

Development of a Thermo-Chemical Energy Storage for Solar Thermal Applications

H.Kerskes, B.Mette, F.Bertsch, S.Asenbeck, H.Drück

Institute for Thermodynamics and Thermal Engineering (ITW)
Research and Testing Centre for Thermal Solar Systems (TZS)
University Stuttgart
Pfaffenwaldring 6, 70550 Stuttgart, Germany
Phone: +49 (0)711 685 63279
Fax: +49 (0)711 685 63242
E-Mail: kerskes@itw.uni-stuttgart.de

Abstract

Solar assisted space heating systems are well introduced to the market and have an increasing market share. The challenging task now and in future is the development of solar only heating systems covering the complete heat demand by using solar radiation as the only energy source. Towards this goal great technological improvements have already been achieved in the last few years. This paper will report the present results of the project CWS (Chemische Wärmespeicherung - Chemical heat storage) in the field of low temperature solar thermal energy storage at the Institute for Thermodynamics and Thermal Engineering (ITW), University of Stuttgart, Germany. The developed concept as well as the main system components for a solar heating system with seasonal energy storage are described. Recent results of experimental and numerical investigations are presented and deliver an insight of the expected system performance taking into account the system and storage efficiencies under energetic and exetetic aspects.

1. Introduction and Background

Certainly one of the main difficulties in applying solar energy for space heating is the shift in seasonal variation of solar radiation and heat demand. To overcome this, a long term heat store is required in order to store the solar heat from summer to winter. Large heat storage capacities, small heat losses and good heat transfer characteristics are the key factors for efficient long-term heat stores required to achieve high solar fractions. Large hot water stores (5 - 30 m³ for a single family house) are already state of the art in some European countries. Many institutes and researchers are engaged in improving existing storage technologies and in developing new concepts for thermal energy stores. Hence the implementation of compact energy stores with higher efficiencies will be the next innovation step. This can be achieved by using chemical reactions for instance the hydration / dehydration process of inorganic salts.

The technology of thermo-chemical heat storage offers some notable advancement compared to traditional sensible heat storage. For long term heat storage purposes these are mainly a much higher storage density and even more important minor heat losses. Adsorption processes as well as reversible chemical reactions are subsumed under this technology. The adsorption of water vapour on porous media is quite interesting. Commercial adsorbents like zeolite or silicagel show good performance and can adsorb huge amounts of water vapour. The heat of adsorption released during adsorption is up to 4200 kJ/kg_{H₂O} (adsorbed water). The underlying physical processes are well known and have been intensively investigated by several researchers. During the past years existing adsorption materials have been improved with the focus on higher performance for thermal energy storage. Furthermore, complete new adsorptive materials have been developed which show very promising capabilities. Making use of the heat of reaction of reversible chemical reactions even in the low temperature application range (below 100°C) receives increasing attention in international research. Compared to adsorption processes this technology provides the potential of once again higher storage densities.

Within a three and a half years joint research project called CWS (Chemical heat storage) the Institute of Technical Thermodynamics (ITT) of the German Aerospace Centre (DLR) and the Institute for Thermodynamics and Thermal Engineering (ITW), University of Stuttgart, have investigated the technical

feasibility of chemical heat storage. ITW is focusing on low-temperature applications, whereas high-temperature applications are being investigated by ITT.

In the following sections the overall concept, the system design and the technology details on the development of a thermo-chemical energy storage system for a solar thermal heating system for buildings with high solar fraction ($>>50\%$) are given.

2. Generic System Concepts

When talking about thermo-chemical heat storage a wide range of different system concepts are conceivable. Starting at the top of a decision tree we need to differentiate between an open and a closed operating mode. In this context an open operating mode describes a system where the storage material is in direct contact with the environment. For example for the hydration reaction process the moisture is taken from the ambient air and during the dehydration reaction the released water vapour is again emitted to the ambient. By contrast, in a closed system the water vapour circulates in a hermetically closed loop. Here the evaporation and condensation of water has to be enforced by technical devices and an additional water reservoir is necessary and typically these systems are operated at negative pressure. From the design point of view the open adsorption has the advantage of a much lower technical effort (no condenser, no evaporator, no water reservoir, working at normal pressure, no low temperature heat source) and a simpler process control.

Using the open system mode, the next step is to analyse whether the ambient moisture, i.e. the partial water pressure is sufficient for a good reaction rate and reaction yield. Otherwise, an additional source of humidity is required. This of course strongly depends on the chosen reaction system. Furthermore, care has to be taken to reduce or to limit the pressure drop when blowing humid air through the reaction system to keep the electricity demand for the blower on a low level. Later on we will point out ways to manage both.

How to design the reactor, where the hydration/dehydration reaction takes place, is a complex decision. Generally, one can differentiate between system concepts with external or integrated reactor design. Integrated reactor design means the storage material reservoir of the solid phase reactant (hydrated / dehydrated salt) constitutes the reactor at the same time. However, to achieve an efficient charging and discharging of the store the process control is a real challenge.

External reactor concepts consist of at least two storage material containments, one for the hydrated and one for the dehydrated salt and a much smaller reactor. The decoupling of reactor and material reservoir has several advantages such as a reduction of thermal masses during the hydration / dehydration process and lower pressure losses when air is flowing through the reactor. Further advantages are a less complex process control and a good scalability. On the other hand, there are the disadvantages of storage material transport between material reservoir and external reactor. This also means additional requirements for the storage material.

