THERMO-MECHANICAL INVESTIGATION OF PACKED BEDS FOR THE LARGE-SCALE STORAGE OF HIGH TEMPERATURE HEAT

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ABSTRACT

Thermal storage systems are central elements of various types of power plants operated from renewable and conventional energy sources. Where gaseous heat transfer media are used, a regenerator-type heat storage based on a packed bed inventory is a particularly cost-effective solution. However, suitable design tools that cover the thermo-mechanical aspects of such a design are still missing today. As a basis for such a tool, this contribution presents a novel approach to investigate the thermo-mechanical behaviour of such a storage under thermo-cyclic operation. The relevant relations are formulated on the basis of the discrete element method (DEM). Results of simulation runs determine the temporal and spatial displacements and acting forces for the individual bodies. Coupling the equations to a simplified thermal model allows to investigate the thermo-mechanical behaviour. Initial results for a thermo-cyclic operation using simplified assumptions are presented.

1. BACKGROUND

Thermal energy storages for the high temperature range are central components for power plants driven from renewable energy: Heat storage allows solar thermal power plants to continuously operate beyond sunshine duration. In fossil CHP power plants they increase the operational flexibility and thus improve the revenue situation. Industrial waste heat use and electricity storage based on Adiabatic Compressed Air Energy Storages (ACAES) are further examples.

An increasing interest in these technologies calls for large-scale storage solutions in a temperature range between 500-1000°C with storage capacities up to 3GWh for discharge durations between 4 and 12h. In many applications the heat is transferred by gaseous heat transfer media, such as air or flue gas. Here, a direct contact between the heat transfer fluid and storage inventory is a particularly cost-effective design solution. Installations of these so-called regenerator-type heat storages have been used in the steel and glass industry for many decades. The storage inventory is stacked from ceramic bricks.

To reach the cost targets for power plant applications, regenerators based on a packed bed inventory are a promising option. They offer a large specific heat transfer area and high heat transfer rates, as well as the potential to reduced investment costs, especially for natural stones as an inventory material.

However, the design of large packed beds is afflicted with technical uncertainties. The punctiform contacts of the particles lead to high mechanical loads and thus make the inventory or the containment insulation prone to failures. To come to improved inventory layouts, suitable simulation tools need to be developed.

2. THE THERMO-MECHANICAL MODEL OF GRANULAR MATERIALS

Mechanical problems that exhibit a microstructure scale that is small compared to the object size are usually solved with a conventional continuum based approach, such as FEM. In contrast, packed beds show a macroscopic behaviour that can more adequately be described as a system of distinct interacting bodies that are subject forces and resulting motions.

Today, simplified packed bed models are based on either continuous or discontinuous approaches [1, 2]. They neglect internal motions and rearrangements inside the packed bed during thermal-cyclic operations.

A more accurate numerical technique is the discrete element method (DEM). The procedure determines the time-varying contact locations of the individual bodies. It considers the mechanical interaction between bodies and numerically solves the associated equation of motion. Also, various particle shapes [3, 4] and containments forms can be modelled. The DEM was originally applied in the context of rock mechanics and geotechnics by Cundall and Strack [5]. Typical industrial applications are in the area of granular flow, for example hopper techniques [6].

So far, the method has been used in “cold” applications. To exploit the technique with heat storage, it is extended to account for thermally induced mechanical loads. For this purpose the DEM equations are coupled to a spatially distributed thermal model of the storage inventory. The considered forces include friction, recoil, damping and gravity force.

In the following, the basic model equations are outlined.

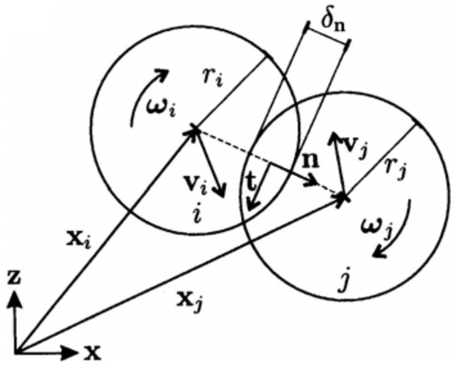
2.1. MECHANICAL MODEL

The DEM describes the motions and rotations of individual particles in time and space. Basic quantities of the DEM are the particle coordinates $\vec{x}$, the particle velocities $\vec{v}$ and its rotational speed $\vec{\omega}$. When particles get in contact, the acting forces on each particle are summed up and the Newton’s equation of motion is integrated to obtain acceleration, velocity and position of the particles at the next time step.

