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Packed Bed Heat Storage: Continuum Mechanics Model and Validation

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Abstract. Thermal energy storage (TES) systems are key elements for various types of new power plant concepts. As possible cost-effective storage inventory option, packed beds of miscellaneous material come into consideration. However, high technical risks arise due to thermal expansion and shrinking of the packed bed's particles during cyclic thermal operation, possibly leading to material failure. Therefore, suitable tools for designing the heat storage system are mandatory. While particle discrete models offer detailed simulation results, the computing time for large scale applications is inefficient. In contrast, continuous models offer time-efficient simulation results but are in need of effective packed bed parameters. This work focuses on providing insight into some basic methods and tools on how to obtain such parameters and on how they are implemented into a continuum model. In this context, a particle discrete model as well as a test rig for carrying out uniaxial compression tests (UCT) is introduced. Performing of experimental validation tests indicate good agreement with simulated UCT results. In this process, effective parameters required for a continuous packed bed model were identified and used for continuum simulation. This approach is validated by comparing the simulated results with experimental data from another test rig. The presented method significantly simplifies subsequent design studies.

INTRODUCTION

Thermal energy storage (TES) systems are central elements of CSP plants with a high solar share. Where air is used as a heat transfer medium in pressurised or non-pressurised air receivers, a regenerator-type heat storage with a packed bed inventory is a straightforward design option, offering cost-effective solutions.

Regenerator-type heat storage technology offers a considerable design freedom and flexibility for both its arrangement and choice of materials. Existing industrial concepts include solutions from steel industry ("Cowper"-stores), from glass industry and air purification systems. The use of packed beds instead of shaped bricks as a storage inventory opens up a significant cost reduction potential. Possible choices for packed bed materials are ceramic pebbles or simply natural stone [1]. Particularly in the case of natural stone, there is a high potential for cost reduction while still offering comparable heat transfer rates to fixed brick installations.

However, such a packed bed design is prone to mechanical failures caused by the punctiform contacts. During the thermal charging and discharging processes of the heat storage system, the pebbles or particles of the packed bed start to expand and shrink, respectively. As a consequence, thermo-mechanical loads are induced which lead to high technical risks for the storage inventory itself and the encircling containment insulation of the heat storage system. When considering thermal cycling on a daily basis, the induced loads might drastically lower the life expectancy of

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the storage system. In order to adequately adjust packed bed installation and container design, knowledge of the occurring stresses and loads is essential. Therefore, numerical models and simulation tools are needed.

METHODS

There exist two basic mechanical methods for simulating packed beds. The first approach consists of a particle discrete model, where each particle is modelled as its own independent physical object. Displacements and movement of the particles are calculated based on the resulting forces of particle-particle contacts or particle-wall contacts. Previous work has shown that the Discrete-Element-Method (DEM) produces highly accurate results and allows valuable insights into the basic phenomena [2, 3], but also it requires high computing time. The other approach relies on a macroscopic perception of the packed bed, where the accumulation of particles is represented as a continuum. Here, the accuracy of the model heavily depends on the quality of the effective material parameters describing the continuum. Opposed to the particle discrete model, the continuum approach always will be limited to non-stochastical results regarding the particle behavior. However, the continuous modelling technique offers a high time-saving potential in terms of computing time.

Discrete-Element-Method (DEM)

The Discrete Element Method is a technique to compute forces between interacting particles and the resulting displacement. It is based on a discontinuous implementation of a multitude of individual particles, whereas each particle contact is represented as a friction-spring-damper system. Therefore, particle-particle and particle-wall contacts will result in spring, friction and damping forces. The algorithm used in DEM enables the determination of time dependent movement and rotation of particles. It follows a sequence of single arithmetic operations, whereas the first step would be the identification of contact pairs. During contact, virtual springs are created at the contact locations and are compressed as the particles interpenetrate. Thus, an increasing penetration results in increasing forces acting on the particles. The ensuing forces of the spring-damper compression can be separated into tangential and normally directed forces. Whereas the tangential directed forces stand for static and dynamic friction, the normally directed forces represent damping and recoil. Gravitation is included as external force in the model as well. By integrating Newton's second law for the given system, the current position and velocity for each individual particle can be determined.

