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Energy Procedia 00 (2013) 000–000

Energy Procedia

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SolarPACES 2013

A design study for regenerator-type heat storage in solar tower plants – Results and conclusions of the HOTSPOT project

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Abstract

Regenerator heat storage is a cost-effective solution to provide solar tower power plant with operational flexibility and load-following capability – a key factor for marketability. The recently completed project HOTSPOT addresses open design questions of this storage technology and reduces technical risks with respect to thermal design, fluid-dynamic and thermo-mechanical aspects. For the first time, design solutions based on packed beds have been looked at, and their specific technical risks have been systematically dealt with. The present paper reports on progress made and summarises some design recommendations.

Energy storage; regenerator storage; central receiver solar power plant

1. Introduction

Operational flexibility and load following capability of solar central receiver power plants are crucial to their successful market introduction. To that end, plants based on air-cooled solar receivers can make use of heat storage regenerators, a cost-effective thermal energy storage (TES) technology that is well suited for a deployment in utility-scale. [1-7]

There has been only little research activity in this field. In the early 1990s, a first conceptual investigation and a system test on such a plant was the subject of the work of the PHOEBUS Technology Program Solar Air Receiver

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.

(TSA) consortium, albeit with systems aspects rather than TES design in the focus of interest. A packed bed storage based on ceramic spheres was part of the system, offering a thermal storage capacity of 1 MWh. The tests could demonstrate the proper functionality of the system. However, due to the high costs of its high grade alumina inventory, an up-scaling of this TES concept to commercial scale is not regarded a promising option.

Fricker presents a design study for PS10 solar plant project in [5]. Different ceramic inventory options such as bricks and packed beds made of spheres or saddles are compared w.r.t. performance and costs. Based on the calculations, Fricker concludes that a storage based on packed bed of ceramic saddle elements is the best solution in this applications. Singh et al. [8] give a review on research towards packed bed solar energy storage systems.

The solar thermal power plant in Jülich, put into operation in 2009 [9], uses a tower-integrated regenerator heat storage based on honeycombs [10]. An experimental test campaign conducted in 2010 [11] determined its thermal performance and verified its functionality. Nevertheless, the scalability of this storage type was still open. Also, some of its design aspects still include technical risks or allow cost reduction, such as the arrangement of inventory and insulation, a proper flow distribution and the selection of durable materials.

The joint project HOTSPOT addresses all these open questions. The project partners were the German Aerospace Center (DLR), Institute of Technical Thermodynamics in Stuttgart and KBA-MetalPrint GmbH in Stuttgart.

2. Project scope and major development aspects

The overall objective of the project was to improve efficiency, reliability and investment costs of this storage type for the pressure-less operation and thus provide the basis for subsequent implementation in demonstration scale. Specific technical objectives were the development and testing of design concepts and to reduce technical uncertainties with respect to thermal, thermo-mechanical and fluid-dynamic design aspects. Where missing, methods and calculation tools have been developed, the qualification of materials has been taken forward. To experimentally substantiate novel ideas, a pilot-scale test-bed has been developed, erected and operated at DLR Stuttgart.

2.1. TES concept development and thermal design aspects

Regenerator storage offers a vast freedom of design that can be used for application-specific optimisation. This includes the type and geometry of materials, the inventory arrangement, the outer dimensions and aspect ratio of the containment, the modularity of the storage configuration and many other design aspects. In particular has the way of inventory arrangement a far-reaching impact on the design features: an inventory setup from e.g. stacked bricks or a packed bed eventually results in two designs with clearly different opportunities and risks. Also, the commercial availability of applicable storage materials, together with the restrictions of their manufacturing processes has been checked in a market analysis. This was to ensure the viability of the single near-term and mid-term design options. From a broad range of possible setups and materials classes a number of TES concepts were generated for further investigation.

As a second step, applications scenarios have been compiled and, based on system level simulations and with support from KAM GmbH München, a set of TES design specifications has been derived. An unpressurized air receiver system driving a steam cycle with a thermal capacity of 150 MWth was used as a reference application. Additionally, a pressurized air receiver system operated at 5 bars with a thermal output of 11 MW has been considered, see Table 1 below.

