Innovative PCM Storage as Power-to-Heat Unit for Process Heat Applications

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Abstract

An innovative high temperature latent heat storage concept for power-to-heat application is presented. The storage is equipped with electrical heating elements, directly immerged into the phase change material to achieve best conversion efficiency. Discharging takes place by an oil cooled plate heat exchanger. For heat transfer enhancement during discharging, a new concept, using moving blades to scrape off the solidifying material, was developed. With this method, the solidified layer of phase change material on the heat exchanger surface is kept at constant thickness, allowing for constant heat flux during the major period of the discharging process. Feasibility of the concept with moving scrapers was demonstrated, showing advantages over the passive concept. First investigations on the crystal size and hardness of Sodium Nitrate were performed to improve the scraper design. A concept for separation of capacity and heat rate is described.

Keywords: *latent heat storage, PCM, high temperature, power-to-heat, process heat*

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1. Introduction

The German Federal Government has set the goal to reduce greenhouse gas emissions until 2020 by 40 % compared to 1990 levels, and cut primary energy consumption by 20 % over rates for 2008. Renewables are to have a 40-45 % share in electricity production by 2025, and a 55-60 % share by 2035. By 2050, the Federal Government seeks to increase the share of renewables in the electricity mix to at least 80 %. This is a tremendous change for Germany's electricity market. The rate of surplus electricity will rise because the average load factor of renewable technologies like wind power and photovoltaic is significant lower than that of conventional power plants. Therefore the required installed capacity needs to be much higher than for the conventional electricity market. The current German electricity market, with approx. 25% of renewable electricity, has still a residual load of ca. 15 GW. In 2035, with a renewable share of 60%, the minimal residual load is expected to fall to minus 25 GW (Federal Ministry for Economic Affairs and Energy (BMWi) 2014).

The increasing share of renewables in today's generation mix and the accompanying fluctuation in generation requires large scale as well as decentralized storage capacities to secure grid stability. In the proposed power-to-heat concept, electricity, produced from PV-plants or small scale wind farms, will be used to heat up high temperature latent heat storages. The heat can be used in industrial processes, e.g. industrial bakeries.

Thermal energy storages can be differentiated into sensible, latent and thermochemical technics depending on the physical principle. The selection of storage type depends on the demands and boundary conditions of the application (temperature range, heat transfer fluid, storage duration, storage capacity, heating rates) (Laing et al. 2012).

Latent heat storage with phase change material (PCM) is using the heat of fusion and offers the possibility of efficient storage of heat with high energy density in a small temperature range. One of the main challenge of PCM storages lies in the low thermal conductivity of the phase change materials. This leads to insufficient heat transfer between the storage medium and the heat transfer fluid, resulting in an unfavorable characteristic within the discharging process. When the discharging process starts, the PCM begins to solidify first at the heat exchanger plates and forms a steadily growing insulating layer. Because of that, the heat transfer from the liquid PCM to the heat exchanger plates drops dramatically. The current state of the art is to build some kind of heat transfer structures into the storage. This can be done by using finned tubes or specially formed structures, preferably made of aluminum (Laing et al. 2013). These build in structures

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improve the heat transfer but cannot solve the problem satisfactorily and they reduce the amount of PCM inside the storage and for this the thermal capacity of the storage.

The newly developed active latent heat storage concept combines three innovative aspects:

1. Electrical heating elements (“power-to-heat”), directly immerged into the phase change material to achieve best conversion efficiency.
2. Moving scrapers to improve discharge and to achieve high and near constant heat rates during discharging. The moving scrapers control the freezing front inside the latent heat storage by keeping the solidified layer of phase change material on the heat exchanger surface at constant thickness.
3. Separation of capacity and heat rate: The concept with moving scrapers requires operation in a mixture of liquid PCM with solidified PCM-particles. Therefore, in the active stage the storage cannot be discharged completely (fully discharge means total amount of PCM is solidified, thus no more movement possible). However, this concept allows for active pumping and moving of salt. During discharging the solidified PCM grains can be removed from the liquid pool and stored in an insulated “cold” tank, while liquid PCM is refilled into the heat exchanger unit from an insulated “hot” tank. During charging, the solid particles will be poured into the heat exchanger unit from the “cold” tank, while liquefied PCM is pumped into the “hot” storage tank.