Further details on DEM theory can be gathered from many different sources, such as [4,5,6].

Continuum Model and Effective Material Properties

Since the discrete model described previously deliver results for large amount of particles in a non-satisfying period of time, another approach of packed bed modeling is necessary. One option is the macroscopic perception of the packed bed, thus treating it as continuum with homogenous and isotropic material properties. These properties obviously differ from the ones of the bulk material. One key parameter for the continuum model is the effective Young's Modulus of the packed bed. Reimann [7] provided a correlation of the effective Young's Modulus as a function of temperature and stress for a variety of packed bed materials used in ceramic breeder blankets:

$$\mathrm{E}_{\mathrm{eff}} = \mathrm{C}_1 \cdot (1 + \mathrm{C}_2 \cdot \mathrm{T}^3) \cdot \sigma^{\mathrm{C}_3} \tag{1}$$

Here, E_{eff} represents the effective Young's Modulus, T *[K]* is the temperature of the packed bed, σ is the uniaxial stress and C_i are material constants.

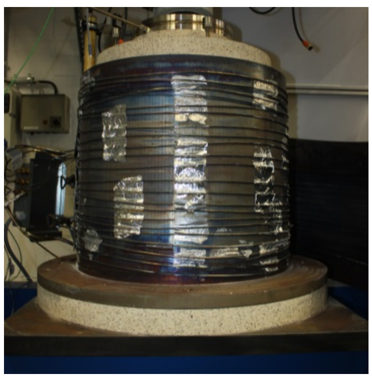
The correlation is based on experimental analysis of the packed bed behaviour under thermal and mechanical loads. Typically, uniaxial compression tests (UCT) provide the required data basis. Thereby, the horizontal sides of the packed bed are restrained while being vertically compressed by external loading. The effective Young's Modulus is a result of the packed bed's compression strain. As a more flexible approach, the present work uses calculated UCT data generated with the mentioned particle-discrete model to determine the stress and temperature dependence of the packed bed's effective Young's Modulus.

EXPERIMENTAL SETUP

The following paragraph introduces two custom-build test rigs to conduct UCTs and to measure particle-wall contact forces in a regenerator-type heat storage. The purpose of first one is to validate particle discrete UCT simulations and to determine the effective Young's Modulus of a selected packed bed. Data gained from the force measurement device is used to validate the continuum model of a heat storage system.

Uniaxial Compression Test Rig

The test rig used for uniaxial compression tests essentially consists of two components: a cylindrical cell and a hydraulic press. The steel made cell (Figure 1) measures 0.5 meters in diameter as well as 0.5 meters in height and is wrapped in heating wires which enables packed bed temperatures up to 600 °C. The cell is thermally isolated using insulation wool wrapped around the cell and fire bricks on the top and bottom of the cell.



(a)

(b)

FIGURE 1. a) Cylindrical pressure cell; b) Pressure cell containing the packed bed

For mechanical loading a press is installed at the top of the pressure cell, which allows stamping up to 160 tons of weight onto a plate covering the packed bed.

The applied pressure on the cover plate is recorded by a load sensor. The displacement of the cover plate caused by compression of the packed bed is recorded by laser range sensors, which are placed at four evenly spread locations. To prevent affection of the measurement precision while operating at elevated temperatures, the measurement instrumentation is thermally decoupled. In addition, there is an active cooling system installed on top of the cover plate to reduce the temperature at the contact point of the press stamp with the cover plate. Still, there are some limitations in measurement accuracy to be considered caused by manufacturing processes. The measuring errors and resolution abilities of the load and range sensors are listed in Table 1.