The forces interacting between particles are described by spring models. During contact, virtual springs are created at the contact locations and are compressed as the particles interpenetrate. This approach is the basic idea behind DEM and is illustrated in figure 1 (left). An increasing penetration thus results in increasing forces acting on the particles.

The geometric and kinematic relations form the method’s fundamental set of equations, which is summarized in figure 1 (right) for the case of spherical two-dimensional particles with radius *r*.

The contact forces are decomposed in the normal and tangential direction. The normally directed forces describe recoil and damping, the tangentially directed forces the friction models. A more detailed description can be found in [8, 9].



Penetration depth

$$\delta_n = \max\left(0, r_i + r_j - \left|\vec{x}_j - \vec{x}_i\right|\right)$$

Normal directed vector at the contact location

$$\vec{n}_{ij} = \frac{\vec{x}_j - \vec{x}_i}{\left|\vec{x}_j - \vec{x}_i\right|}$$

Relative velocity vector at the contact location

$$\vec{v}_{ij} = \vec{v}_i - \vec{v}_j + \vec{\omega}_i \times \left(r_i \vec{n}_{ij}\right) - \vec{\omega}_j \times \left(-r_j \vec{n}_{ij}\right)$$

Tangential directed vector at the contact location

$$\vec{t}_{ij} = \frac{\vec{v}_{ij} - \left(\vec{v}_{ij} \cdot \vec{n}_{ij}\right)\vec{n}_{ij}}{\left|\vec{v}_{ij} - \left(\vec{v}_{ij} \cdot \vec{n}_{ij}\right)\vec{n}_{ij}\right|}$$

Tangential velocity vector at the contact location

$$\vec{v}_t = \vec{v}_{ij} - \vec{v}_n = \vec{v}_{ij} - v_n \vec{n}_{ij}$$

Normal velocity at the contact location

$$v_n = \vec{v}_{ij} \cdot \vec{n}_{ij}$$

Figure 1: Illustration of the DEM concept for spherical 2D particles [10] (left) and the basic geometric and kinematic equations (right)

The recoil force is calculated from Hook's law using the normal directed spring constant k_n and the penetration depth δ_n. The normal damping force, described by the normal component of the relative velocity v_n and the damping coefficient C, dissipates a part of the kinetic energy. The normal force between two bodies i and j is expressed as:

$$\vec{F}_n^{ij} = -\max\left(0, k_n \delta_n + C v_n\right)\vec{n}_{ij} \qquad (1)$$

Dynamic and static friction forces F_F are the reaction forces in tangential direction. Classical friction models consist of velocity dependent components that can be combined in various ways. Here, the simplified calculations are based on a velocity $|v|$ dependent component (I) for the static friction and Coulomb friction (II) for dynamic friction as illustrated in figure 2.

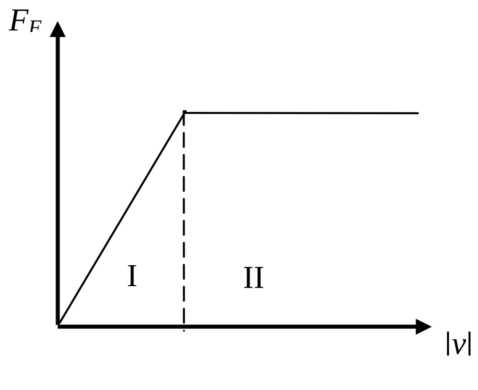


Figure 2: Static friction force (I) and dynamic friction force (II)

Static friction plays a significant role with static packed beds. An adequate model uses a virtual tangential spring as outlined above for the normal force. At the moment when two bodies get in contact (t_0), the calculation procedure creates a spring of zero length. During contact time, the spring is stretched by the excursion ξ in the tangential direction for the duration of a time step $\Delta t'$:

$$\xi = \left(\int_{t_0}^{t} \vec{v}_t(t')\Delta t' \right) \cdot \vec{t}_{ij}$$

The tangential directed forces between two bodies *i* and *j* are thus expressed as:

$$\vec{F}_t^{ij} = -\min\left(\mu\left|\vec{F}_n^{ij}\right|, k_t\xi\right)\frac{\vec{\xi}}{\left|\vec{\xi}\right|} \qquad (2), \qquad \vec{\xi} = \xi \cdot \vec{t}_{ij}$$

where μ is the Coulomb friction coefficient and k_t is the spring constant for tangential direction. If sliding occurs, ξ is limited by the following relationship:

$$k_t \cdot \xi_{\max} = \mu \cdot \left|\vec{F}_n^{ij}\right| \; .$$

Besides the normal and tangential directed forces, gravitation is included as an external force in the model [10]. The particle-containment interaction is treated similarly to a particle-particle contact.

