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Analysis of the thermal ratcheting phenomenon in packed-bed thermal energy storage using Discrete Element Method

Packed-bed thermal energy storages (TES) play a major role in energy technology. During energy absorption, hot air flows through the content of the TES in top-down direction. During the heating process, the expansion of the heat-storing medium (bulk material) leads to a stress increase on the walls of heat-storage tanks. These occurring loads are to be considered by means of a discretized model. Furthermore, it is of interest how the loads modify during several loading and unloading processes (thermal ratcheting phenomenon). In this paper, it will be investigated how this behaviour can be modelled using the DEM approach.

Keywords: Thermal energy storage (TES), Discrete Element Method (DEM), thermal ratcheting, thermal stress, calibration

1. INTRODUCTION

In course of a NEFI (New Energy for Industry) project, the waste heat of a cement plant with a temperature of around 300-400°C shall be used for energy recovery. For this purpose, a storage in form of an air-flowed packed-bed thermal energy storage (TES) [8] has to be implemented. Since 2018, this goal has been pursued at the Vienna University of Technology in a project of the Department of Engineering Design and Material Handling (KLFT) in cooperation with the Institute for Energy Systems and Thermodynamics (IET).

In simplified terms, packed-bed TES are tanks that are filled with bulk material. The bulk material serves as a heat-storing medium. The most important goal of TES systems is to decouple the generation of thermal energy from its use, since the renewable energy can be used by a neighbouring company.

The expansion of the heat-storing medium (bulk material) during the heating process leads to a stress increase on the walls of the heat storage tank. Previous results [1], [5], [6], [7] have shown that increasing contact forces of the bulk material and the associated stress increase on the heat storage walls can lead to damage (see Figure 1).

The special feature of this project is to consider this thermal expansion of the bulk material and to investigate the thermal ratcheting phenomenon (increasing stress due to several loading and unloading cycles).

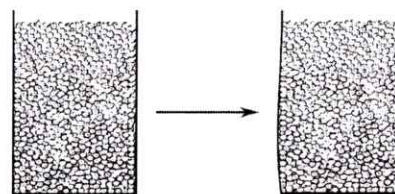


Figure 1. Damaged packed bed thermal energy storage

With increasing temperature the size of particle enlarges. The thermal expansion leads to the following effects:

- The contact forces between the individual particles rise (see Figure 2, left). This can cause damage to the bulk material.
- The contact forces between particles and the tank wall of the TES also rise (see Figure 2, right). This can cause damage to the tank wall.

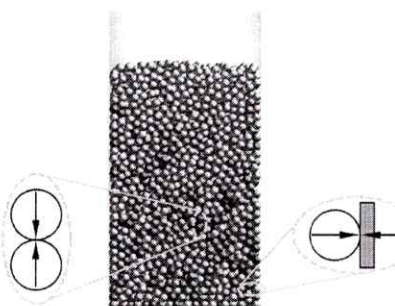


Figure 2. Contact force particle-particle, particle-wall

Under this directive, a vertical air-flowed cylindrical TES with a diameter of 17 m, a height of 15 m and filled with round gravel up to a height of 12 m shall be investigated. At the beginning, the analysis is performed on a reduced test geometry with enlarged particles. When charging (heating), air flows in top-down direction, while discharging (cooling) takes place with air flowing bottom-up.

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Firstly, a DEM model is created with EDEM in which expansion and the stresses caused by one loading and unloading cycle can be shown. After that, several cycles are taken into consideration. The planned calibration of the particle parameters is going to be discussed at the end.

2. ANALYTICAL CALCULATION OF THE PRESSURE

In order to achieve better comparability of the stress change, the occurring normal stresses are normalized. The hydrostatic pressure (1) on the one hand and the horizontal bulk pressure (3) on the other have been taken into account (see Figure 3).

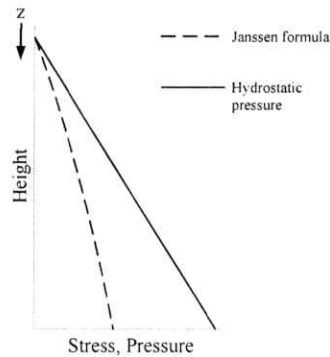


Figure 3. Hydrostatic and horizontal bulk pressure

The hydrostatic pressure is given in equation (1). z denotes the depth of the bulk material from top to bottom.

$$p(z) = p_0 + \rho_b \cdot g \cdot z \quad (1)$$

In bulk material, a stress $\sigma_{h(z)}$, which is smaller than the vertical stress $\sigma_{v(z)}$, occurs due to a vertical load in horizontal direction. This relation is referred to as stress ratio λ (2).

$$\lambda = \frac{\sigma_{h(z)}}{\sigma_{v(z)}} \quad (2)$$

The horizontal bulk pressure according to Janssen [2] can be calculated with (3) using the following relation:

$$\sigma_{h(z)} = \frac{\rho_b \cdot g \cdot A}{\tan \varphi_x \cdot U} \cdot \left[1 - e^{-\frac{\lambda \cdot \tan \varphi_x \cdot U \cdot z}{A}} \right] \quad (3)$$

According to Janssen, the results of the DEM simulation are divided by the horizontal pressure on the ground in order to achieve standardized values.