Table 1. Operating conditions and boundary conditions of investigated solar systems

	System 1 „demonstration unpressurized“	**System 2 „pilot storage pressurized“**
Discharge heat rate [MW_{th}]	150	11
Mass flow, discharging[kg/s]	260	24
Discharging capacity [h_{fl}]	7,5	2
Pressure [bar]	~1	5
Inlet temperature, charging [°C]	700	800

Inlet temperature, discharging [°C]	120	180
Temperature decrease during discharge [°C]	<60	<80
Thermal heat loss [%/day]	<3	<3
Site, design day	Huelva (Spain), March 21st	

Now, to narrow the number of considered design options and to finally down-select the concepts to a short-list, a ranking has been established in two steps: extensive design studies have been performed with an increasing level of modelling detail, and selection criteria have been applied to the design results to sort out unfavourable solutions. Starting with simplified models that focussed on the thermal aspects of the design and used simplifying assumptions elsewhere, a sizing of the major subcomponents was done und used for initial investment cost estimates. Later design studies also considered further details of the design, such as fluid-dynamic and mechanical aspects and their impact on performance and costs.

For each of the storage subcomponents and their setup several choices exist: The containment could be made from welded steel, concrete or could be assembled on-site from prefabricated steel parts. The storage inventory may consist of a stacked arrangement of regularly shaped refractory brickwork or a packed bed. Usable inventory materials include oxide ceramics, such as alumina-silicate ceramics, some metals or natural stone, opening a wide range of thermal and mechanical properties, possible shapes and also costs. Market-size TES designs are still feasible in a single, monolithic arrangement, but a modular approach offers additional freedom of design that can be used to further optimise performance. Table 2 below summarises the final shortlist of preferred TES option, Figure 1 shows a side view of TES concept #3.

Table 2. Short-list of TES concepts

TES concept	#1	#2	#3
Inventory type	packed bed (broken basalt)	packed bed (ceramic spheres)	ceramic honeycomb
Insulation	insulating firebrick	insulating firebrick	ceramic fiber
Containment	cylindrical steel vessel	cylindrical steel vessel	octagonal steel construction, assembled on-site from prefabricated steel parts
# Containments	2	2	5

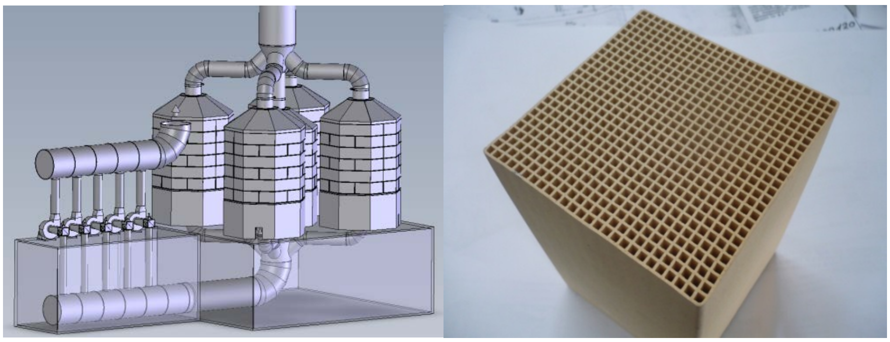

Fig. 1. Left: View of the TES concept #3 (honeycomb ceramics in an orthogonal shaped containment). Right: honeycomb ceramics (length x width x height: 150 mm x 150 mm x 300 mm)

As a result of the design study it turns out that, in principle, each of the considered TES options can meet the above-named design specifications, albeit with different technical effort. Figure 2 (left) depicts the space of some design solutions in terms of storage mass and permissible drop of outlet temperature during discharge cycle. The latter is, besides the materials thermo-physical properties and heating surface, a main influencing factor. The coloured lines enclose the spaces of technically viable solutions, i.e. of design solutions that meet all specifications and result in reasonable aspect factors for the containment. This also includes specifications to be met for a sufficiently low pressure drop level, which was fixed at values as typically found at heat recovery boilers.

As an obvious result and a trend for all storage variants, the required inventory mass increases with an increasing demand on the thermal performance, i.e. with improving constancy of the discharge temperature. It can be seen that for a permissible discharge temperature drop below 60 K the required storage masses differ substantially for the considered TES options, up to a factor of 6. Large mass values reflect a limited heat transport capability in the storage inventory, resulting in a poor thermal utilisation of the material. Honeycomb ceramics and ceramic saddles perform best, essentially due to their large specific surface. Unfortunately, both options typically have a relatively large void fraction. This reduces the achievable energy density, increases containment costs and thus partly offsets their thermal advantage.