The current focus lies on the first two points, to proof feasibility of the active concept.

2. Description of concept

Fig. 1 shows a scheme of the newly developed active latent heat storage concept with moving scrapers (Laing et al. 2015). For electrical heating, heating elements are used that are integrated in aluminum plates to have very good heat conduction and therefore near constant temperature over a large heat exchange surface. Discharging will take place by oil cooled flat plate heat exchangers. Here the so called “pillow plate” method was applied as a cheap design applicable to higher pressures. For heat transfer enhancement during discharging, a new concept, using moving scrapers to scrape off the solidifying material, was developed. With this method it is intended to keep the solidified layer of phase change material on the heat exchanger surface at a thin and constant thickness, allowing for constant heat flux during the major period of the discharging process.

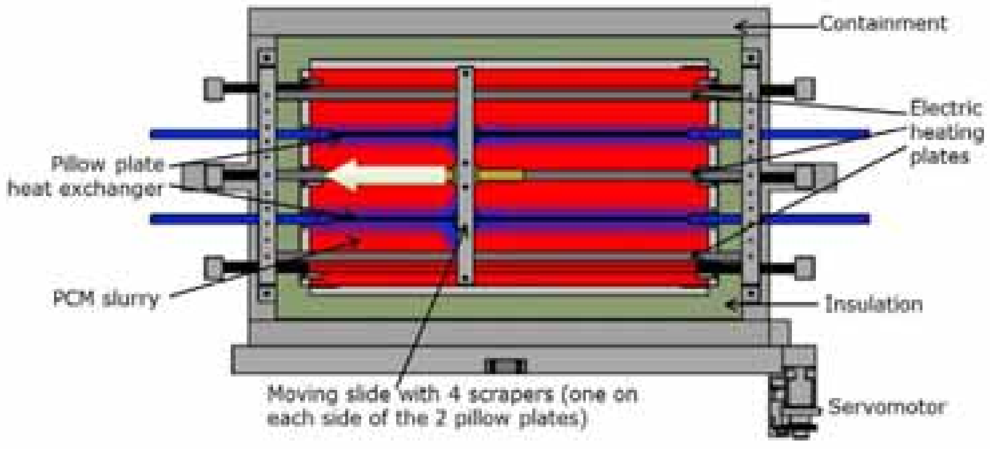

Fig. 1: Principle of the new storage concept with three heating plates, two pillow plates as heat exchanger plates and the scraper mechanic at the beginning of the discharging phase.

A first test storage unit was built and integrated in the test loop (Fig. 2). It has a total volume of 0.36 m³ and is currently filled up with ca. 375 kg of Sodium Nitrate (approx. 65% of complete filling). The storage is equipped with three specially designed electrically heated aluminum plates with an electrical heating power of 4 kW, each. For discharging, two oil cooled pillow plates are emerged into the salt. The moving scrapers are located on each side of both pillow plates, with a gap of approximately 8 mm between scraping surface and pillow plate surface. They are mounted with a metal slide on a rod, supported on the top of the storage tank, and are moved linearly back and forth from one end to the other by a servomotor. With the current setting, the scraper takes about 14 seconds for one direction. The velocity is continuously adjustable. When the discharging process starts, the scrapers begin to move. By stirring the liquid PCM, the heat transfer on the freezing front is improved. Once the solid PCM has filled up the gap between heat exchanger surface and scraper, the thickness of the solid layer of the PCM on the pillow plates is limited to this size by the scrapers. This is the point, from which the heat rate stays almost constant, as the temperature in the liquid PCM-volume is at phase change temperature and the heat resistance is constant due to the constant thickness of the solid layer.