TABLE 1. Technical details of measurement devices

	Load sensor	Range sensor
Measuring error	± 0.025	± 0.16 %
Measuring resolution	± 0.579 kN	± 10 µm

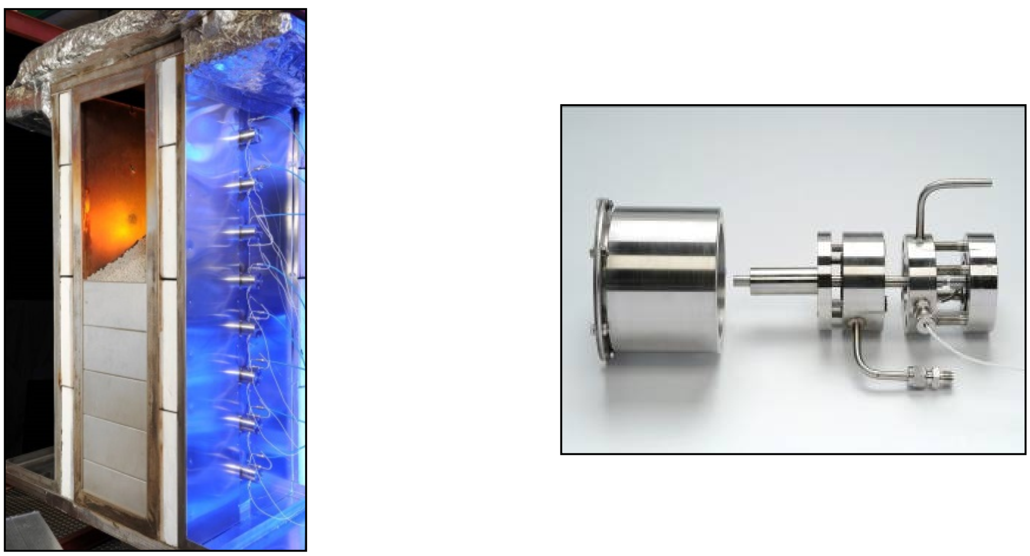
The first step of the test procedure contains the positioning of the cover plate on top of the packed bed. Afterwards, pressure is applied on the cover plate stepwise until a predefined strain is achieved. Those steps are reversed afterwards as the packed bed gets decompressed by subsequently releasing the pressure from the cover plate. After each step the currently applied pressure and the displacement of the cover plate are recorded. The void fraction of the pebble bed decreases with each step of compression due to internal rearrangement of individual particles, resulting in a denser packing. The entire cycle of compressing and decompressing is repeated multiple times to ensure all of the densification process to be completed. The main physical properties of the studied pebbles, which are commercially available, are summarized in table 2.

TABLE 2. Properties and characteristics of the studied pebbles

Material composition	Young's Modulus [GPa] (at 20 °C)	Density [kg/m^3]	Poisson's ratio [-]	Diameter [mm]
< 80 % SiO_2 > 20 % Al_2O_3	71.9	2340	0.24	14

Force Measurement Device

The objective of the force measurement device is the detection of particle-wall contact force during thermal cycling of packed beds. This test rig is based on the principle of regenerator-type heat storage with a storage filling volume of 0.9 m^3, a quadratic cross-sectional area of 600x800 mm and a bed height of 1700 mm. The containment walls consist of 5 mm stainless steel plate, a layered insulation design and are reinforced by fins on its outside surface to increase the stiffness of the thermal storage device, see figure 2. The packed bed is filled inside of the container and can be thermally charged or discharged by a continuous airflow. The structure of this test rig facilitates maximum operating temperatures up to 600 °C.



(a) (b)

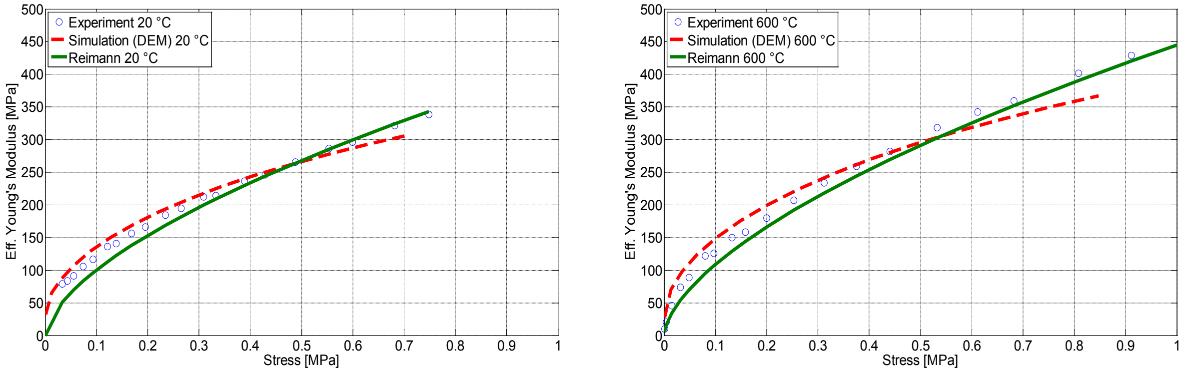
FIGURE 2. a) regenerator-type heat storage; b) force measurement device