The chosen reactor design determines the way how the thermo-chemical heat storage system can be connected to space heating and to the solar thermal system. In the past years two systems were discussed in the literature. In the "MODESTORE" project (Wagner et al., 2006) a closed adsorption system with an integrated reactor using silica gel as adsorbent was built up and experimentally investigated in a demo building. Another approach was the "MonoSorp-Concept" (Kerskes et al., 2006) where an open adsorption system, again with an integrated reactor design, was connected to an air heating system in combination with mechanical building ventilation and heat recovery. For this concept the "prove of concept" in lab scale was performed at ITW. Since moist ambient air is used as the "water vapour carrier", only an "open cycle" mode is possible. Compared to the usually employed packed beds, a major improvement was achieved by the application of zeolite honeycomb structures which have additional advantages when used in sorption storage systems. Within the Task 32 "Advanced storage concepts for solar and low energy buildings" of the Solar Heating and Cooling Programme (SHC) of the International Energy Agency (IEA) the "MonoSorp-Concept" was assessed as one of the most promising concepts. The "MonoSorp-Concept" will be further developed in a following-up project.

3. The CWS-NT-Concept

A new concept has been developed within the CWS Project at ITW and was first presented at the German Solar Thermal Energy Symposium in 2009. In order to further improve the performance, the system integration and the scalability of thermo-chemical storage concepts compared to concepts discussed before, a innovative concept was chosen which is characterized by the following distinguishing marks:

- Thermo-chemical heat store acts as long term heat storage (seasonal solar thermal heat storage)
- Open adsorption/hydration system using ambient air or exhaust air to provide the humidity required for the reaction
- Thermo-chemical heat store works as low power heat supply system
- Connection of the thermo-chemical heat store to a typical combistore store of solar thermal system via collector loop heat exchanger
- Combistore operates as buffer store to cover load peaks
- External reactor designed as cross-flow reactor with low pressure drop and structurally integrated heat exchangers
- Integration of air/air heat exchanger for optimal power output
- Storage material transport through the reactor by gravity forces with continuous or quasi-continuous mass flow
- Bidirectional active storage material transport between storage material reservoirs and reactor using a vacuum blower

The efficient integration of the chemical heat storage system, including reactor and storage material reservoir, into the hydraulic scheme of a solar thermal combi system for domestic hot water preparation and space heating was one of the challenging tasks of the project. Different design concepts, depending on the different strategies for process control, have been developed and assessed. Finally, the following scheme was identified as the best solution. Figure 1 shows a sketch of the CWS-NT-Concept including the solar thermal heating system and the thermo-chemical heat storage. It is foreseeable that a conventional solar combi system, designed for relatively small solar fraction ($< 30\%$) turns to a solar seasonal heating system by adding the thermo-chemical heat storage without any changes to the conventional heating system. From the hydraulic point of view the connection between solar combisystem and thermo-chemical heat storage is simple. The main components of the system are the solar combistore, the collector array, the material reservoir, the reactor and a control system.

During periods of high solar irradiation (mainly in the summer) heat energy from the collector array is directly charging the combistore. When the energy provided by the collector field exceeds the heat demand for hot water preparation and space heating, the available solar energy is used for the endothermic dehydration reaction of the storage material (regeneration mode). During periods of low solar irradiation when the energy from the solar collector field cannot cover the heat demand the chemical heat store is used. The heat of the exothermic hydration reaction is released by blowing humid room exhaust air through the reactor and the thermo-chemical energy store (TCES) is charging the combistore (heating mode). Depending on the system dimension the backup heater can even be removed completely.

The TCES has to fulfil two key functions: It shall provide a storage container for the material and, on the other hand, a reactor where the heat and mass transfer takes place during the endothermic or exothermic reaction. The reactions occurring inside the reactor are outlined in equation 1. Water vapour is supplied to, or transported out of the reactor via airflow. The reaction is performed with ambient or humid room exhaust air. This has the advantage that no further energetic effort is needed for evaporating water. Another important element for an efficient process design is the air to air heat exchanger, preheating the supply air by the reactor outlet airflow. This results in a very low temperature difference between supply and exhaust air and hence in low heat losses via the air flow (cmp. section 6, experimental investigations).