The storage unit is connected to a temperature control unit for heating and cooling, using synthetic thermal oil, stable up to 350°C. It has a heating rate of 20 kW and a cooling rate of 80 kW. For cycling tests, the storage unit will be heated directly through the electric heating plates immersed into the PCM. However, for preheating of the PCM close to the melting temperature, heating can be supported by the thermal oil loop to accelerate testing.

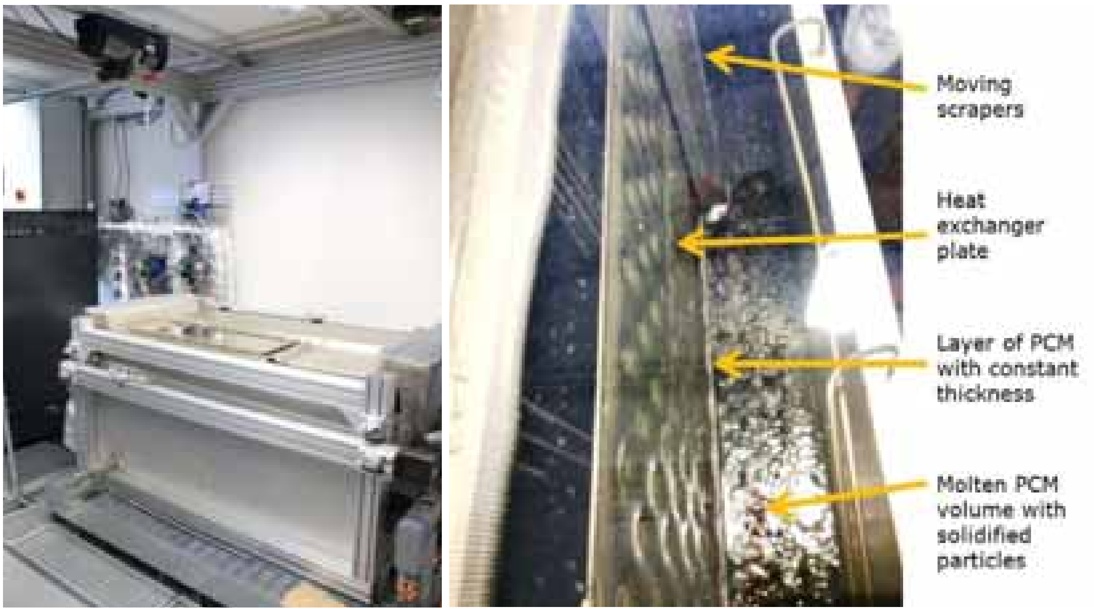

Fig. 2: Test facility with storage unit (left). Storage during commissioning, showing moving scraper that keeps frozen PCM layer at constant thickness (right).

3. Results and Discussion

3.1 Test results of storage operation

Figure 3 shows a comparison of storage discharge with and without movement of the linear scrapers. In both cases the complete storage mass was at 330 °C before discharge was started with a set temperature of 295 °C for the heat transfer fluid (HTF) at storage inlet. The dashed lines represent behavior without and full lines with scraper movement. Volume flow for the thermal oil is 20 l/min for all cases. Heat flow is calculated with the measured values and the temperature dependent density and specific heat capacity of the HTF. Apart from HTF inlet and outlet temperatures (Temp-HTF-inlet, Temp-HTF-outlet), the average temperatures of the PCM next to the cooling plates (Temp-PCM-HX) and in the middle between heating and cooling plates (Temp-PCM-liquid) are shown. To indicate the load on the scraper, the current for the scraper engine is measured (Current for scraper movement). The distance between scrapers and heat exchanger plates of the four different scrapers is not the same, due to thermal distortions of the plates and the containment. Therefore, the value of the current, shown here, is just a rough indication of the contact between scraper and solid PCM. The oscillation of the HTF temperatures and therefore the heat flow at the beginning of the discharge process is caused by the temperature control process of the cooling system.

