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A novel heat battery to save energy & reduce CO_2 emission

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Abstract

In our labs and pilot sites, a novel heat battery for dwellings and offices is being developed. Based on a thermochemical sorption reaction, space heating, cooling and generation of domestic hot water will eventually be demonstrated in an existing dwelling by using solar or waste heat in the CREATE project. Developments of the active materials, of the reactor and components, and of the system were mainly performed in the MERITS project, and results are briefly described. Upon wide-spread use, the technology of compact thermal storage can be the game changer in the transformation of our existing building stock towards near-zero energy buildings.

Keywords: *thermal storage, energy storage, sorption storage, thermochemical storage, seasonal storage*

1. Introduction

For the transition to a 100% renewable energy economy, the application of solar energy (including electricity and thermal energy) is essential. As solar energy strongly fluctuates not only during the day but also during a year, it will be necessary to store large amounts of energy during at least half a year. Diurnal thermal storage can be arranged by mature boiler technology (sensible storage), but seasonal storage requires considerably lower heat losses. Besides, seasonal heat storage for domestic applications requires compact systems. Thermochemical storage provides a favorable solution, theoretically being loss-free during storage, and very compact. In this paper, we show (Fig. 1) that for the first time thermochemical energy storage has been demonstrated on a large and relevant scale.

Fig. 1: MERITS Field Test Demonstrator 3D systems model (left) and Field Test Demonstration container during pre-testing in Lleida, Spain (right)

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In practice, energy storage densities can be reached that are in the order of boiler technology storage densities, but with much reduced thermal energy losses during storage periods. The current paper describes results obtained from the MERITS project (www.merits.eu), which was aimed at designing, building and evaluating prototypes of a compact seasonal solar-thermal energy storage system based on thermochemical storage materials, i.e. a thermal battery. The team worked with a novel thermochemical material reaction having high energy density that can supply required heating, cooling and domestic hot water (DHW) for a dwelling with up to 100% renewable energy sources throughout the year. Furthermore, an outlook of future improvements to be performed in the CREATE project (www.createproject.eu) will be given. The CREATE project has as main aim to develop and demonstrate a heat battery, i.e. an advanced thermal storage system based on Thermo-Chemical Materials, that enables economically affordable, compact and almost loss-free storage of heat in existing buildings. To this end, demonstration will eventually take place in a dwelling.

2. Improvement over available thermal energy storage techniques

Loss-free compact affordable thermal energy storage would greatly enhance the use of sustainable heat from solar or waste sources. Different forms of thermal energy storage exist today: sensible storage, latent storage (through phase-change materials) and thermochemical storage.

Sensible storage makes use of the thermal capacity of a liquid or solid. Through heating, a certain quantity of heat can be sensibly stored in said materials, e.g. in hot water systems. Roughly 50 m^3 of water would be needed for storing 10 GJ (2778 kWh) of heat in a temperature range between 40 and 90 °C. Even when this volume would indeed be available in domestic applications, it will have insufficient storage capacity because of the thermal losses.

Latent thermal energy storage makes clever use of melting/solidification of certain classes of materials (phase change materials, PCMs). Examples are ice/water, different kinds of salts, or paraffins, having storage densities roughly between 0.2 – 0.4 GJ/m^3 (roughly 56 – 111 kWh/m^3) on a materials level and for temperature ranges for domestic applications. Although slightly more compact than sensible energy storage, losses play a large role here as well.