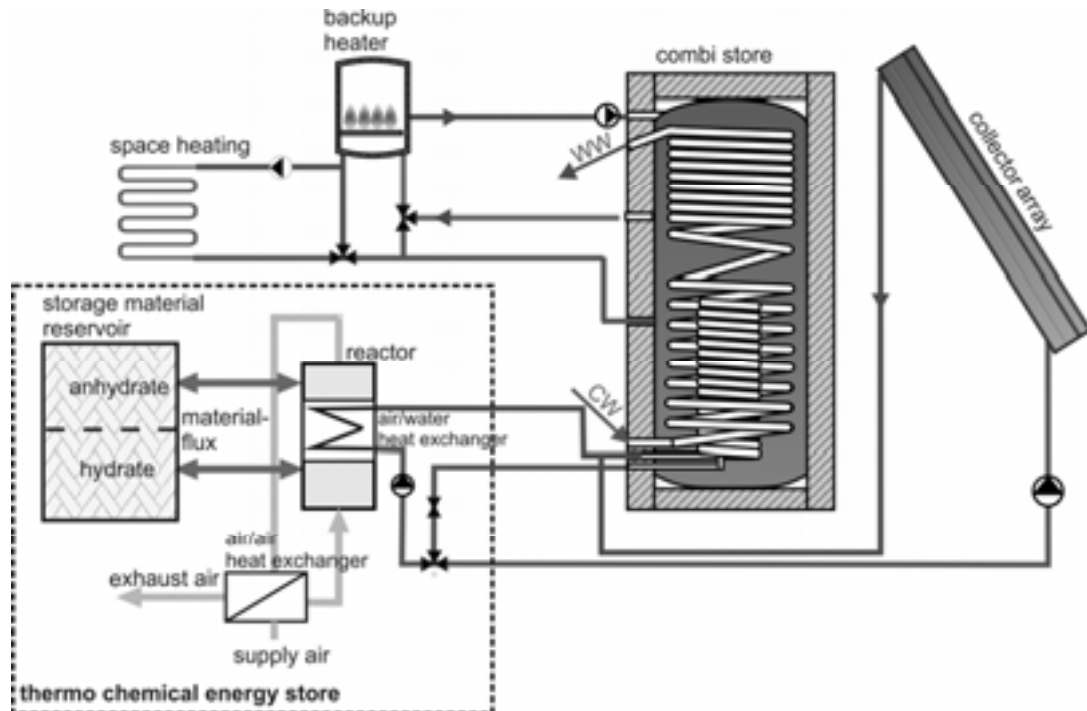


Figure 1: Schematic of the CWS-NT-Concept using the example of an upgraded solar thermal combi system.

The reactor design of the CWS-NT-Concept

A very detailed description of the reactor design developed for the CWS-NT-Concept is given in Mette et al. (2011). In this article a brief overview of the functionality and the key features of the reactor concept are given.

Figure 2 (left) shows a sketch of the cross-flow reactor concept, indicating the mass flows involved in the reaction system when operated in heating mode. The vertical material flow is driven by gravity through the reaction chamber. In horizontal direction, an air flow is transporting humidity as well as heat into or out of the reaction chamber, depending on the operation mode. In heating mode, the released heat is transferred from the airflow to the water loop by an air/water heat exchanger; see Figure 3 (left). For material regeneration, the air flow direction is reversed and the heat exchanger is used for transferring the heat required for regeneration from the solar loop into the reaction chamber via the air flow, see Figure 3 (right).



Figure 2: Cross-flow reactor concept in heating mode (left), test reactor in lab-scale (middle) and construction plan (right).

The choice of concept has been mainly determined by the following aspects:

- the limitation of the *airflow pressure drop* in the reactor, which is correlated to the electrical power consumption of the blower, is one of the most crucial designing factors; the cross-flow concept allows the realisation of a large cross-area and a minimal bulk width in flow direction
- the *material transport* through the reactor chamber can be realised in a reliable and technical inexpensive way with low material stress; special considerations are given to a homogenous material movement (see section 6)
- a robust and efficient *process control* allows complete material regeneration and complete heat release at reasonable high temperature levels
- a compact construction with short distance between heat source and heat removal, i.e. between reaction chamber and heat exchanger, is favourable to minimize heat losses to ambient

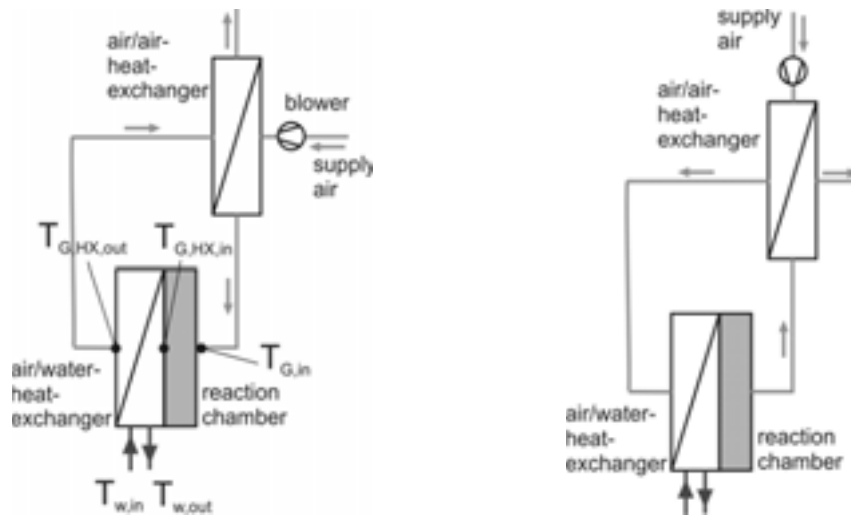
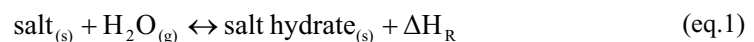


Figure 3: Schematic of air loop in heating mode (left), including positions of temperature sensors T_G in air-flow and T_w in water loop for test operation (cmp. section 6); air loop in regeneration mode (right).

4. Thermo chemical storage materials under investigation for low temperature applications

As a precondition for the reactor design, particular importance was paid on the storage material itself during the entire CWS-project. A great variety of hydration/dehydration reactions of salts have been investigated as storage material for thermo-chemical energy storages. The specific material characteristics (storage density, reaction behaviour) determine the boundary conditions of the reaction such as reaction temperature and inlet air humidity.

Up to a demand temperature of approximately 100°C salt to salt hydrate reactions are under investigation as thermo-chemical storage material (Bertsch et al. 2009 and 2010, van Essen et al. 2010, Posern and Kaps 2010, Zondag et al. 2010, Hongois et al. 2010). These reaction mechanisms are outlined in equation 1. A dry salt reacts exothermal with water vapour (H_2O) to a salt hydrate with heat release. The reaction enthalpy ΔH_R depends on the material used and its current water loading. Typical materials are salt chlorides and sulphates.