The following advantages can be observed from the test with scraper movement (Fig. 3).

1. By stirring the hot salt, the heat transfer rate is higher than without, as long as the salt temperature is above the phase change temperature because of convection and delayed beginning of solidification. The higher heat flow in the first 45 minutes clearly proofs this statement.
2. With scraper movement, the temperature in the liquid PCM-volume reaches the phase change temperature of 306 °C after 56 minutes. Without scraper this temperature is reached only 17 minutes later.
3. Once the whole storage is at phase change temperature, the scraper movement is controlling the thickness of the solidified layer on the heat exchanger surface at constant level, resulting in a constant heat flow. This can be well observed in the last one hour of the scraper movement (scraper stopped after approx. 2 h of operation).

It can be observed that the current for scraper movement is still rising, even when there is a constant thickness of the solidified layer on all four heat exchanger surfaces and after approx. 2 hours of discharge operation the scraper movement stops. Due to the heat losses of the storage, PCM also solidifies on the containment walls. Once this layer of solidified PCM at the bottom of the storage unit reaches the front end of the scraper, there is a significant additional load on the scraper. It is assumed, that this load is the reason for the further rising current of the servomotor and that it finally causes the scrapers to stop due to overload.

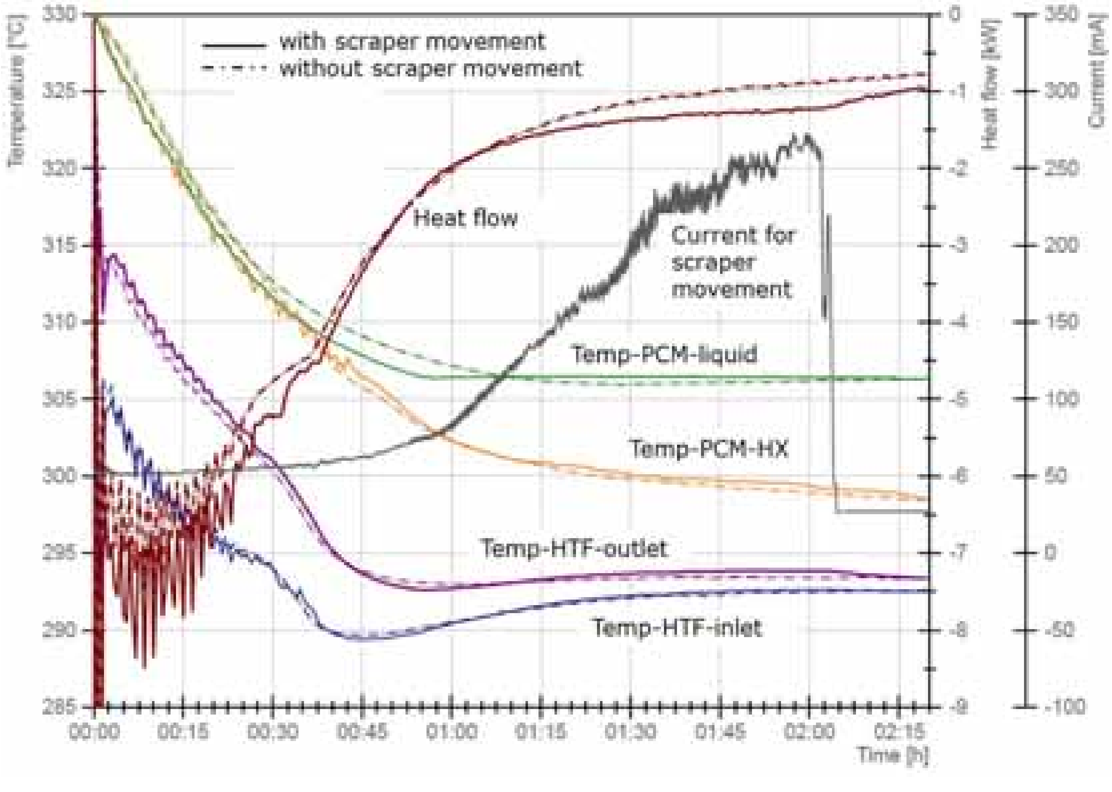

Fig. 3: Comparison of temperatures and heat flow for storage operation with and without scraper movement; current of servomotor for scraper movement.