Strain gauges are considered an adequate measurement technique to detect forces under static and dynamics conditions, with high accuracy and with small installations sizes. To handle the high temperatures under thermal cyclic operations an additional cooling system was integrated into the measurement devices. They are attached at one of the containment walls to measure the particle-wall contact forces under isothermal and thermal cyclic operation.

The acting forces on the measurement disc are transferred via the rod to the strain gauge sensor. To allow only axial loads towards the strain gauge sensor, the measurement disc as well as the guidance rod are conducted with bearings. To control the operation temperatures at the strain gauge sensor, ambient air is used to cool the measurement device. These novel devices are calibrated in a temperature range from 20 to 60°C and force loads between 10 and 500N to compensate the constructional effects of the segmented cell design.

RESULTS

The effective Young's Modulus of a ceramic packed bed was identified using the DEM for simulating uniaxial compression tests. The simulation results are compared to the experimental results of the uniaxial compression test rig at 20 °C and 600 °C during uniaxial compression, as shown in figure 3. The examined packed bed consists of monosized pebbles of 14 mm in diameter, wherein the pebbles are composed of oxide ceramics, see table 2. The dimensions of the DEM model is matched with the UCT test rig, which measures 0.5 m in diameter and 0.5 m in height.



(a) (b)

FIGURE 3. Stress dependent effective Young's Modulus for a ceramic packed bed under uniaxial compression at: a) 20 °C; b) 600 °C

Regarding the results at 20 °C and at 600 °C, a good agreement between the experimental and simulation data can be observed. Negligible differences are mainly caused by the simplified assumptions (perfect smoothness and sphericity of particles) implemented in the DEM model. When comparing the 20 °C results and the 600 °C result, a slightly higher effective Young's modulus at any given stress state is observable. This is a consequence of the likewise increasing Young's Modulus of the bulk ceramic material at higher temperatures. Compared to the bulk material, the effective Young's Modulus for the packed bed at the given stress range is over two orders of magnitude smaller, which matches with the results of Ying [8]. As shown, the effective Young's Modulus of the packed bed depends on temperature and stress state and thus can be expressed as a continuous function. In this work, Reimann's approach (see eq. (1)) is applied. The parameters C_i were fitted to minimize the discrepancy between experimental data and the equivalent calculated values. A good agreement can be stated when comparing the curves to each other, which points to the suitability of Reimann's approach. The fitted parameters are listed in table 3:

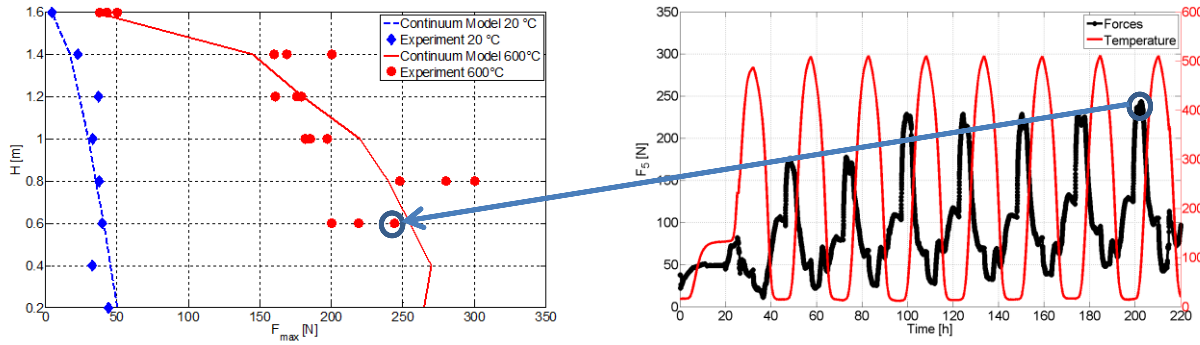
TABLE 3. Reimann fit parameters for the examined ceramic packed bed only.