Depending on the process design the storage material shall be transportable, no dust production or agglomeration shall occur and the material shall have a high storage energy density combined with a fast reaction rate. The investigations done at ITW have shown that those physicochemical properties are hard to find using a powder of a pure salt. Although it was possible to identify process conditions which lead to high reaction yields, a slow reaction rate was observed (Bertsch et al. 2009). Another problem using pure salt is caused by its particle size of below 1 mm. A constant air flow through a packed bed is difficult to obtain and correlated with a high pressure drop, hence energetically extensive.

One way to enhance the reaction rate and thus the heat release, and at the same time to lower the pressure drop is to use a composite material. A composite material is built of an active (e.g. zeolite) or a passive (e.g. ceramics), usually porous, supporting material. In contrast to passive supporting materials, an active supporting material is directly involved in the process of thermo-chemical energy storage. The supporting material primarily defines the structure, consistency and form whereas the salt enhances to the energy storage capacity.

In Figure 4, an overview of some selected storage materials is given. The charging of the storage material was done at 20°C with a water vapour pressure of 20 mbar. The regeneration was carried out at 120°C for MgCl₂, 150°C for CaCl₂ and 180°C for zeolite and MgSO₄ respectively. The storage density of water refers to a temperature difference of $\Delta T = 50$ K. Especially the composite materials consisting of zeolite and magnesium sulfate, measured by ITW as well as by Hongois (2010, “EDF”), and magnesium chloride on a passive carrier measured by Zondag (2010, “ECN”) are characterized by a high energy storage density combined with all required physicochemical properties mentioned above. These materials are very well suited for thermo-chemical heat storage systems and promise a high thermal performance for solar thermal applications.

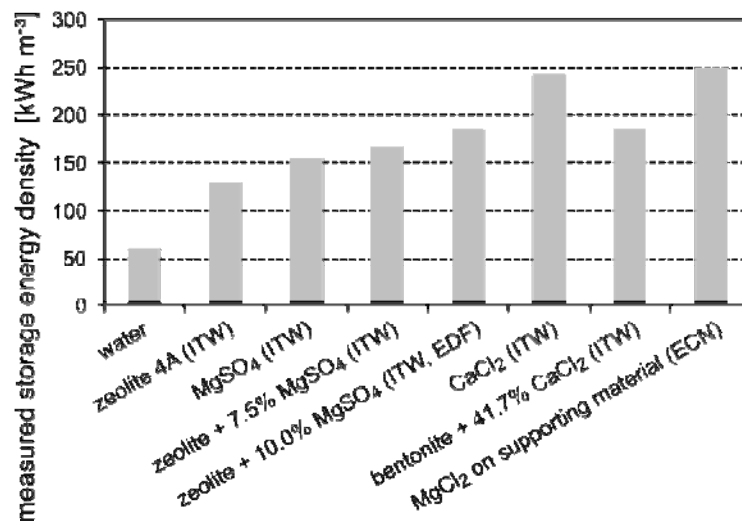


Figure 4: Overview of experimentally measured storage energy densities of selected materials for thermo chemical energy storage. Storage density of water refers to a temperature difference of $\Delta T = 50$ K (Bertsch 2010, Hongois 2010, Zondag 2010).

5. Thermal performance of the CWS-NT-Concept

Within the CWS project one emphasis was set on the numerical modelling of the reaction process and the heat and mass transfer in the reactor. Detailed numerical simulations have been carried out to analyze the main parameters of influence of the reaction behaviour and to design the thermal layout of the reactor.

Furthermore, the achievable energy savings are a decisive factor in the design of the optimal system. Due to the multitude of physical phenomena (chemical reaction, heat and mass flux, heat sources and sinks) and seasonally fluctuating operation conditions, the technical feasibility and energy saving of the complete system are hard to predict. Therefore, the thermal performance of the CWS-NT-Concept has to be analysed over a whole year by using a dynamic system simulation tool. For this purpose, a simplified model of the thermo-chemical cross-flow reactor (described in section 3) has been derived and implemented into the simulation tool TRNSYS, based on a much more detailed CFD model developed by Mette et al. (2011). The simplified TRNSYS model takes into account the basic physical processes and limits, like reaction equilibrium, heat- and mass fluxes, however, not having the numerical complexity of a spatial discretization. The validity of the simplified TRNSYS model has been verified by comparison with the detailed CFD model.

Boundary conditions of the system simulations

For the system simulation, the following assumptions were made:

- the yearly heat demand for space heating is $35 \text{ kWh m}^{-2} \text{ a}^{-1}$ at a net dwelling area of 128 m^2
- the building is supplied with an mechanical ventilation system
- the daily hot water demand of 4 persons is in total 200 l at 45°C
- reference weather data at the location Würzburg, Germany is used for the simulations
- the thermal collector is a CPC vacuum tube collector, the total area is 28 m^2
- the combistore volume is 900 l
- the storage energy density is estimated with 185 kWh m^{-3} .
For the simulations it is assumed that the material has similar adsorption isotherms as zeolite 4A
- the maximum airflow through the reactor is 250 kg h^{-1}
- the regeneration temperature is at least 180°C
- the reaction enthalpy of the storage material is $\Delta H_R = 3600 \text{ kJ kg}^{-1}$
- exhaust room air from the ventilation system is used as reactor feed

As depicted in Figure 1 the heat of adsorption from the reactor is released to the combistore by an air/water heat exchanger. For a sufficient heat transfer a temperature difference of approximately 15 K between the two fluxes should be attained. The adiabatic air temperature lift ΔT_G is calculated according to equation 2:

$$\Delta T_G = \frac{\Delta x_G \cdot \Delta H_R}{c_{p,\text{air}}} \quad (\text{eq. 2})$$

with Δx_G (kg kg^{-1}) as difference in the water load of inlet and outlet air of the reactor and $c_{p,\text{air}}$ as specific heat capacity of the air.