3.2 *Material aspects*

In order to minimize the own power consumption of the scraper unit a more detailed knowledge of the properties of the salt is required. For this purpose, various investigations on separate samples and on samples from the storage were conducted.

The force needed to scrape off a layer of salt has been measured at ambient temperature on a sample shown in Figure 4. The sample was molten in the oven in a ceramic crucible and was left in the oven to solidify. The crystal size of the sodium nitrate changes from the surface to the inner part of the sample. On the surface, the first 3 mm have very small crystal size, followed by larger crystals. Inside the sample is a large void and the salt can be damaged manually. Cooling on the surface occurred faster than inside the probe, therefore the crystals on the outer layer are smaller and less homogenous than inside. Fig. 4 (left) shows a cross section of the sample with the outer layer on top.

For the force measurement, the sample has been prepared with a defined edge (Fig. 4, right). Then a chisel with 6 mm width has been moved along the surface with different depths. Measurements with 0.1 mm and 0.2 mm depth are shown in Fig. 5. Two aspects can be observed. First, the force needed for the first 12 mm is higher than that needed for the second 12 mm section. Secondly, the force doubles, when the thickness of the layer is doubled. The oscillation of the signal is probably due to the inhomogeneous crystal structure.

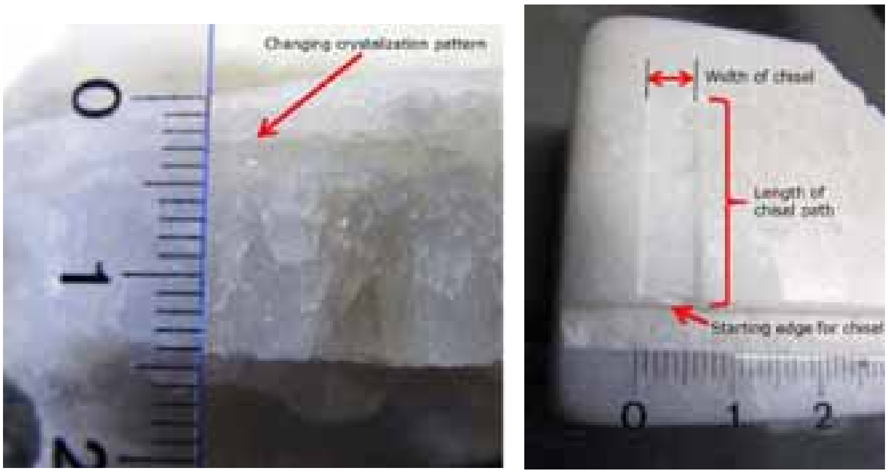

Fig. 4: Sodium Nitrate sample; left: cross section, right: chisel path.

