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# DEVELOPMENT OF A SEGMENTED SORPTION STORE WITHIN THE PROJECT "SolSpaces"

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**Abstract**

An advanced segmented sorption heat store with improved efficiency of the adsorption and desorption processes is presented in this paper. The basic concept of the solar thermal space heating system with high solar fraction using an effective long-term sorption store integrated in a conventional mechanical ventilation system has been developed in previous research projects. Many improvements concerning the system design and storage material have been achieved in the recent years. A modular storage design with segmented adsorption units is developed in the current work. A prototype store has been build and experimentally investigated. The results of the numerical simulations are in good agreement with the experiments.

Key words: thermo-chemical heat storage, adsorption, solar heating, high solar fraction, segmented sorption store

## 1. Introduction

Solar assisted space heating systems are already 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. Effective long-term heat storage is one of the crucial aspects for achieving this goal. In this context the technology of thermo-chemical heat storage offers the advantage of high energy storage densities and minor heat losses. Hence, adsorption heat storage, a sub category of thermo-chemical heat storage, is being under intensive research in recent years. This contribution will present the development of a new segmented adsorption storage design with a significantly improved operating behavior as well as its integration in the so-called "SolSpaces" building.

## 2. Solar thermal heating system

Thermo-chemical energy storage represents a very promising storage technology for solar energy, due to high energy storage densities and significant reduced heat losses. In fact, if a complete air tightness of the storage unit can be assured, energy losses appear only while charging and discharging the store.

Very good experiences in laboratory scale and with prototype stores have already been achieved with the adsorption of water on zeolite. Storage densities up to 180 kWh/m³ have been measured, which is a factor of three compared to water for a temperature difference of $\Delta T = 50$ K. However, to reach solar fractions higher than 70 % under Central European climate conditions storage volumes of several cubic meters are necessary even for single family houses. In a previous research project the concept of a solar thermal space heating system using a sorption store integrated in a conventional mechanical ventilation system with heat recovery


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has been developed /Kerskes et al., 2006/. In the current follow-up project this concept will be implemented for the first time in a real building. The building of the type "Flying Spaces" from the company SchwörerHaus KG in Oberstetten, Germany is a prefabricated building. It was selected for testing and demonstrating the newly developed solar only space heating concept because of its dimensions this building sets highest requirements on the compactness and integration of the heating system. In figure 1 the "SolSpaces" building located on the campus of the University of Stuttgart near to the premises of ITW, is shown. The building consists of a living room, a bathroom and a utility room in which the sorption store will be installed in the autumn of 2014.


**Fig. 1: SolSpaces building at ITW, University of Stuttgart, Germany**

The newly developed solar heating concept is based on a solar thermal system in combination with a sorption heat store and is designed for very high solar fraction (up to 100 %).
In figure 2 the operating modes of the solar heating system during winter and summer are schematically shown. The sorption store is integrated between the mechanical ventilation system of the building and the indoor exhaust air leaving the space heating zone. In the winter mode the required moisture to drive the adsorption process to release heat from the sorption heat store for space heating is supplied by the wet indoor exhaust air. The indoor exhaust air at room temperature (~ 20°C) is allowed to pass through the sorption storage. The storage material adsorbs the moisture from the air and hence heats up significantly above 20°C by gaining heat of adsorption. This warm air is then allowed to pass through the heat exchanger, where it heats the incoming fresh ambient air which is transferred into living space for room heating. Thus, the space heating continues until the sorption store gets saturated with water vapor by the end of the winter season.