3. DEM MODEL

The DEM model is constructed with the classical Hertz-Mindlin model and an implementation for thermal expansion [3]. Before the bulk material undergoes thermal expansion, the content of the TES is filled and divided into n layers.

With the loading and unloading start time t_n of the individual layers, the thermal expansion of the particles can be regulated for each layer at any time. This allows to display the temperature distribution during the loading and unloading processes of the TES.

In reality, the bulk material filled into the heat storage expands or contracts depending on the change of temperature ΔT and the coefficient of thermal expansion α_p .

The scaling velocity v_s and the time step Δt are needed in order to compute the scaling factor ψ_s , which is then used to implement this effect in the DEM model. When the TES is getting charged, the term $v_s \cdot \Delta t$ is used positively in the equation. When the TES is discharging, it is used negatively.

$$\psi_s = 1 \pm v_s \cdot \Delta t \quad (4)$$

The scaling velocity v_s can be used to set the speed at which the particles are enlarged or reduced. For the diameter D_s to increase or decrease as a function of the temperature, the original particle diameter D_p is scaled with ψ_s (5).

$$D_s = D_p \cdot \psi_s \quad (5)$$

When D_{max} is reached at the maximum temperature, the enlarging process stops (6).

$$D_{max} = D_p \cdot (1 + \Delta T \cdot \alpha_p) \quad (6)$$

Finally, the number of loading and unloading cycles can be used to simulate several runs and thus to investigate whether the load changes during several cycles or not.

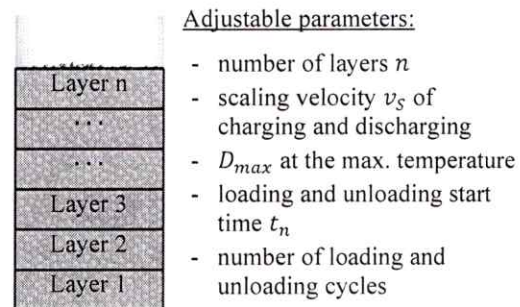


Figure 4. Structure of the DEM model with thermal expansion

Since the volume of the particles increases or decreases during the loading or unloading process, the particle mass also changes. This change in mass can be neglected because it is below 1%.

4. RESULTS OF THE DEM SIMULATION

In the simulation model a heat storage system with a reduced scale geometry of 1:10 was filled with crushed gravel, as calibrated material parameters are already available for it (properties see Table 1). Later on, the calibration for the bulk material that is actually going to be used (see Figure 8) must be carried out (see section 5). The walls are considered as rigid.

Table 1. Used properties

bulk material	geometry of the tank	number of particles	particle diameter
crushed gravel	D = 1,7 m H = 1,5 m	25.000	50 mm

Figure 5 shows the normal stress of the tank wall in the initial state (= before first heating) as a function of height (black line). Furthermore, the horizontal bulk pressure (grey dotted line) according to (3) and the hydrostatic pressure according to (1) are shown.

As you can see, the initial state matches the horizontal bulk pressure after Janssen quite well. As described in section 2, the normal pressure of the abscissa is plotted in a normalized manner (see Figure 6).

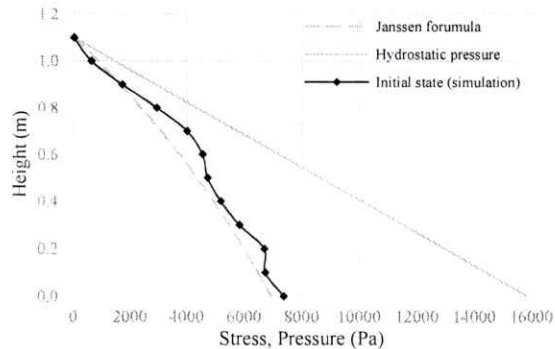


Figure 5. Normal stress in the initial state

Starting from the initial state in Figure 6, the heating of the bulk material leads to the resulting charging states 1 and 2. The line of the initial state shifts to the right with increasing loading and assumes higher stresses at any altitude (grey lines).

In charging state 1, the bulk material has already experienced a temperature change in the upper part. In the lowest layer, no temperature change has been observed yet. Therefore, the stress is the same as in the initial state. In charging state 2, the temperature has already been distributed over the entire height, but the final temperature has not been reached in the lowest layers yet.

At the end of the charging process, the load reaches its maximum (black line). When the heating is over, cooling starts. At the end of the discharge process, the horizontal pressure shifts to lower loads while unloading (black line). This shows that, after completion of the unloading process, the maximum load on the ground is slightly higher than at the beginning of the initial state.