With this set of geometric, kinematic and force equations the motions of each single particle are determined. The force balances around the individual particles constitute the right hand side of Newton's equations of motion:

$$m_i \cdot \frac{\partial^2 \vec{x}_i}{\partial t^2} = \sum_{j=1, j\neq i}^{N} \left[\vec{F}_n^{ij}(\vec{x}_i, \vec{\omega}_i) + \vec{F}_t^{ij}(\vec{x}_i, \vec{\omega}_i)\right] + m_i\vec{g} \qquad (3), \qquad \vec{x}_i(t=0) = \vec{x}_{i,0}$$

$$J_i \frac{\partial \vec{\omega}_i}{\partial t} = \sum_{j=1, j\neq i}^{N} \left[r_i \vec{n}_{ij}(\vec{x}_i) \times \vec{F}_t^{(ij)}(\vec{x}_i, \vec{\omega}_i)\right] \qquad (4), \qquad \vec{\omega}_i(t=0) = \vec{\omega}_{i,0}$$

where m_i is the mass of particle *i*, $\vec{g}$ is the gravitational acceleration and J_i is the moment of inertia.

Equations (3) and (4) are discretised in time and solved numerically using a Verlet integration scheme to obtain the positions and velocities at the next time step. For satisfying results, the time step $\Delta t'$ must be sufficiently small. It is determined on the basis of the maximum stiffness and the smallest mass of a particle. An often used relationship can be found in [11].

$$\Delta t' \approx \sqrt{\frac{m_i}{k_n}}$$

Apart from particle positions and velocities, a simulation run provides the forces at each particle at the contact locations. To compare the mechanical load with permissible material strengths, the concept of averaged stress is introduced. For the individual particle, a mean stress tensor is calculated from the acting forces and the normal vector of the contact plane [12]:

$$\sigma_i^P = \frac{1}{V_P}\sum_{c=1}^{m}\left(\vec{l}_i^{\,c} \otimes \vec{F}_j^{\,c}\right),$$

where V_P is the volume of a single particle and the eigenvalues of the tensor constitute the principle norm stress levels.

2.2. THERMAL MODEL

The thermal model provides the temporal and spatial temperature variation of the particles. It considers the storage inventory as a heterogeneous porous medium, calculating the heat balances for the fluid and solid phase [7]. As a simplification that is well justified for large installations, radial gradients are neglected and adiabatic conditions are assumed.

With these assumptions and a normalisation of time t^* and space variables z^*, the one-dimensional thermal behaviour of the solid medium T_S and the heat transfer fluid T_F in axial direction can be written as

$$\frac{\partial T_S}{\partial t^*} = \frac{k \cdot O \cdot \tau}{m_S \cdot c_S} \cdot \left(T_F - T_S\right) = \Pi \cdot \left(T_F - T_S\right) \qquad (5), \qquad T_S\left(t = 0\right) = T_0$$

$$\frac{\partial T_F}{\partial z^*} = \frac{k \cdot O}{\dot{m}_F \cdot c_F} \cdot \left(T_S - T_F\right) = \Lambda \cdot \left(T_S - T_F\right) \qquad (6), \qquad T_F\left(t = 0\right) = T_0 \ ,$$

where k is the total regenerator heat transfer [7], O the heat transfer surface, τ the charge/discharge duration, m_S the total storage mass, $\dot{m}_F$ the mass flow rate and c_S and c_P the specific heat capacities of the solid and fluid. In this formulation, the thermal operation can be described with only two dimensionless parameters, the reduced period duration Π and the reduced regenerator length Λ.

2.3. MODEL COUPLING

The coupling of the mechanical model to the thermal model allows to investigate the mechanical behaviour of packed beds during thermal cycling. A coupling equation is given through a term for the thermal expansion of the particles. For spherical particles and a linear expansion coefficient α_W, the local diameter is written as:

$$d_i(z) = d_{i,0}(z) \cdot \left[1 + \alpha_W \cdot \Delta T_{t_0}^{t}(z)\right] \qquad (7)$$

The calculation procedure consists of a sequential application of equations (5) and (6) to calculate the temperature field, equation (7) for the particle size, equations (1) and (2) to calculate the interacting forces and, finally, application of equations (3) and (4) to calculate the particle motions. This constitutes a one-way coupling of the models: small effects of particle rearrangements on the thermal model are neglected.