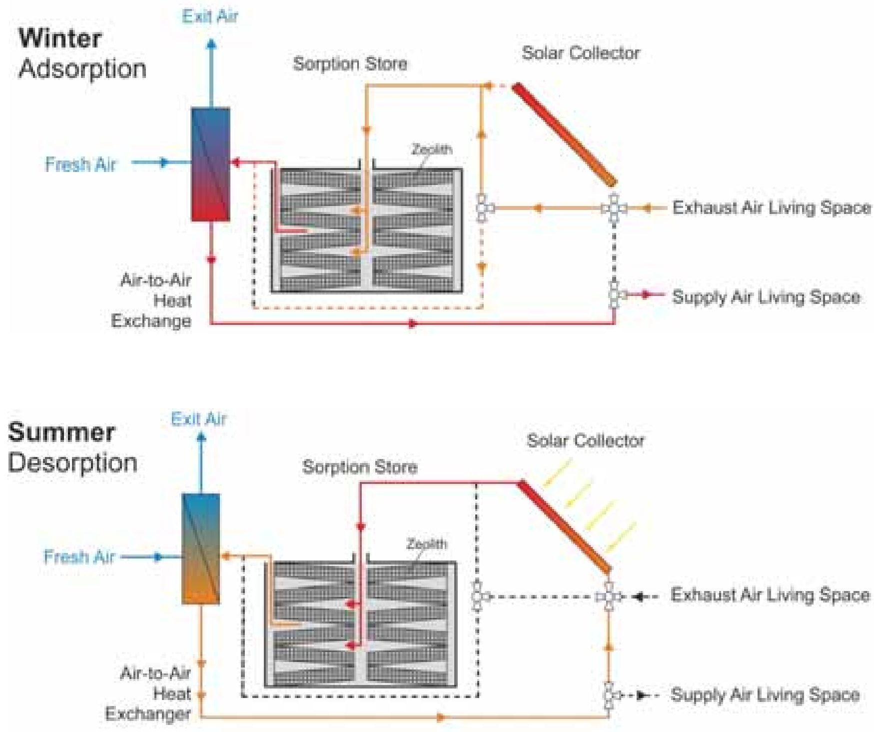


**Fig. 2: Winter and summer operation mode of the solar thermal space heating system with sorption store**

In the summer months, when solar radiation is present in excess, the storage material is regenerated (desorption); this means charging of the sorption store. Vacuum tube solar air collectors are used to heat the ambient air. The hot air is then allowed to flow through the sorption store system, in order to activate the regeneration process of the storage material. The warm and humid air leaving the sorption system is then passed through the air to air heat exchanger to preheat the incoming ambient fresh air, before it enters the solar collectors.

## 3. Development of the new segmented storage design

From the points of flow resistance and heat and mass transfer it is not favorable to pass the airflow, used for charging and discharging, through the store as a whole. The main disadvantages are a very high pressure drop when blowing an air stream through the entire store, a very large thermal capacity which makes the thermal behavior of the store very inertial and high heat losses during the adsorption because the entire amount of storage material has to be heated at once. Especially under transient operation conditions like solar thermal applications these aspects cause some drawbacks.

A segmented store subdivided into individual sorption units has therefore been developed in the current research project “SolSpaces”. The sorption store with a cubic shape is planned with a volume of 4 $m^3$. For efficient operation, it is necessary to subdivide the sorption store into individual segments. For each segment the adsorption/desorption process can be performed individually. Due to segmentation a significant reduction of pressure drop is achieved and also a reduction of the mass and thermal capacity of storage material involved in the adsorption/desorption processes at once. This leads to reduced heat losses due to a smaller thermal capacity. On the other hand a regular and homogeneous flow distribution within each segment is an important requirement for the efficiency of the store.

These considerations result in the storage concept, which is schematically depicted in Figure 3. Four areas arise by two vertical separators on the diagonals and each of them is subdivided by 6 horizontal planes. In this way, in each storage quarter three pairs of super-imposed segments exist which can be passed through independently of each other. The air stream exiting the segment is collected in a horizontal air duct. At the exit of each air duct a flap mechanism is installed to led the air flow to the active pair of segments.

When hot air is required for space heating, the cold and humid air is supplied through a central, vertical inlet pipe. The segment pair in operation is passed through. Due to the occurring adsorption process the air is heated up and leaves the segment pair through the air channel that is opened by the flap (see Fig 3, a - c).