From the selected storage variants, for a permissible discharge temperature drop of 60 K, the lowest inventory mass of about 10 t/MWh_{th} is obtained with ceramic saddles, multi-layer media and honeycomb ceramics. This is due to large specific surfaces and the resulting high thermal utilisation of these materials. However, for the selected application, ceramic saddles and multi-layer media, due to their limited stability, tend to provide solutions that are difficult to up-scale and must therefore be implemented with a large number of modules, which in turn increases plant complexity and may represent a barrier to economy of scale. Packed beds from ceramic media, or packed beds from broken basalt and stacked checker bricks still have a favourable specific mass demand of about 20 to 30 t/MWh_{th}, but, to comply with the thermal specifications, should offer a specific surface of at least 75 m^2/m^3. With cast iron and sawn basalt, the highest mass requirements are obtained.

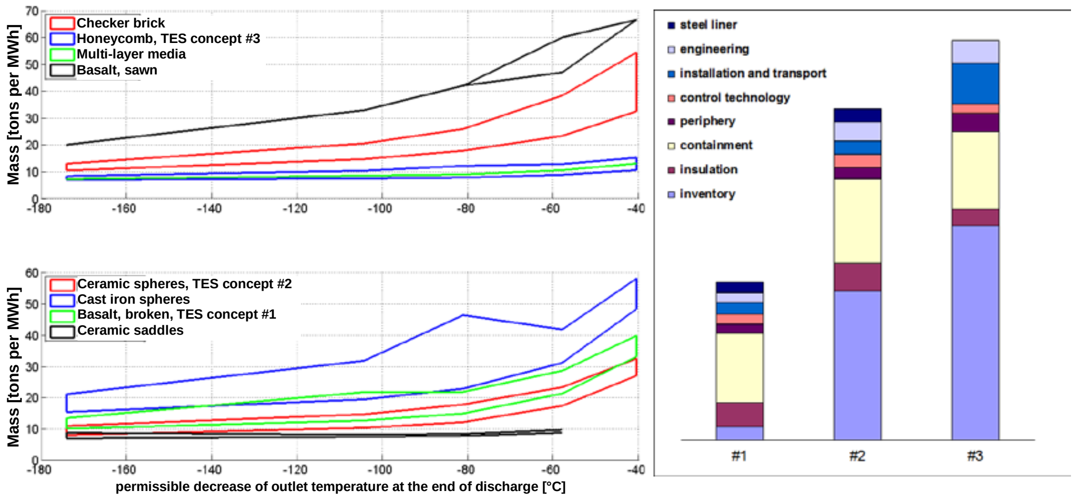

Fig. 2. Left: Space of design solutions for different TES concepts based on shaped bricks (top) and packed beds (bottom): Specific inventory mass versus permissible temperature decrease. Right: Relative investment costs for three different TES concepts for use in an unpressurised solar system ("System 1")

As the technical parameters alone do not give a clear picture, investment costs have been chosen as a major basis for concept ranking. Also, additional criteria have been accounted for. Considered cost factors include inventory material, the insulation, the container, and other peripherals and services such as instrumentation, power supplies, transport and engineering. To properly describe scaling effects, cost functions have been prepared and used for each of the TES subcomponents.

All TES concepts exhibit relatively low absolute overall costs. Figure 2 (right) summarises the investment cost estimates in a relative presentation. The most eye-catching feature in the cost breakdown is the clear difference in inventory costs. For concept #3 (honeycomb-based TES) inventory is the determining cost fraction. Though more costly, the use of honeycomb ceramics is well justified: its shape allows an excellent thermal utilisation und this inventory type is a low-risk variant when applied to a modular containment configuration with moderate height. TES concept #2 (packed bed with ceramic balls) can save part of the inventory costs; this however at the expense of additional technical risks stemming from the thermo-mechanical loads in the bed. These loads also add to the costs of the high-temperature insulation, which must be protected with the help of additional functional layers. TES concept #1 (packed bed with broken basalt) taps further cost reduction potential, but introduces further technical uncertainties with respect to durability and erosion.

