limit in energy density by pure desorption without charge boost.

The application developed by the author suggests the use of the charge boost technology to recharge an already discharged main storage unit in winter. The theoretical calculations suggest an efficient process for the increase in energy storage density. An increase in energy storage density could indeed be achieved, however not to the extent the model predicted. This is most likely due to the pressure increase caused by inert gases in the system. Removing the influence of inert gas leakage would be the next step towards future experimental research.

Nonetheless, the results show that the charge boost technology will be an important step in the process of getting sorption thermal energy storage systems market-ready. It tackles the problem of space uptake and material requirement by increasing the maximum possible energy storage density of the system. Furthermore, it increases the number of conducted cycles which in return decreases the specific cost of energy per mass unit storage material. It can be stated that the charge boost technology is a viable option for the improvement of sorption thermal energy storages and a promising candidate for further research projects.

Acknowledgements
This work was performed over the course of the project Tes4seT, an Austrian lead project concerning new applications for sorption thermal energy storages. The project was funded by the Austrian FFG programme Energieforschung under grant agreement no. 845020. The authors would also like to thank the team at AEE INTEC for their continuous support and the good working atmosphere during the preparation of this paper.

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