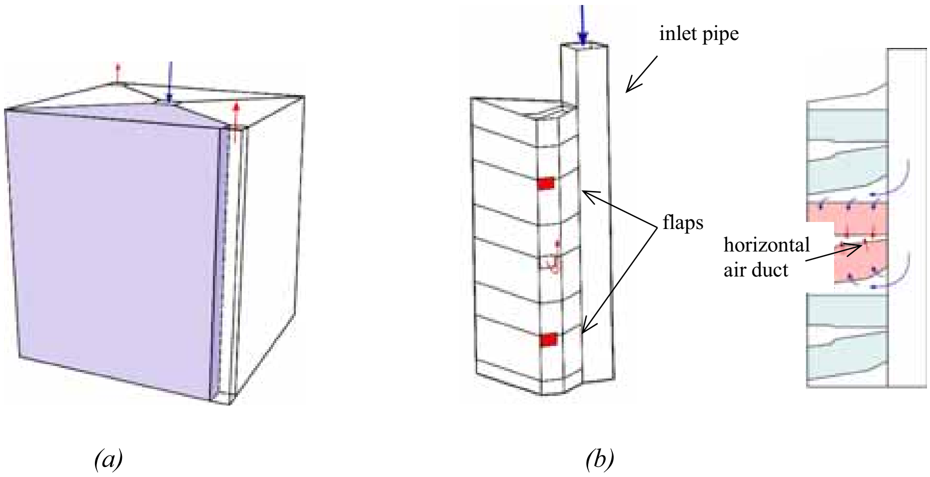


**Fig. 3: Concept of the sorption store: complete store (a), quarter of the store (b) and vertical section through the center plane of the store (c)**

A prototype of the segmented sorption store has been designed using CFD methods (CFD: Computational Fluid Dynamics). The main aim was the development of a first segment geometry. By a large flow cross-section and the flat design of the segments, which leads to a short pass length through the fixed bed of zeolite, a low pressure drop should be achieved. The finally chosen geometry is shown as cross sectional area in Fig. 3 (c). Figure 4 shows the 3D CAD model of a segment pair as well as an example of the results of the CFD analyses performed. The fixed bed of zeolite has been modeled as a porous media. The velocity profile inside the fixed bed is calculated with the extended Brinkman equation. For this analyses no adsorption or desorption processes have been taken into account.
The results of the CFD simulations show an almost homogeneous flow distribution on the inlet and outlet surface of the segments. Only in the edge region higher velocities occur. This is depicted in fig 4 (left picture). In the right picture the flow velocity on the center plain is shown. This also shows a uniform distribution expect the edge region. Slightly higher velocities occur in the region of the air duct where the flow length is smaller.

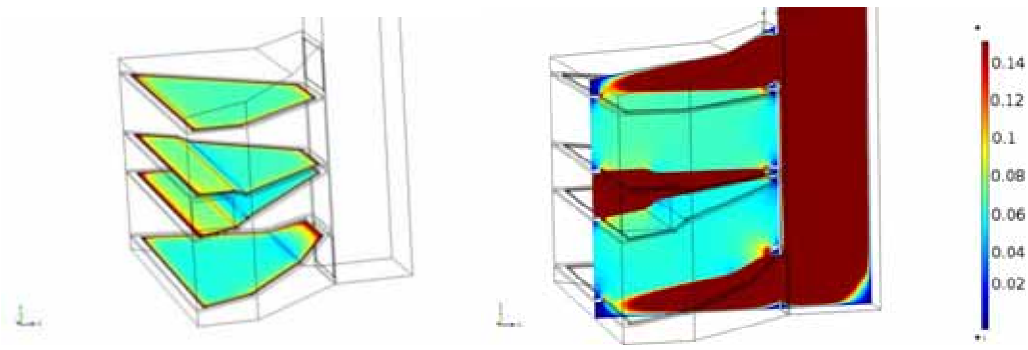


**Fig. 4: Results of CFD simulation study: flow velocity (m/s) on the inlet and outlet surface of a segment pair (left) and in the center plain (right)**

The elaborated design of the store with its individual sorption units (segment pairs) fulfills the requirements concerning low pressure drop and homogeneous flow distribution quite well.

## 4. Experimental investigation of the lab scale segmented storage design

A laboratory store with the geometry described in the previous chapter was first constructed in scale 1:4 and investigated using experimental and numerical methods.. Taking advantage of the symmetry design of the store only a quarter of the store was build. The aim of the preliminary tests on the lab scale store was to analyze the adsorption and desorption process and the flow behavior in a pair of segments to gain experience for the development and construction of the prototype store in real size with a volume of 4 $m^3$. In Fig. 5 the experimental set up used is depicted schematically. Photos of the set up are shown in Fig.6.