These results suggest that all three TES concepts are well justifiable. They can be regarded as development steps towards a further improved cost-effectiveness of the technology: TES concept #3 is an advancement of the storage technology used in the Jülich tower, is ready for demonstration-scale solar deployment or for use in other industrial applications. Packed bed TES as outlined in concepts #1 and #2 is an interesting alternative with excellent prospects, both cost-wise and with respect to installation costs. Though substantial progress could be made in the course the HOTSPOT project, it still needs further development and further testing in pilot-scale to address remaining open questions on the thermo-mechanical implications and on the material questions. For concept #3, the industrial realization has been looked at in more detail: a blueprint planning including project time schedule and further manufacturing aspects has been worked out.

The elaborated design tools and TES concepts have also been experimentally validated in pilot scale. To that end, a test bed for the investigation of high-temperature regenerator-type TES was designed, erected and finally put into operation at DLR Stuttgart in early 2010. It has a wide operation range and allows to investigate TES concepts with an inventory mass of up to 5 tons at charge temperatures of up to 830 °C with repeatable test conditions, see Figure 3 (right). The experiments have provided valuable insight into the relevant thermal effects and thus helped to achieve a reliable prediction of the TES operation.

As an example, Figure 3 (left) shows the temperature variations of the measured and calculated outlet temperatures of a packed bed setup during thermal cycling. Starting at a bed temperature of about 100 °C, a cyclic charge and discharge at constant inlet conditions finally leads to a storage operation in cyclic steady state. This can well be seen from the variations of the discharge outlet temperature, having approximated to a settled course after five cycles. A good agreement between simulation results and measurements was achieved, with deviations below 50 °C at the hot and cold end of storage which are mainly due to boundary effects such as flow distribution and plant-specific radiation losses. It can also be observed that even small model inconsistencies accumulate from cycle to cycle and thus clearly manifest in the comparison.

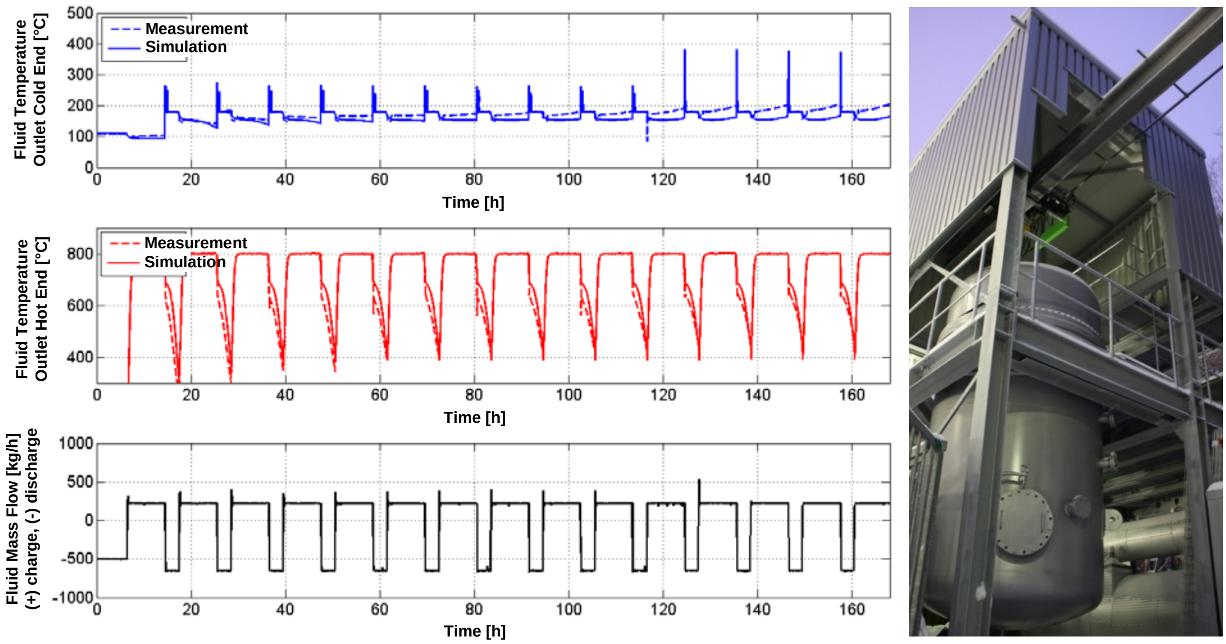

Fig. 3. Left: Time variation of the inlet and outlet temperatures during thermal cycling of a packed bed TES concept (blue: cold end temperature, red: hot end temperature, black: mass flow). Right: Pilot-scale test-bed HOTREG at DLR Stuttgart

2.2. Fluid dynamic aspects

The project also aims to challenge the widespread misunderstanding that regenerator storage is afflicted with an inevitably high pressure loss and, as a result, with excessively high parasitic losses. Actually, there is sufficient design freedom to optimize the pressure drop across the storage. It can in fact be made so small that potential flow maldistributions need to be addressed as part of the design work.