Assuming a perfect water uptake of the storage material, an air humidity of $x_{\text{min}} = 4 \text{ g}_{\text{water}}/\text{kg}_{\text{air}}$ will lead to an adiabatic temperature lift of 14.4 K and constitutes the minimum air humidity for a suitable reaction. The daily humidity production of 4 people living in a building can be assumed to be 10.4 kg per day (Hartmann, 2001). Hence the average building air humidity is almost $2 \text{ g}_{\text{water}}/\text{kg}_{\text{air}}$ higher than the outdoor air humidity. Thus, even in the dry winter months (December to February) the indoor air humidity exceeds the minimal limit of $4 \text{ g}_{\text{water}}/\text{kg}_{\text{air}}$ in more than 600 hours per month.

To realise the required high temperature for regeneration of the storage material in an efficient way, a temperature controlled charging multiplexer model has been implemented into TRNSYS. This model regularly (every 30 min) provides an estimate whether the regeneration set temperature is reachable in the collector array within a given time. Depending on this estimate, charging of the combistore is continued or the collector loop is temporarily switched off and, as soon as the collector temperature exceeds 180°C , the heat is transferred to the reactor for material regeneration.

Results of the system simulations

To interpret the results obtained within the numerical simulation study of the CWS-NT-Concept, some characteristic factors are introduced, namely the yearly fractional energy saving, the system efficiency and the store efficiency. The yearly fractional energy saving is calculated according to equation 3:

$$f_{\text{sav}} = \frac{Q_{\text{conv,net}} - Q_{\text{aux}}}{Q_{\text{conv,net}}} \quad (\text{eq. 3})$$

whereas $Q_{\text{conv,net}}$ (kWh a^{-1}) is the total heat demand of a conventional (non-solar) heating system to cover the space heating and hot water demand and Q_{aux} (kWh a^{-1}) the residual heat demand required to cover the space heating and hot water load delivered by the backup heater.

The system efficiency is calculated according to equation 4:

$$\eta_{\text{sys}} = \frac{Q_{\text{conv,net}} - Q_{\text{aux}}}{G_{\text{glob}} \cdot A_{\text{c,tot}}} = \frac{Q_{\text{conv,net}}}{G_{\text{glob}} \cdot A_{\text{c,tot}}} \cdot f_{\text{sav}} \quad (\text{eq. 4})$$

G_{glob} ($\text{kWh m}^{-2} \text{ a}^{-1}$) is the global irradiation in collector plain, $A_{\text{c,tot}}$ (m^2) the total collector area.

The storage efficiency is the ratio of the solar heat extracted from the store (or stores) to the solar heat fed into the store (or stores). It is calculated according to equation 5:

$$\eta_{\text{sto}} = \frac{Q_{\text{D}} - Q_{\text{aux}}}{Q_{\text{col}} - Q_{\text{lp}}} \quad (\text{eq. 5})$$

Q_{D} (kWh a^{-1}) is the heat discharged from the store, Q_{col} (kWh a^{-1}) is the heat delivered by the collector array and Q_{lp} (kWh a^{-1}) the heat loss of the piping in the collector loop.

Using the presented boundary conditions, dynamic system simulations of a CWS-NT-Concept have been performed. For a better interpretation of the results, an equivalent system with a large hot water store instead of the CWS-NT-concept has been simulated. The results are depicted in Figure 5. The yearly fractional energy savings are plotted against the collector area and the corresponding store volume respectively. If a yearly fractional energy saving of 70 % shall be achieved, a “standard” solar thermal system using a hot water store of a volume of 15 m^3 with a collector area of 38 m^2 is required. Using similar system components, but the CWS-NT-concept instead of the hot water store, the same results can be achieved with a material reservoir of approximately 8 m^3 and a 13 m^2 smaller collector array of 25 m^2 . The TCES material used for these simulations has a storage energy density of 185 kWh m^{-3} , which is 30 % higher compared to zeolite 4A. A reduction of the storage volume of almost 50 % compared to water as storage medium can be achieved.