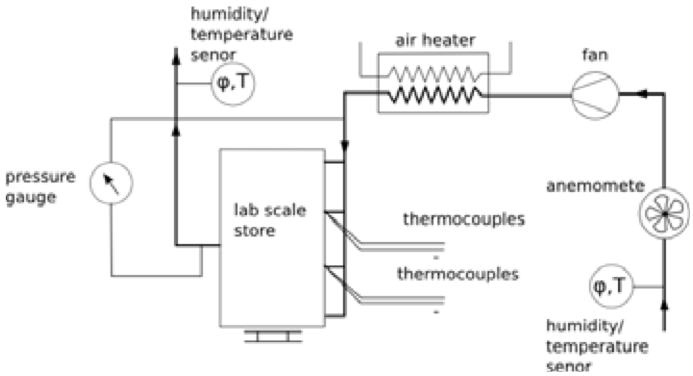


**Fig. 5: Sketch of the experimental setup**

Since the flow inside the store is hard to measure a number of thermocouples are used to detect the temperature distribution inside the zeolite bed. The movement of the temperature front inside the bed is a direct indicator for the flow distribution. In total 40 thermocouples are distributed over the volume of the segments on significant positions. In Fig. 7 the position of the thermocouples are depicted.

A uniform flow through the fixed bed in each segment and an equally long discharge time of both segments of a segment pair are important to achieve a uniform energy discharge of the segments. In this case the outlet temperature of the heated air remains at a constant level for a relative long time and thus a maximum use of the stored energy can be achieved.

**Fig. 6: Photos of experimental setup with laboratory sorption store (right)**

In order to illustrate the operation during the adsorption processes, the temperature profiles in the fixed bed of segment 4 in level 3 (near the outlet surface) are depicted during an adsorption experiment in Fig. 8 as an example. The schematic flow of the segments 3 and 4 is shown in Figure 3 c). The air enters the segment with a flow rate of 25 $m^3/h$ and an inlet temperature of 20 °C. The inlet moisture corresponds to the humidity of the air in the laboratory and is in the range of 3.4 g/kg to 4.5 g/kg. The goal is to achieve a homogeneous flow distribution at the inlet surface of the segment. Thereby a homogeneous flow distribution will also occur in the bed. In this case the adsorption front will move with the same speed through the entire bed. The migration rate of the adsorption process can be detected with the help of the temperature measurement. The experiment depicted in Fig. 8 shows a temperature rise of 14 K in the bed due to the heat of adsorption. The outlet temperature is constant over a long period of 8 hours. The subsequent temperature drop at all measured positions is steep. However, the beginning of the temperature drop at the different measuring points occurs in a time window of about 4 hours. This behavior indicates a not quite homogeneous flow. The ideal case would be a simultaneous drop in temperature at all measuring positions. Both the flow and the initial load of the storage material have an impact on the adsorption time. The temperatures at position 3 in rows 1 and 3 fall off at first. The reason may be the fact that the flow length at positions 3 is shorter and hence the flow rate is higher. Further improvements on the geometry have to be done to achieve a even more homogeneous flow distribution. This is discussed in chapter 5 (numerical simulations).

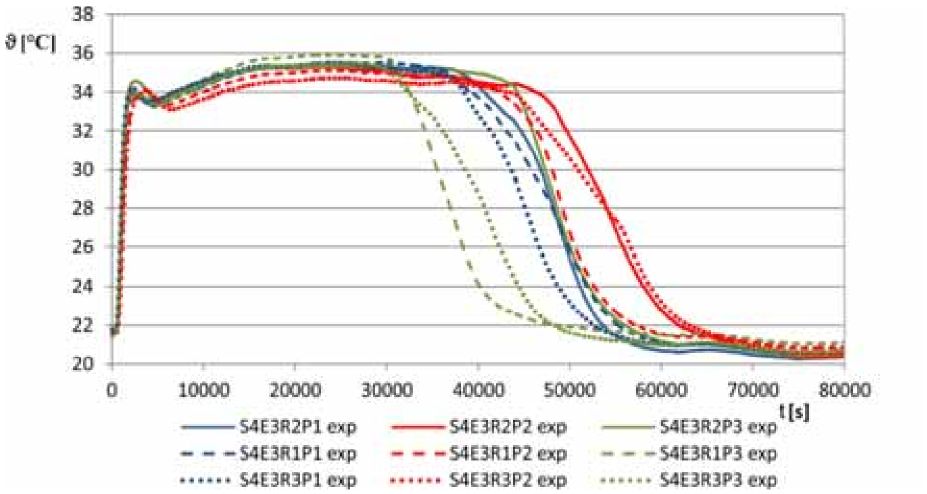


**Fig. 8: Temperature profiles in the fixed bed of segment 4 (level 3) during an adsorption experiment (Key: S segment, E level, R row, P position, numbering see Fig. 7)**

In Fig. 9, the temperature profiles of segment 4 in row 2 are plotted during a desorption experiment. The air inlet temperature was approximately 165 °C. There is a nearly uniform temperature of around 160 °C achieved in the entire bed that regenerates the storage material homogeneous. At some positions in row 1 and 3, a lower temperature is reached compared to the other measuring points at the end of the experiment. The reasons for this may be the heat losses to the environment or a non-uniform flow distribution.