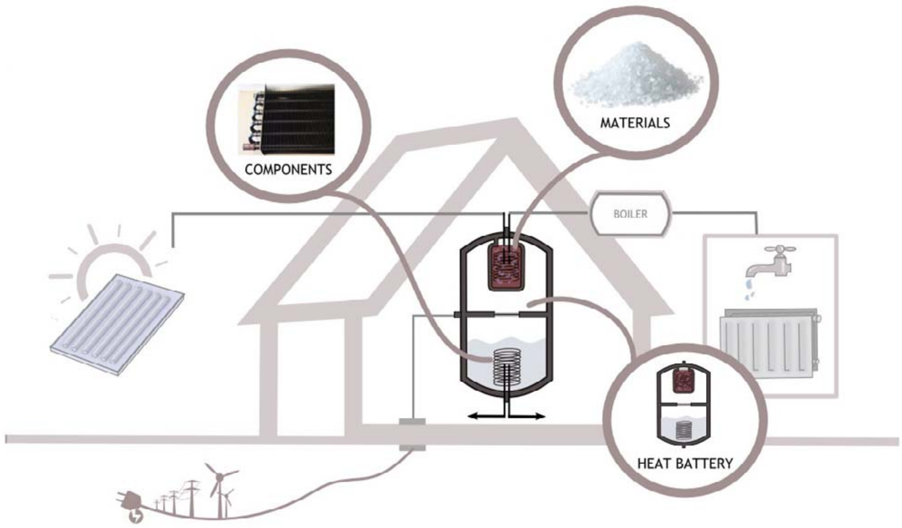

Fig. 2: Schematic of the project concept for heat battery development for dwellings application (Low-temperature heat source not shown)

Thermochemical storage is the process of using heat of reaction (enthalpy) of reversible chemical reactions for thermal storage applications. In theory, very high thermal storage densities can be reached (as high as 1-3 GJ/m^3 or 278 – 833 kWh/m^3 at the level of storage material for typical sorption reactions of salt hydrates around temperatures of 60-140°C). In addition, no thermal losses occur during storage. For this reason, the MERITS project ultimately targeted demonstration of thermochemical storage solutions for dwelling applications. Further key development issues are delivery of heat on different dedicated temperature levels for heating, cooling and DHW, design and development of a dedicated solar collector, integrated design for the components and enhanced thermochemical materials, including the control system, and development of business models and market strategies to foster swift market take-up. Many of these developments have been described already elsewhere (see e.g. de Jong et al., 2014; Solé et al., 2015; Volmer et al., 2015)). The follow-up project CREATE aims to deal with 3 key aspects:

- Economical affordability: For the existing building stock our project will target at least a reduction of 15% of the net energy consumption on building level with a potential simple payback time shorter than 10 years;
- Compactness: Novel high-density materials will be used in order to limit the use of the available space to a maximum of 2.5 m^3 thermochemical material;
- No heat losses during storage: This is an intrinsic material/system property of thermochemical storage technology, thereby enabling long-term storage.

As sub-objectives of these aspects, stable and efficient materials for thermochemical storage, a long life-time, affordable technology, efficient and high power discharge, and safe and reliable operation are specifically addressed. In addition, the future value-chain is mobilized, having all the required key players in the supply and value chain from the material level up to the system level and the energy grid in the current consortium. The project concept is based on advanced compact thermal storage for existing dwellings using thermochemical storage materials (Fig. 2). The heart of the system is a modular setup consisting of vessels that contain the salt. In the time between dehydration and hydration the energy is stored in the salt. We envision two applications for the heat battery:

- Decentral thermal energy storage bridging supply and demand of renewable thermal energy;
- Decentral grid-connected storage for increasing energy efficiency and introducing flexibility in the electricity grid, e.g. using a heat pump.

A more efficient system design will enable demonstration of the concept in the real conditions: the system will be installed into a single family house in Warsaw, Poland, where a continental climate delivers both cold winters and warm summers.

3. Thermochemical storage – principle

Several possible examples of reversible thermochemical reactions taking place in the relevant temperature range are given below:

$$K_2CO_3 + 1½H_2O \rightarrow K_2CO_3.1½H_2O \quad \text{(eq. 1)}$$

$$Na_2S.½H_2O + 4½H_2O \rightarrow Na_2S.5H_2O \quad \text{(eq. 2)}$$

$$MgCl_2.2H_2O + 4\ H_2O \rightarrow MgCl_2.6H_2O \quad \text{(eq. 3)}$$

$$CaCl_2 + 2H_2O \rightarrow CaCl_2.2H_2O \quad \text{(eq. 4)}$$

The same hydration states occur in the reverse reactions.