A low pressure drop design can be achieved through a proper selection of inventory material and through an adapted shaping of the containment. A small height-to-diameter ratio allows to keep the air velocity along the flow path sufficiently small without seriously compromising heat transfer between air stream and storage material. This however makes the flow prone to a non-uniform velocity distribution, provoking a poor thermal utilization of the material and, finally, an underperforming operation. Therefore, this design aspect requires a careful CFD-based treatment.

A specific task is to ensure a proper flow distribution at the inlet cross-section into the storage material through a sufficient dimensioning and an adapted shaping of the TES's inlet sections. CFD-models have been set up to describe the flow behavior for different shapes, and systematic parametric studies have been performed to relate flow quality and geometries in a parameter space of practical applications. Now, to avoid the necessity of repeated CFD-calculations for initial design estimates, the results have been condensed into a compact correlation based on reduced numbers for flow uniformity, geometry, and the flow's Eu-number and Re-number, see [12] for further details.

The TES's inlet section can be designed as a hemispherical, conical or cylindrical form with one or more pipes attached in axial or radial direction. General findings on possible layouts are: An increased volume and an increased number of pipe flanges tend to improve the flow quality. With radially attached pipes, a cylindrical inlet section is more effective than a conical form. No advantage could be observed for rotating flows. Pipe attachments designed as cone-shaped diffusers are an additional effort, but can help to reduce pressure loss for both radially and axially attached pipe.

But not only the inlet section's shape, also the inventory itself may have an impact on how an initial maldistribution is further propagated along the flow path: packed beds tend to "cure" a non-uniform flow to a certain extent, whereas in an arrangement of stacked bricks with a similar pressure drop the maldistribution is passed through almost unchanged, see Figure 4 below. Thus, the thermal capacity of a packed bed TES can be expected to be less prone to be affected by flow effects than an arrangement with shaped bricks. For details on the physical model considered in CFD analysis see [13].

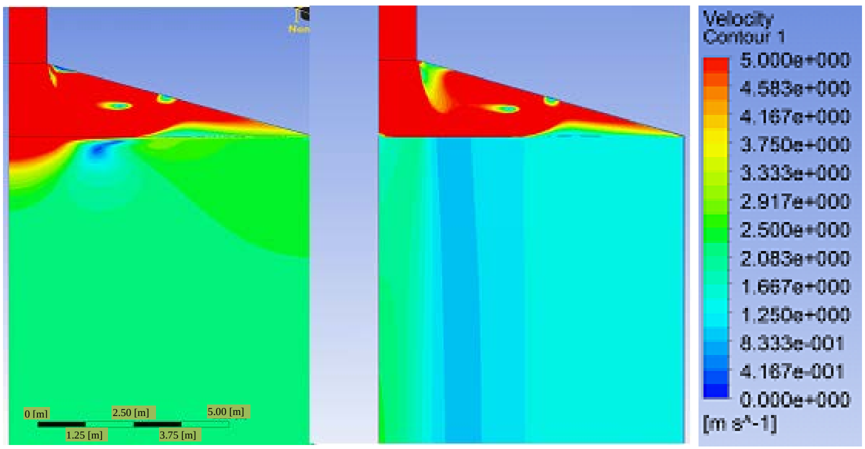

Fig. 4. Velocity field of the air flow in a packed bed storage (left) and in a honeycomb-based storage (right)

2.3. Thermo-mechanical design aspects

Large-scale regenerator storage based on a packed bed has advantages with respect to cost and performance, but is subject to technical uncertainties stemming from thermo-mechanical aspects: The punctiform contacts of the particles may lead to high mechanical forces and could cause material damage at the inventory or the containment insulation. In particular during thermo-cyclic operation periods of bed expansion and shrinking tend to continuously increase the mechanical forces on the particles and the containment walls.