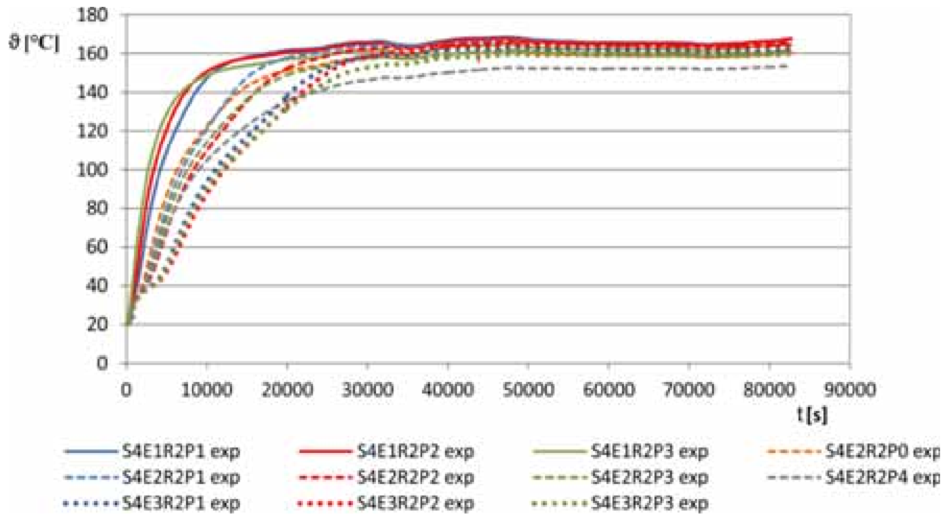


**Fig. 9: Temperature gradients in the fixed bed of segment 4 (row 2) during desorption experiment (Key: S segment, E level, R row, P position, numbering see Fig. 7)**

It should be noted that the relative heat losses to the ambient of the prototype store installed in the SolSpaces building will be less than for the laboratory store, because the side panels of the laboratory store (only a quarter has been constructed) are then interior walls inside the store.

Furthermore the investigations carried out have shown that the water vapor diffusion between loaded and unloaded segments during a standstill period of 24 days between desorption and subsequent adsorption is negligible.

## 5. Numerical investigation to optimize the segmented design

In addition to the experiments on the laboratory store the segmented sorption store concept was further investigated using detailed CFD simulations. At this stage a numerical model of the adsorption and desorption behavior has been implemented into the software COMSOL Multiphysics

The heat and mass transport inside the reactor is described with a quasi-homogenous model, which means that no difference is made between the solid and fluid phase temperature. The effective transport parameters for the radial and axial heat conduction and diffusion are calculated with the so-called $\Lambda_r$-model. The adsorption equilibrium of the used binderless zeolite 13X in a temperature range from 25 °C up to 200 °C was determined by gravimetric measurements of the water vapor adsorption isotherms. The measurements were performed in a sorption analyzer IGA-002 (Hiden Isochema). The adsorption equilibrium is approximated using the Dubinin-Astakhov equation. The adsorption enthalpy $\Delta H_{ads}$ as a function of the water loading of the zeolite is calculated from the adsorption isotherms by applying the van't Hoff equation. The adsorption rate is modeled by a linear driving force (LDF) approach. In the LDF-approach, the mass transport resistant from the fluid phase into the micro pores of the zeolite pellet is reduced to an overall mass transport resistant. Details of the numerical model applied can be found in /Mette et al., 2013/.
The simulation model has been validated with the measured data of the experiments on the laboratory sorption store. Overall, a satisfactory agreement with the measured data and the simulation results could be found, so that the CFD model can serve as a suitable tool for further investigations.