When heating the hydrated salt to 80°C and condensing the water at a temperature below 20°C, both dehydration steps can theoretically be used and a very high theoretical storage density (up to 2.9 GJ/m^3 hydrate or 806 kWh/m^3 hydrate, at the level of the storage material) can be achieved forming the dried salt and water. On hydrating the salt by evaporating the water again at a temperature of >10°C, heat is released at temperature levels that can be used for heating and DHW purposes (>60°C). Keeping the compounds separate ensures storage of the reaction enthalpy, i.e. the heat. Typically, a low-temperature heat resource, e.g. a nearby lake, canal, or ground-source, takes care of the heat necessary for evaporation and of condensation upon drying. Unlike in the sensible and latent thermal storage techniques, thermochemical storage takes place at ambient rather than at elevated temperatures because technically chemical potential is stored. In turn, it makes efficient thermal storage independent of storage times. Only when the products are brought together the enthalpy of reaction is released again, thereby generating heat. Uniquely, this ultimately enables long-term low-loss heat storage with very high thermal energy storage densities. The MERITS technology has been previously shown to enable theoretical storage densities around 1000 MJ/m^3 (278 kWh/m^3; de Jong et al., 2016). Further requirements playing a role are of course cycleability, safety, and toxicity, alongside cost.

4. Field test demonstration

The current system, the demonstration system of the MERITS project containing various subsystems such as solar collectors, short term storage vessel, long term thermochemical storage modules, underfloor heating, ceiling cooling, and a DHW system, was designed in July 2014. All compartments, i.e. the heating & cooling systems, the technical space and the single family dwelling compartment complete with windows, ventilation and door, are integrated in a 45 ft. sea container and fully equipped with measuring and control equipment (Fig. 1).

The performance of the MERITS Field Test Demonstrator (FTD) (Fig. 3) has been tested successfully at different levels: subsystem testing, where each component (i.e. Short Term Storage Vessel (STSV), High Temperature Solar Collectors (HCS), Space Heating Distribution System (HDS), Adsorption Cooling Distribution System (CDS), Domestic Hot Water Distribution System (WDS), Long Term Storage System with Thermochemical Storage Modules (LTS), Power supply, and data acquisition and control system) is tested under specific initial and boundary conditions; scenario testing, where each component is tested according to its standard operation; and ‘MERITS mode’ testing, where all subsystems are tested altogether according to the standard operation of the whole field test demonstrator.

The long term storage system, the main innovation in the FTD, is connected to the short term storage vessel and in periods with surplus of solar heat, used to sequentially charge the long term storage modules. During periods wherein the solar collectors do not provide sufficient heat, the modules are discharged into the short term storage vessel to provide sufficient temperature in the storage vessel, to provide DHW and heating of the dwelling at all times. All relevant volume flows and temperatures and additionally also the pressures inside the TCM modules are measured and recorded using the data acquisition and control software.

Until now, the actual application of thermochemical storage in the built environment has not been demonstrated. The main reason for this is that the thermochemical storage system is currently still complex, and as yet still too large and costly. Laboratory tests have been performed with thermochemical storage modules in an emulated environment, using the parameters below for loading and unloading the thermochemical material.