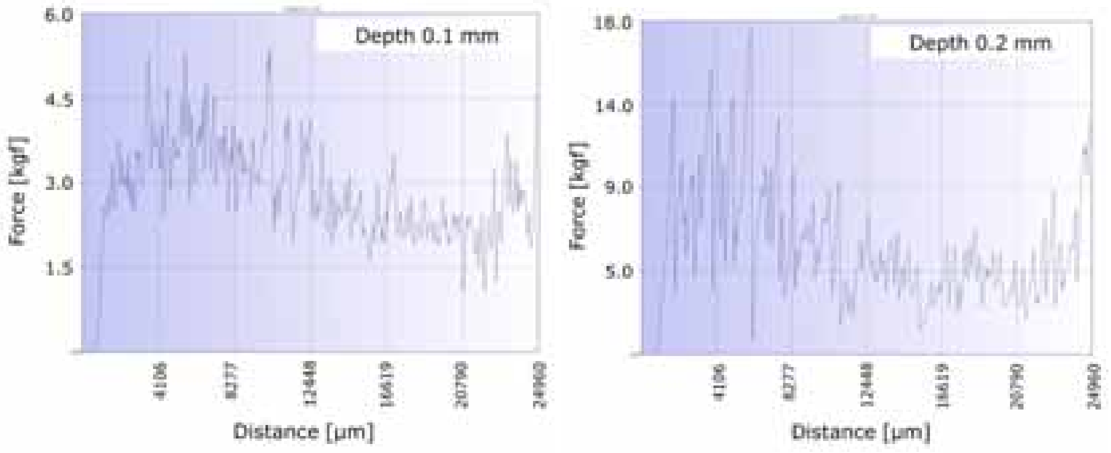

Fig. 5: Load-displacement diagram of Sodium Nitrate sample; left with 0.1 mm depth, right with 0.2 mm depth of the chisel

The examination of the sample as well as samples of the salt from inside the storage unit showed that the cooling rate affects the crystal size (see Fig. 6). As long as the scraper moves, not only a removal of the solidifying salt takes place but also a higher temperature is at the boundary layer between the solid and liquid PCM. As a result of this, the growing of the crystals is slower and it looks more homogeneous. This further improves the heat conduction in the already solidified PCM.

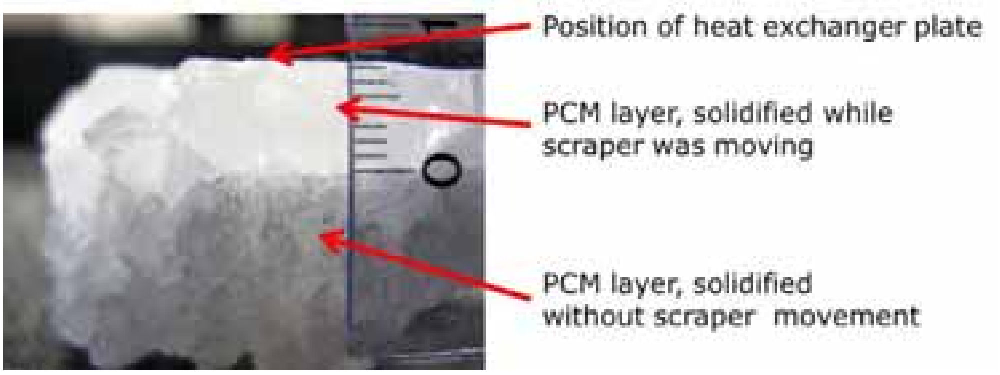

Fig. 6: Sodium Nitrate sample from inside the storage, showing the layer between heat exchanger plate and scraper on the top.

4. Conclusions and Outlook

Feasibility of the concept with moving scrapers was demonstrated, showing advantages of the active over the passive concept. With this first prototype, scraper movement stopped after approx. 2 hours of discharge operation. Due to the heat losses of the storage, PCM also solidifies on the containment walls. Once this layer of solidified PCM at the bottom of the storage unit reaches the front end of the scraper, there is a significant additional load on the scraper, which finally causes the scraper to stop. In the next generation design, the scrapers will be redesigned, to also scratch off the salt freezing at the bottom. The early limitation of the scraper movement did not allow the investigation of the maximum discharge capacity.

The cooling rate has a significant influence on the crystal size. For further design of the scrapers, a better understanding of the required forces is needed. Especially the hardness of the solid Sodium Nitrate close to melting temperature needs to be investigated.

In the second generation design it is intended to combine the electrical heating with the cooling plate to minimize the amount of components and material inside the storage and to maximize the available heat exchanger surface. With this solution, the same heat exchanger surface can be used for charging or discharging. For low temperature applications, using paraffin as phase change materials, first prototypes have been built, using resistance heating foils glued onto the heat exchanger surface. If possible, a smooth surface will be chosen, to allow a very narrow gap between scraper and heat exchanger plate. In addition investigation will be done, if the adhesion between PCM and heat exchanger surface can be reduced by nanotechnology or any other means.