To quantify the resulting mechanical loads and as a design tool, suitable simulation tools have been developed. They are based on a particle-discrete mechanical model of the packed bed coupled to a thermal model describing the development of the temperature field. As a result, the spatial and temporal distribution of the forces acting on each single particle is obtained. These are again used as an input for a continuum-based contact model to calculate the local contact stress between the particles and the insulation wall, see [14], [15], [16] for further details on the modelling approach.

As an illustrative example, Figure 5 (right) depicts a calculated spatial force distribution in a packed bed of spheres. The results provide a detailed description of all relevant effects, such as bed densification, particle movements and the stochastic nature of the mechanical process. The simulations have also been successfully validated with experiments.

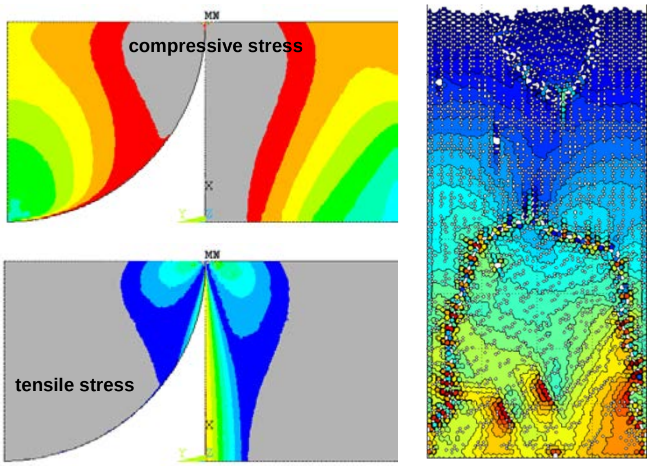

Fig. 5. Local contact stresses at the contact point of particle and inner insulation (half-turn symmetry): compressive stresses (left, top); tensile stresses (left, bottom) and an example of a calculated spatial force distribution in the packed bed storage (right)

Figures 5 (left) shows the distribution of the mechanical stresses at a single particle-insulation contact point before thermal-cyclic operation (symmetry exploited). As expected, the stress analysis reveals compressive loads both at the contact point and at some distance from the contact point, see figure 5 left top. Less expected, also tensile stresses occur in adjacent zones around the contact point, due to the stretching of the near-surface insulation, see figure 5 left bottom in blue colors. The location of the maximum tensile stress is in immediate vicinity of the contact point and quickly decreases to a flat curve with increasing distance. Due to the cyclic thermal excitement, also these contact loads vary cyclicly, see [14], [15], [16] for further details.

The application of the model to a full-scale application indicates that for the critical part of the assembly, the ceramic insulation, the resulting stress level is moderate and manageable through a proper design. Bed heights of more than 10 m require measures to protect the high-temperature insulation.

3. Summary and conclusions

Regenerator heat storage are best suited to provide CSP plants with air-cooled receivers with load-following capability and thus to promote their marketability. The recently completed project HOTSPOT addresses open design questions of this storage technology and reduces technical risks with respect to thermal design, fluid-dynamic and thermo-mechanical aspects. For the first time, design solutions based on packed beds have been looked at, and their specific technical risks have been systematically dealt with.

A choice of TES concepts has been developed, based on target figures for market-scale CSP. Design studies and investment cost estimates for a number of options have identified three lead concepts, based on honeycomb ceramics and two packed bed variants. They have also been successfully tested in pilot-scale. Cost estimates reveal their cost-effectiveness, and also indicate a substantial cost reduction potential with the packed bed variants, which however come with a higher degree of technical uncertainties. The honeycomb-based concept on the other hand is an advancement of existing technology and is considered ready for demonstration and industrial use.

A low pressure-drop design of regenerator storage is feasible, but raises the need for a careful fluid-dynamic analysis to avoid non-uniform flow distributions. CFD-based simulation studies yield recommendations on an optimised containment shaping. The results also show that packed bed configurations are less prone to a flow-induced loss of storage capacity.

Thermo-mechanical design calculations are essential to avoid material damage with packed beds. Particle-discrete models can well describe the relevant phenomena and can well predict the loads on insulation and particles. The resulting stress levels are not negligible, but can be handled through proper design.

The project results indicate excellent prospects for the technology, but also point out solutions for a near-term demonstration in the 100 MWh scale.

Acknowledgements

This work has been funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety under contract 0325048. This financial support is gratefully acknowledged.

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