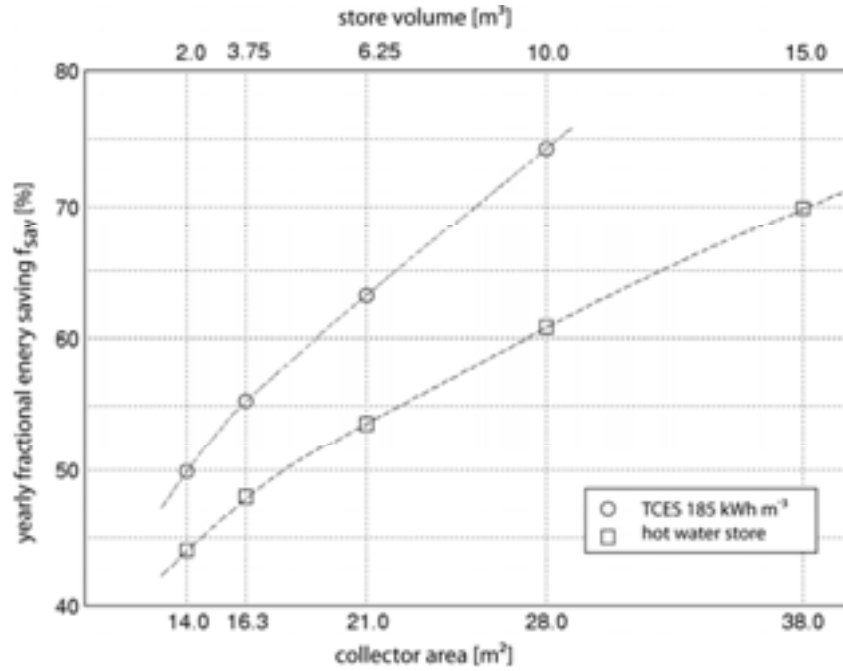


Figure 5: Comparison of the fractional energy saving of a combisystem with a hot water store and the CWS-NT-concept

Using equation 3, 4 and 5 the characteristic factors can be calculated for both systems. In Table 1, the results are summarized. As already seen in Figure 5, the fractional energy saving of the CWS-NT-concept is almost 15 % (absolute) higher with the same collector area. As the heat losses of the CWS-NT-concept are strongly reduced, the system efficiency η_{sys} rises from 14.3 % of the hot water store system to 18.7 % of the CWS-NT-concept. Due to the same effect, the store efficiency η_{sto} of the TCES is more than 20% (absolute) higher compared to the hot water store.

Tab 1: Yearly summary of the system simulations of a hot water store system and a TCES system, both with a total collector area of 28 m^2 .

| | f_{sav} (-) | η_{sys} (-) | η_{sto} (-) |
|---|----------------------|-------------------------|-------------------------|
| 10 m^3 hot water store | 0.608 | 0.143 | 0.429 |
| 10 m^3 CWS-NT-concept (185 kWh m^{-3}) | 0.752 | 0.187 | 0.640 |

The simulation study illustrates the advantage of the CWS-NT-Concept for seasonal heat storage. The benefit is not only a smaller storage volume but also a much smaller collector area required to achieve high solar fractions far above 50 %.

6. Experimental investigations on the CWS-NT-reactor

An important target of the CWS project is to build up a thermo-chemical heat storage as described above in lab scale. According to the theoretical and numerical analyses a first prototype of a cross-flow reactor has been realized. The aim of the experimental work is to investigate the mass flow of storage material and air through the reactor and the spatial distribution over the cross section. Another important aspect concerns the thermal properties of the reactor design which will be investigated closely. Furthermore, the experimental results serve as a basis for validation of the numerical models developed in this project.

Experimental investigation of the material flow

A homogenous material transport through the reaction chamber and the avoidance of “dead zones” is essential for an optimal reactor performance. “Dead zones”, i.e. regions with resting material become inactive in reaction after a while, leading to reduced efficiency both in heating and regeneration mode. To analyse the trickling behaviour of bulk material within the reaction chamber, the test reactor was filled with zeolite particles, see Figure 6 (middle). By opening the shutter at the material outlet, a vertical material core flow develops in the middle of the reaction chamber, whereas “dead zones” with hardly any material movement are observed at the bottom corners¹. This well known phenomenon results in a typical material V-cone as shown in Figure 6 (left).

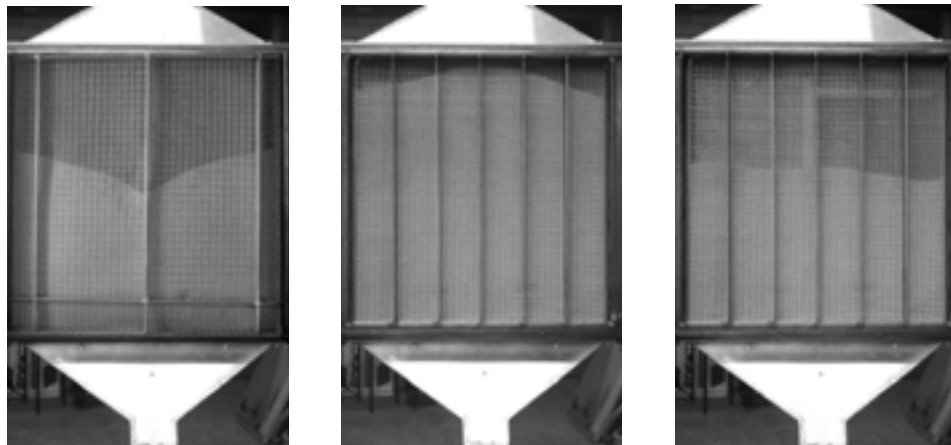


Figure 6: Material flow experiments in the test reactor, starting with a filled reaction chamber (middle):
- a core flow above the outlet and dead zones at the bottom corners are formed (left),
- guiding components within the outlet cone produce a more homogenous material flow (right).

An almost homogenous material flow could be realized by installing guiding components into the bottom outlet cone, which successfully prevents the development of a centered core flow; a corresponding image is shown in Figure 6 (right).