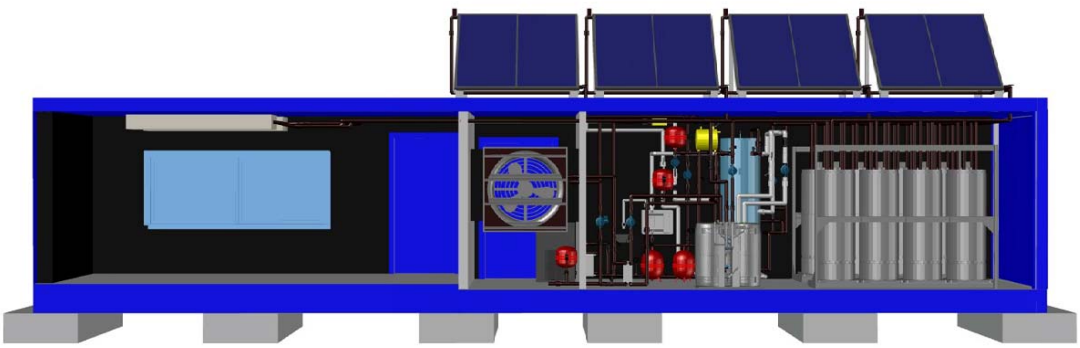

Fig. 3: 3D Visualization of the FTD

The goal of field test demonstration of a heating system with thermochemical storage modules is to enable scientists and application engineers to assess characteristics of the full system including all interactions outside of laboratory circumstances. Not only is the tested system more complex and more voluminous than any tested laboratory setup, variations in conditions deliver 'real' and ever changing use-case conditions. Whereas in the laboratory the external conditions can be fully specified and controlled, in a real environment these conditions vary widely with time (day/night, seasons) and this will have a great impact on the system performance; especially the influence of condenser heat sink and evaporator heat source temperature fluctuations on system performance should be properly assessed. The system behavior with these varying circumstances offers a wealth of data for analysis and improvement. Moreover, the field test container is mobile, and therefore enables testing in different climate zones.

The long term thermochemical storage system (heat battery) in the MERITS project consists of 8 modules providing a low-loss design thermal energy storage capacity of 482MJ delivered from the water and salt working-pair. The 8 modules are placed into two racks (Fig. 4). Each rack is equipped with header piping, actuator valves and electronics to control the water flow through the TCS module and control the internal valve of TCS module. In order to limit the thermal energy losses during the start-up processes before the actual charge or discharge of a module can be executed, the choice has been made to build 4 smaller modules per rack rather than one big one. In addition, modularity helps to tune the system to the local needs without the need to make dedicated designs for every particular case.

Fig. 4: Rack with 4 thermochemical storage modules inside the Field Test Demonstrator

5. Active materials cycling – results

For the FTD's, 7 batches of ~90kg salt hydrate powder have been produced after which the modules were filled. After finishing of the modules, they have been tested in the lab before integration into the FTD container. Constant and well-defined testing conditions have been applied to evaluate both the potential storage density as well as the dynamics of charging and discharging. Additional tests with closed internal valve have been performed to evaluate the thermal losses. In addition, after integration of the modules into the FTD container, more charging and discharging tests have been performed before the system was actually run with the automated system control.

Fig. 5 shows a typical example of the measured powers on evaporator/condenser side and on absorber/desorber side for a discharge/charge/discharge cycle with a desorber inlet temperature of 80°C during charging reaching 52°C during discharge at a constant evaporator/condenser inlet temperature of 10°C both for charge and discharge. During discharge a power >500W with a plateau between 600 and 700W is delivered for about 12h (Fig. 5 red line, first half cycle). In sum, more than 30 MJ of energy is released in this module under these conditions. After recharging for 30 hours (Fig. 5, second half cycle), another discharge took place with similar characteristics (Fig. 5 red line, third half cycle). Taking into account the losses (especially internal losses between reactor and evaporator) and the thermal mass of the reactor (heat exchanger, active material), an amount of about 9 kg of water is cycled under these conditions. This is roughly half of what would theoretically be possible from material equilibrium data.