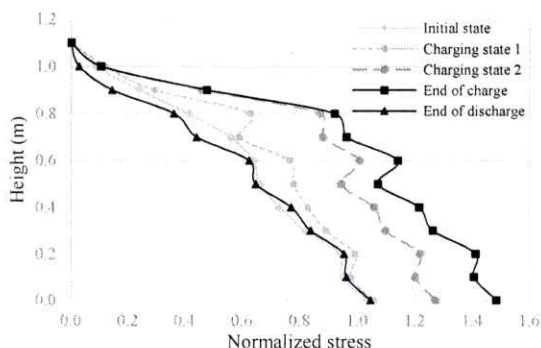


Figure 6. Normalized stress of charging and discharging

Until now, only one charging and one discharging process were considered. Furthermore, it is of interest whether the load changes in the course of several cycles or not. For this purpose, the maximum occurring

normalized horizontal pressure (normalized with the maximum horizontal pressure of Janssen) was plotted as a function of the number of loading and unloading cycles (see Figure 7). The upper line shows the maximum stresses at the end of the loading cycles ($T = 400^\circ\text{C}$) and the lower line the maximum stresses at the end of the discharging cycles ($T = 100^\circ\text{C}$). As the result shows and according to Janssen, the stresses increase to 1.5 times the horizontal pressure when loaded. With each further loading, the stresses increase only slightly.

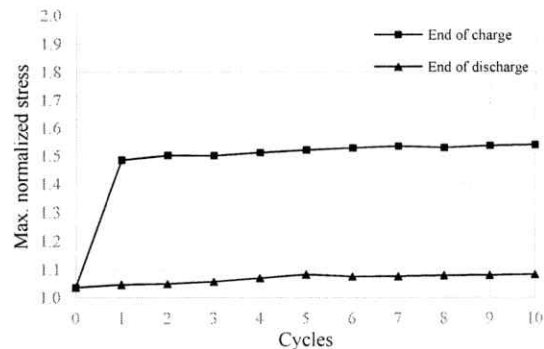


Figure 7. Multiple charging and discharging cycles

5. CALIBRATION

In order to finally use the correct material properties, the bulk material has to be calibrated. Despite the simplifications required for DEM simulation, a calibration of the bulk material parameters is necessary in order to map the bulk material behaviour correctly (see Figure 8).

These simplifications are in particular the spherical mapping of the grain shape as well as the increase of the particle size and the reduction of the particle stiffness. Thus, the computing time can be reduced considerably.



Figure 8. Bulk material (round gravel) to be calibrated

Although the simplifications mentioned usually apply to almost every DEM simulation, there is currently no standard calibration method. In most cases, the Angle of Repose (AoR) test is used for calibration. However, only one parameter in the form of this angle is considered in order to calibrate the friction parameters. To include more independent values for the determination of the two friction parameters, the draw down test according to [4] is used. Here, in addition to the AoR ($^\circ$), the mass flow (kg/s) and the remaining mass fraction (%) in the upper chamber are also measured.

In this project, a new device for calibration experiments according to [4] was developed and built in order to perform the planned draw down test (Figure 9).

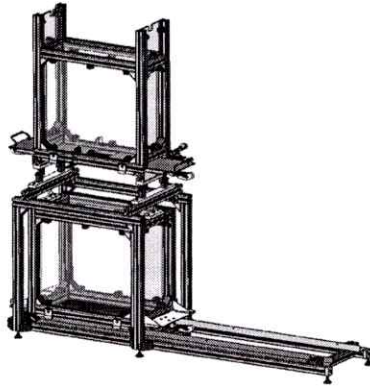


Figure 9. Calibration experiment device at KLFT, TU Wien

6. SUMMARY AND OUTLOOK

With the DEM model developed, influences of temperature effects in bulk material can be represented. The change of contact forces between the single particles and the change in the contact forces between the particles and the wall as a result of increasing and decreasing temperature play an important role in dimensioning packed-bed heat storage systems.

It is essential that the effects of several loading and unloading cycles - also known as thermal ratcheting phenomenon - are taken into account. As the investigations have shown, the load on the container walls increases with the number of cycles up to a maximum.

In further ongoing studies, the bulk material is calibrated with the draw down test. In order to validate the simulation results, experimental measurements must be carried out. Together with the IET, experimental investigations on bulk materials are carried out at the KLFT laboratory. Finally, the investigations will be transferred to the original heat storage geometry.

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NOMENCLATURE

A	Area of the thermal energy storage
D_{max}	Maximum diameter where the enlarging process stops
D_p	Original particle diameter
D_s	Diameter to increase or decrease as a function of the temperature
g	Acceleration due to gravity
n	Number of layers
$p(z)$	Hydrostatic pressure
p_0	Atmospheric pressure
t_n	loading and unloading start time t_n
U	Perimeter of the thermal energy storage
v_s	Scaling velocity
z	Depth of bulk material in thermal energy storage

Greek symbols

α_p	Coefficient of thermal expansion
λ	Stress ratio
φ_x	Wall friction angle
ψ_s	Scaling factor
ρ_b	Bulk density
$\sigma_{h(z)}$	Horizontal bulk pressure
$\sigma_{v(z)}$	Vertical bulk pressure
Δt	Time step
ΔT	Change of temperature