Test of heating mode in quasi-continuous reactor operation

In order to verify the basic operation principles, first preliminary experiments have been performed, using a simplified reactor test rig without heat recovery of the outlet air flow (the air/air-heat exchanger shown in figure 3 is missing). These experiments were performed to clarify

- whether pressure loss and thus air flow rate is in accordance with the dimensioning,
- to which degree the released heat is removed in the air/water heat exchanger (i.e. whether reactor concept and dimensioning of the heat exchanger is promising),

¹ For visualization reasons, during these experiments no material has been refilled. This is different from regular operation, when the reaction chamber is continuously refilled from the top material inlet.

- whether the air flow temperature lift in the reactor is approaching the theoretical adiabatic value (i.e. to which degree reactor heat losses are influencing the performance),
- whether the material exchange needed for quasi-continuous operation of the reactor is practically realisable.

For the following test of the heating mode, the reactor chamber has been filled with 20 l of dry zeolite 4A. A blower with an electric power of 20 W produces an air-flow, taken from ambient with a mean inlet humidity of $x_{G,in} \approx 5.5 \text{ g}_{\text{H}_2\text{O}}/\text{kg}$. After reaching a stationary state, a material volume of 2 l is drained every 20 min at the material outlet.

In Figure 7 (left), measured temperatures around the test reactor are depicted; the position of the temperature sensors are given in Figure 3 (left). The experiment is performed without any thermal insulation. Therefore, to limit the heat losses to ambient, comparably low inlet temperatures have been chosen: both the water loop, which transports the useful heat out of the CWS-NT system, and the air loop enter at temperatures slightly below ambient temperature, $T_{w,in} \approx T_{G,in} \approx 17 \text{ }^\circ\text{C}$. Passing the reaction chamber, the air temperature is increased to $T_{G,HX,in} \approx 37 \text{ }^\circ\text{C}$ at the inlet of the heat exchanger (cmp. Figure 3, left), which is in good accordance with the expected, adiabatic temperature lift of approximately 20 K for zeolite 4A at the given air inlet humidity. Within the plate-fin heat exchanger the air temperature is finally reduced to $T_{G,HX,out} \approx 22 \text{ }^\circ\text{C}$; considering the even slightly higher heat exchanger outlet temperature of the water loop $T_{w,out} \approx 23 \text{ }^\circ\text{C}$, the air/water heat exchanger seems adequately dimensioned. However, still a significant ratio (roughly 30%) of the released heat of reaction is lost by the outlet airflow, which can be seen by a significant remaining temperature lift at the outlet $T_{G,HX,out} - T_{G,in} \approx 6 \text{ K}$ compared to the reaction temperature lift of about 20 K. To recover these air-flow heat losses, which are expected to be even more significant in regeneration mode, is the aim of the air/air heat exchanger, which is already implied in Figure 3 but not yet installed in the test rig.

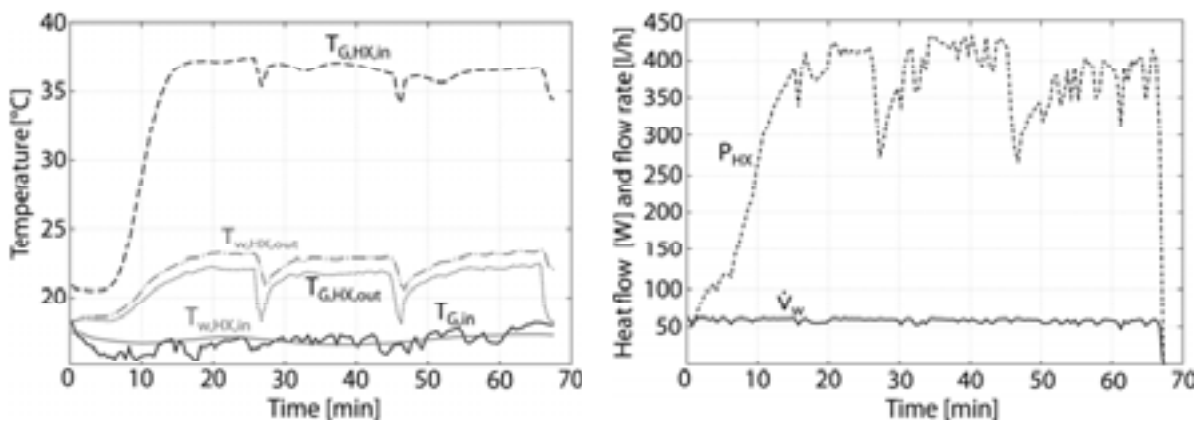


Figure 7: Air-loop (T_G) and water-loop (T_w) temperatures (left) and heat flow P_{HX} transferred to the water loop (right) during test of heating mode.

In Figure 7 (right), the heat flow rate P_{HX} transferred to the water loop by the heat exchanger has been calculated. Neglecting the intervals of material exchange when the airflow has been interrupted, an almost constant power of approximately 400 W could be removed out of the test reactor. By an optimized air-flow rate, the extension by the air/air recovery heat exchanger and by up-scaling of the reactor, a considerable increase in the nominal power is expected.

Material transport: Concept and realization

Material transport is required from the material reservoir to the reactor and vice versa. In Figure 8, a schematic of the material transport (left) and its lab-scale correspondence (right) are depicted. In addition to the material reservoir, a daily reservoir is situated below the reactor. From the material reservoir to the reactor and from the reactor to the daily reservoir the material transport is gravity driven. The daily reservoir, which is usually emptied once a day, allows an energy efficient use of the vacuum blower. In the pilot plant, a vacuum blower from the company GlobalTec is used. The electric power is approximately 1600 W corresponding to a hauling capacity of 1000 kg h^{-1} . Assuming an material energy storage density of 250 Wh kg^{-1} (approximately 185 kWh m^{-3}) the ratio of electric consumption to useful thermal power will be as low as $13 \text{ W}_{el}/\text{kW}_{therm}$.