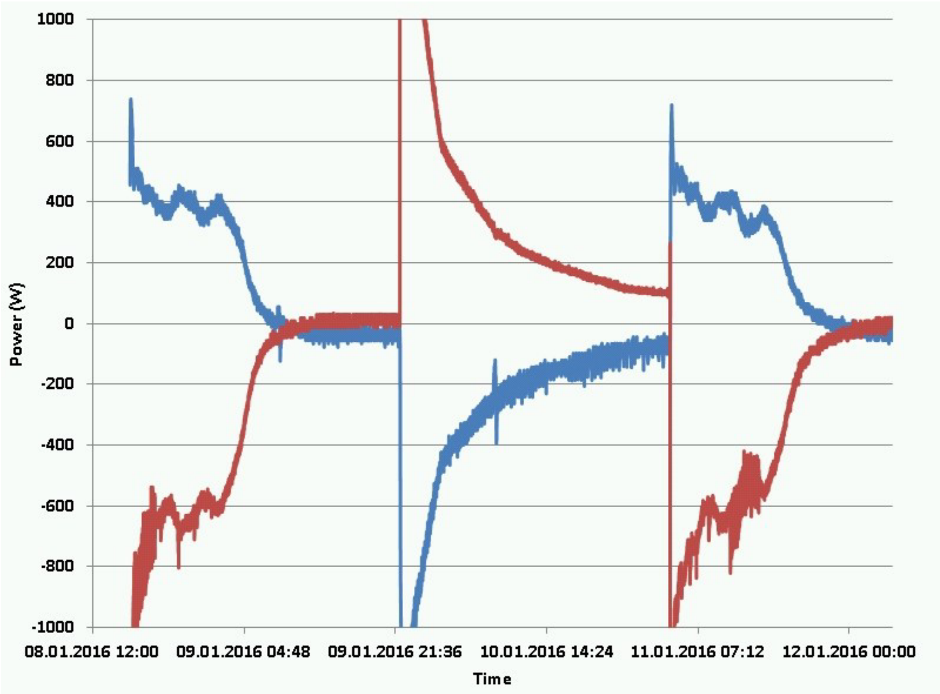

Fig. 5: Power of a typical module during 3 consecutive half-cycles (discharge/charge/discharge) of 30 hours each, showing reversible behavior during loading and unloading of the thermochemical material under relevant operating conditions, with power exerted in the absorber/desorber in red, and power exerted in the evaporator/condenser in blue; + is heat delivered to heat exchanger; - is heat delivered by heat exchanger.

During operation of the FTD, it became clear that several operational issues still have to be resolved. For example, the low amount of water cycling inside the field test demonstrator might be due to the fact that the charging power drops to very low values due to an additionally observed gas pressure in the charging phase that reversibly disappears during discharge. Furthermore, additional losses in the external hydraulic circuit and specific behavior of the discharge control are thought to be to blame for this.

6. Conclusions & outlook

For the first time, a thermochemical storage system has been demonstrated on a relevant scale for domestic application (heating & DHW), with thermochemical energy storage densities in the order of sensible storage density on a module level, but without thermal energy losses during storage periods. Initial results demonstrate the applicability of the compact long-term storage system for seasonal solar energy storage. In the present studies, our initial results show a storage density of around 100 MJ/m^3 (28 kWh/m^3) on a module level, i.e. in the same order of magnitude of some existing sensible thermal storages but with the benefit of unlimited storage times. In the CREATE project, salt selection is still under investigation. In future application in the CREATE project, a theoretical thermal energy storage density of up to 600 MJ/m^3 (168 kWh/m^3) should be achievable on a module level, i.e. well beyond existing thermal storages on the market today.

The system heat storage density depends on much more than just the active material reaction storage density, because additional components such as vapor and heat conducting structures (e.g. tubing, vessel, heat exchangers, etc.) are present. The main challenge of designing the FTD was to dimension all components properly. Another challenge was the scale-up of the material production from lab-scale to full size prototype-scale.

Future research is directed towards further clarifying the cyclic behavior of the thermochemical storage modules, amongst others by clarifying cycling behavior of the active materials alone or as composites. In addition, the major points of attention are to increase thermal storage density in the modules significantly, and to increase the storage capacity on a system level. Also an in-depth life-cycle analysis will be performed after the first major improvements have been made.

In short, during operation of the FTD, it became clear that several operational issues still have to be resolved. Implementation of the CREATE project concept taking into account many of these issues is foreseen in typical European dwellings. To demonstrate applicability of the thermochemical storage solution and its operation in real life conditions and to receive early user feedback, a full scale solar TCS system will be installed in a single-family house in Warsaw, Poland, where a continental climate delivers both cold winters and warm summers. Optimizing the current compact storage technology to its full extent will lead to reduction of CO_2 emission and energy savings due to better use of available renewable energy sources instead of fossil energy.

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