The result of the experiments discussed above show that there is still some potential for optimization with respect to the uniform and concurrent flow through the segments. In this regard geometry changes of the segments have been studied numerically. In Fig. 10 the calculated temperature distribution of an adsorption process in a segment pair of the laboratory store is shown at different times for the original geometry and an optimized one. After a period of 13000 s (3.6 h), the adsorption front has passed almost completely through the upper segment of the existing store, while the adsorption in the lower segment is not yet complete. The temperature of the air exiting from the sorption store will drop and thus the remaining energy from the lower segment cannot be fully utilized.
The three figures in the lower part of Fig. 10 below show the temperature fields in an optimized geometry. The adsorption front passes through both segments in the same time. With this geometry, an equally long discharge duration is achieved in both segments. This results in a simultaneous drop in temperature in both segments. In addition a better utilization of space is achieved by this measure the effective usable energy and hence also the storage density will improve by approximately 15 % compared to laboratory store geometry.
This geometry shown in the lower part of Fig. 10 is optimized with respect to archive the same charging and discharging time in both segments. However, the influence on the pressure drop by the smaller gap between the segments and the smaller horizontal air duct has to be investigated.

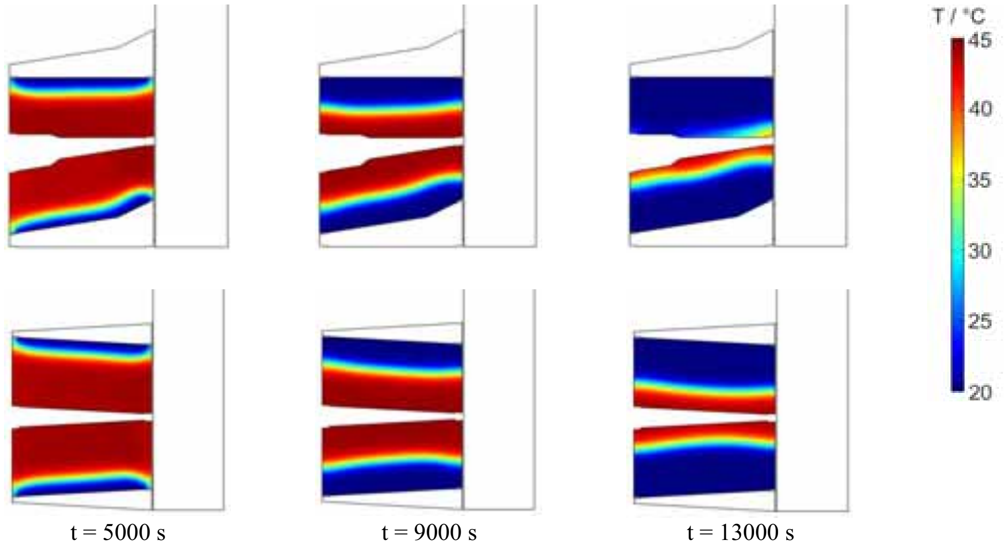


**Fig. 10: Temperature distribution in a segment pair at three different times during adsorption process, geometry of laboratory store (top) andoptimized geometry (bottom)**

## 6. Conclusions

A new sorption storage design to be used in an open sorption process has been developed focusing on two requirements. The thermal mass of the storage material which has to be heated up at the same time should be reduced to an amount that can be heated up with the heat available from the solar collectors in a period of several hours. The second requirement is a reduced pressure drop while passing air through the storage. In open cycle processes low pressure drop is important to minimise the electric power consumption of the fans/blowers.

The elaborated storage design with its individual sorption units, realized as segment pairs, fulfills these requirements. Furthermore a homogeneous flow distribution is import to achieve a high efficient discharging of the store.

The functionality of the newly developed design has been studied by measurement in a laboratory facility using a store with a reduced scale. Important information and findings were derived from these experiments. In addition the experimental data has been used to verify the numerical model, developed to analyze the adsorption and desorption processes inside the store. Due to the fact that the flow distribution was not optimal the numerical tool has also been used to redesign the shape of the segments.

The experimental and numerical investigations have shown that the idea of the segmented sorption store is very suitable. Already in this first development stage all the postulated requirements have been achieved satisfactorily. Progress has been made in the development of a compacted storage containment equipped with individual compartments that can be adsorbed and desorbed independently. Compared to a non-segmented sorption store, where the entire storage volume is heated up at once, the advantage of the new design is characterized by lower heat losses, a lower pressure drop and much higher flexibility in operation.

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