The proposed concept with moving scrapers has the one disadvantage that the storage unit can never be discharged completely when using the scraper. However, it allows for a major advantage, to be able to remove solidified particles during discharge from the heat exchanger unit, while at the same time filling up the unit with liquid salt. During charging, solid particles can be refilled into the unit and liquid salt pumped back into an external storage tank. This concept (see Fig. 7) will allow for separate dimensioning of the heat exchanger unit and the storage capacity. Additional electrical charging can be easily done by immersion heaters in the “hot” tank. This would even allow for a certain power-to-heat buffer when the heat exchange unit is only charged through the heat transfer medium.

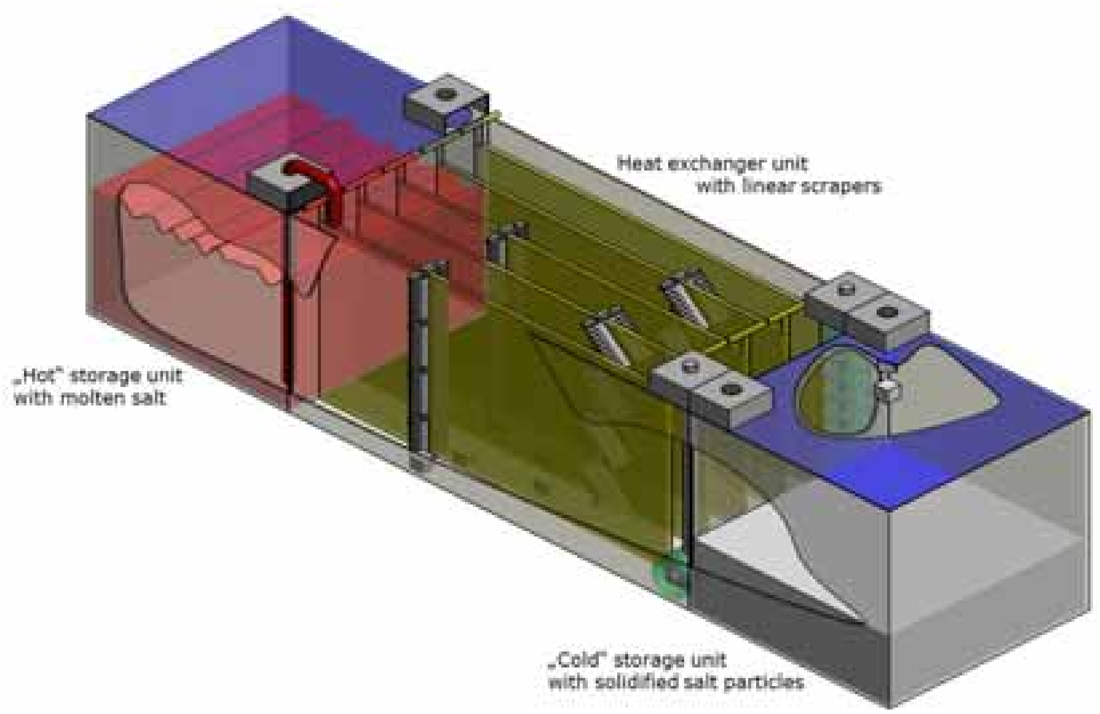

Fig. 7: Principal scheme of the storage concept with separation of capacity and heat rate

The solidified salt that is scraped off by the scraper accumulates on the bottom of the storage tank in fine granular form, due to the higher density of the solid phase. First tests with a manual slider plate showed that the grains can be easily moved to the edge of the storage. A device to remove the solidified PCM grains from the liquid volume, e.g. a conveyor screw, needs to be integrated on one side of the heat exchanger unit.

5. References

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