3. SIMULATION AND FIRST RESULTS

Based on the simplifying assumptions above, the thermo-mechanical behaviour of a packed bed is looked at in the following.

An example packed bed consists of 1014 spherical particles (ρ_S = 2500 kg/m^3, μ = 0.5, α_W = 4e^{-5}/K) with a diameters of 0.1 m in a containment with a height of 4.8 m and a diameter of 2.1 m. The normally and tangentially directed spring constant calculated from the modulus of the elasticity and the Poisson number are 100 MN/m and 70 MN/m respectively. The damping coefficient C to be determined from experiments is estimated to 11000 kg/s.

The initial conditions for each particle are chosen after a falling bulk of particles with randomly chosen starting coordinates and zero starting velocity.

The application of calculation procedure determines the particle trajectories and, when reaching the static solution, the final positions of the falling bodies. This system state is depicted in the left graph of figure 3, where the resulting principle norm stress level of the individual particles is given as a grey tone variation.

It can be seen that structures have evolved for the spatial distribution of the stress level. Basically, the mean stress level increase with increasing depth. But clearly, local minima and maxima exist, caused through irregularities in the arrangement.

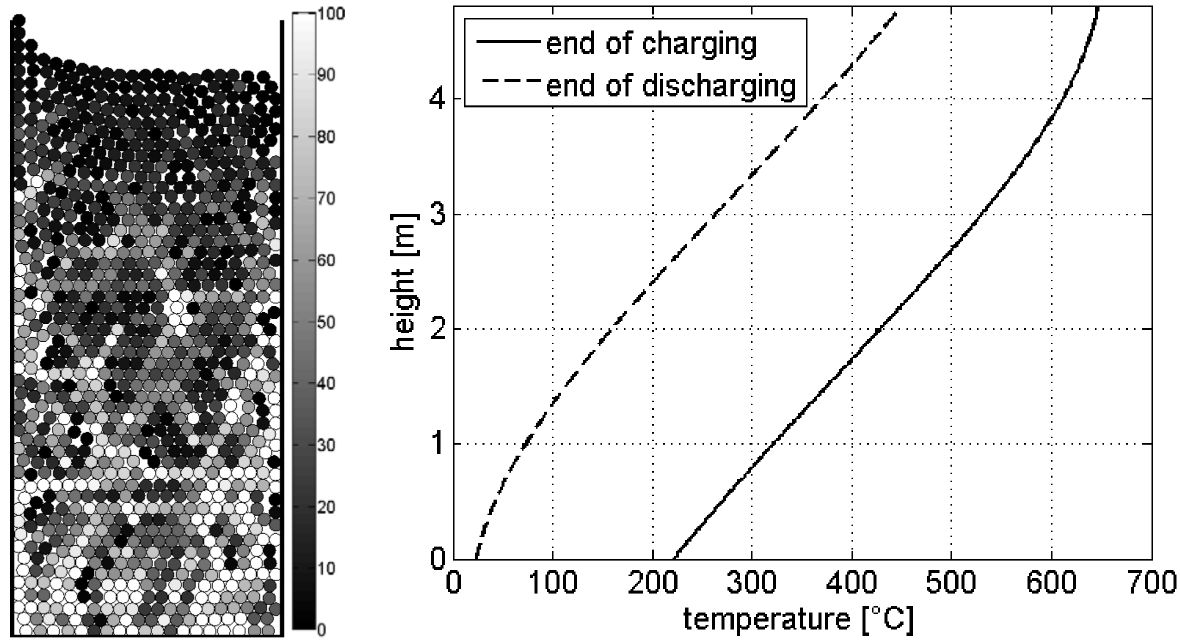


Figure 3: Principle normal stress for steady state solution after initial filling of the containment (left) and axial temperature profiles at the end of charging and discharging (right)

As a subsequent step, thermo-mechanical loads are induced through a thermal excitation of the model. Imposing time-varying boundary conditions calculates a storage operation with inlet temperatures that alternate between 650°C and 20°C. The dimensionless thermal parameters - the reduced period duration Π and the reduced regenerator length Λ - are set to values of 4 and 8. The resulting temperature profiles at the end of charging and discharging are presented in figure 3 (right). For the selected parameters, the particles experience a mean temperature spread of about 200°C between end of charging and discharging.