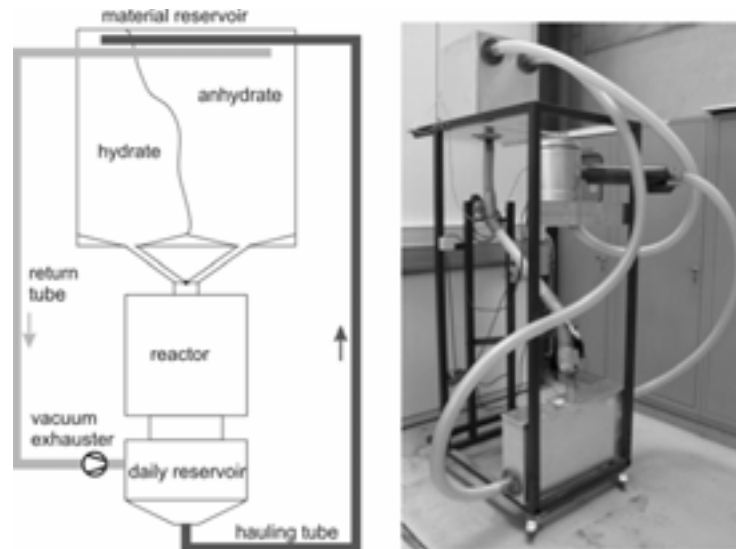


Fig 8: Schematic of the material transport system (left) and lab realization (right).

Ongoing and future work on CWS-NT reactor concept

Currently, the reactor test rig is extended by a thermostat, acting as heat sink in heating mode or as heat source in regeneration mode. As soon as the air loop is completed by the air/air heat exchanger, realistic test cycles can be performed at arbitrary temperature levels. Concerning the reactor design, some adaptations are planned to optimize the start-up process of the quasi-continuous reactor operation. Finally, the reactor test rig shall be combined with the external material transport system driven by the vacuum blower, which has already been tested in a separate experimental setup. The aim of this final setup is to carry out automated lab-scale tests of a complete CWS-NT-concept regeneration and heating cycle in fast motion.

7. Conclusion

Thermo-chemical energy storage is one of the most promising heat storage technologies for the future. Especially for solar thermal heating purposes this technology provides the necessary properties for efficient long term heat storage: a high energy storage density and a high storage efficiency. These are the important key elements to realise high solar fractions or solar only heating systems even for applications with high heat demand.

At the research and testing centre for thermal solar systems (TZS) of the Institute for Thermodynamic and Thermal Engineering (ITW) a new concept of a thermo-chemical energy storage called “CWS-NT-Concept” has been developed. For the first time, a system with external reactor working in an open thermo-chemical reaction loop has been developed, built up in lab scale and investigated experimentally. The first aspect was to find a storage material that fulfils the physico-chemical properties required for the external reactor concept. It was found that composite materials are a good compromise with respect to performance and function. The chemical reactor is designed as a cross-flow fixed bed reactor in quasi-continuous operation mode, i.e. replacement of small amounts of storage material in periodic intervals and continuous airflow. The material transport is realised by a vacuum blower in an energy efficient way. The thermo-chemical storage system is designed to be integrated into a conventional solar combi system and connected via the collector loop. Detailed simulation studies have shown in an interesting way the thermal performance of the new concept. Compared to a similar system with a hot water store of same volume the CWS-NT-Concept reaches a higher solar fraction, higher system efficiency and much higher storage efficiency. Experimental investigations have shown so far that the reactor concept is suited to achieve a sufficient temperature lift even under room air condition and an almost constant power in the quasi-continuous operation mode. To bring the promising technology of thermo-chemical energy storage to marketability, extensive research and development in all sections (storage material, reactor design and system integration) have to be done. Moreover, demonstration projects are necessary to investigate and optimize the complete system and especially the thermo-chemical energy storage under realistic operation conditions.

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9. Nomenclature

| Symbol | Unit | Quantity |
|--|-----------------------------------|--|
| G_{glob} | $\text{kWh m}^{-2} \text{a}^{-1}$ | global irradiation in collector plane |
| $Q_{\text{conv.net}}$ | kWh a^{-1} | total heat demand of a conventional (non solar) heating system to cover the space heating and hot water demand |
| $A_{\text{c,tot}}$ | m^2 | total collector area |
| f_{sav} | - | yearly fractional energy saving |
| Q_{aux} | kWh a^{-1} | residual heat demand required to cover the space heating and hot water load delivered by the backup heater |
| Q_{D} | kWh a^{-1} | total heat demand for space heating and hot water |
| Q_{col} | kWh a^{-1} | heat delivered by the collector array |
| Q_{ip} | kWh a^{-1} | heat loss of the piping in the collector loop |
| Δx_{G} | kg kg^{-1} | difference in water load of inlet and outlet gas |
| ΔH_{R} | kJ kg^{-1} | reaction enthalpy |
| $c_{\text{p,air}}$ | $\text{kJ kg}^{-1} \text{K}^{-1}$ | mean specific heat capacity of air |
| ΔT_{G} | K | temperature lift of airflow |
| $T_{\text{w}}, T_{\text{G}}, T_{\text{S}}$ | $^{\circ}\text{C}$ | water, air (gas) and material (solid) temperature |

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