C_1	C_2	C_3
406.69	5.24e-10	0.52

These parameters are only valid for the specific packed bed under investigation. Testing different shaped particles or a packed bed with particle size distribution will lead to different parameters. Additionally, particle breakage will also influence the characteristic of the packed bed. In this case, no particle breakage was found after a close examination of the tested packed bed.

With careful parametrization, a thermo-mechanical continuum model can well predict the relevant loads in packed bed storage in cyclic operation. The parameters listed above serve for the implementation of said model, using the finite element method (FEM). Further information about possible continuum models and relevant parameters can be gathered from the works of Bühler, Tucker et al. and Kamlah et al. [9,10,11].

For validation purposes, simulation results of the FEM-model were compared to experimental results obtained from the force measurement device, see figure 4a. For these tests the bed was thermally charged with an inlet temperature of 600 °C and discharged with an inlet temperature of 20 °C. The process of thermal charging and discharging was repeated for up to ten thermal cycles. After completion of one measurement procedure the particles were newly refilled for the next run to gain comparable initial conditions of the packed bed. A total of three test runs were conducted. Exemplarily, the progression of the recorded forces on the container wall over eight thermal cycles at bed height of 0.6 m is shown in figure 4b. At this bed height, the temperature of the packed bed reaches maximum temperatures of 500 °C. The experimental data displayed in figure 4a refer to the maximal occurred forces during cyclic operation of the test rig.



(a) (b)

FIGURE 4. a) Maximal forces acting on the container wall; b) Force progression over multiple thermal cycles at 0.6 m bed height

For the results at 20 °C (before thermal operation), the continuum model is able to predict the acting forces on the container wall with high accuracy. For both the measured and the calculated results, the particle-wall contact forces at the disk increase with increasing bed depth starting at 0 N at the top of the bed to about 50 N at the bottom. During charge operation the contact forces increase due to the thermal expansion of the particles and decrease during discharging. With increasing number of cycles, the measured and calculated force variations become increasingly similar, caused by an increasing bed densification and a reduction of initial irregularities.

In the case of the measurement with charging temperatures of 600 °C, results from three individual test cycles are displayed for different heights. Those results vary in between themselves, which is a result of the stochastic nature of the packed bed behaviour. By using the measured temperature profile at the time of maximum forces as input data for the simulation, a moderate agreement of simulation and experimental results is visible and thus, the continuum model is validated. In spite of the simple character of Reimann's approach without using further effective parameters, e.g. the effective Poisson's ratio, the model can be seen as solid tool to calculate time-efficiently the thermally induced loads. Compared to the contact forces before thermal operation, the spatial distributed contact forces of the thermally charged packed bed in average are increased by factor 5-6.

CONCLUSION

Packed beds represent a promising design option of heat storage material and open up a potential for cost reduction. For design calculations, a computationally efficient continuum packed bed model is necessary. It was shown that the parametrisation of such a model can be achieved with the help of particle-discrete models, without the need for alternatively time-consuming UCT tests. The validation succeeded by comparing UCT simulations with experimental data. By implementing the resulting non-linear effective Young's modulus into a FEM model, it is possible to efficiently simulate the acting force on the container wall during thermal cycling of a packed bed. Experimental data gained from a force measurement device validate the prediction of said model. The relevant effects inside a packed bed, increasing forces due to expansion of the particles, decreasing forces due to shrinking particles, can be well described using the presented procedure and models. It is therefore considered a solid basis tool, allowing to develop appropriate design solutions for upcoming applications of this storage type. In further works, possible long-time effects like thermal creep and fatigue of material will be experimentally investigated and additional effects, e.g. plasticity, must be implemented in order to allow a deeper insight into the packed bed nature.

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