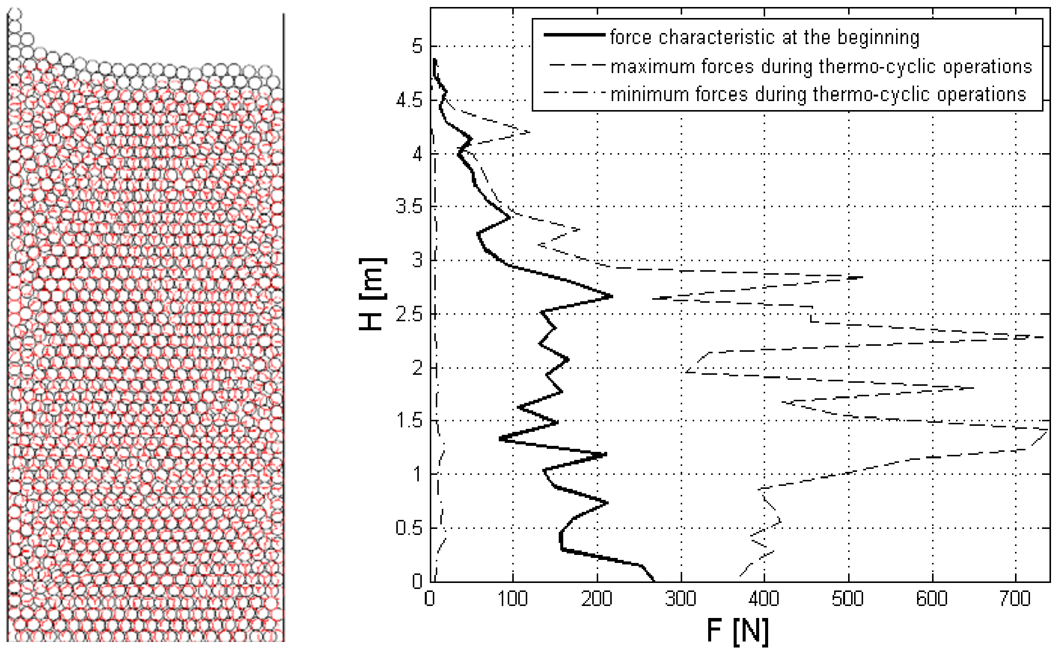


Figure 4: Rearrangements of the particles after five thermal cycles (left) and radial average force characteristics before cycling, maximum and minimum forces during cycling (right)

The resulting cyclic thermal expansion of the particles leads to a rearrangement of the particles inside the packed bed. The final particle positions after five thermal cycles are shown in the left graph of figure 4. The local particle arrangements, especially at the walls, have changed to a more uniform distribution. For this case of equally sized spherical particles, the displacements lead to a more compact bed with an increased bulk densitiy of 0.85 at the end compared to 0.81 initially.

A plot of the radially averaged forces versus storage height (figure 4, right) reveals the mechanical impact of the cyclic densification: where space for particle motion is reduced, locally increased values for the mean particles forces appear. For the presented example, the maximum values are up to four times higher compared to the initial values.

Comparing the force curves before and after thermal cycling shows that the forces in the denser bulk have a maximum and decrease with depth. This force distribution is ascribed to an increased friction at the containment wall.

4. CONCLUSIONS AND OUTLOOK

Regenerators based on a packed bed inventory are a promising solution for large-scale heat storages in many applications. A design tool that can predict the mechanical loads for the particles and the containment under thermo-cyclic operation is prerequisite for a further development of this storage technology. The present contribution describes a calculation procedure that can serve as a basis for such a design tool together with first results.

Basically, it consists of a spatially distributed model for the mechanical interactions between the individual particles, formulated on the basis of the discrete element method (DEM) and a thermal model for the packed bed. These models are coupled through a term for the thermal expansion of the particles.

The first results for an example packed bed reproduce the particle arrangement in the bed and their rearrangement under thermal-cyclic operation. An observed bed densification becomes apparent in the simulation results. The resulting temporal and spatial distribution of forces acting on particles and containment are determined and can be used as an input to stress analyses. Thus, the presented approach is considered a good basis for a of design tool that can identify low-stress solutions for packed bed stores in large scale installations.

However, some open questions have to be dealt with before the method can be effectively exploited. These include the stochastic properties of the results that make a specific treatment necessary. Also, quantitative statements on material durability need to be elaborated. For this purpose, the computed results are used to further investigate local stresses at contact points with a view to deriving probabilities of failure for the involved materials.

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