International Journal of Thermodynamics (IJoT)
ISSN 1301-9724 / e-ISSN 2146-1511
www.ijoticat.com

Vol. 18 (No. 1), pp. 54-58, 2015
doi: 10.5541/ijot.76797

Thermo-Mechanics in Packed Beds: Modeling and Design of High Temperature Heat Storage

V. Dreißigacker

DLR (German Aerospace Centre), Institute of Technical Thermodynamics,
Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
E-mail: volker.dreissigacker@dlr.de

Received 07 November 2014, Revised 08 January 2015, Accepted 24 January 2015

Abstract

Several novel power plant technologies, such as concentrating solar power (CSP) plants or adiabatic compressed air storage (ACAES), depend on heat storage systems as a central plant element. Where gaseous heat transfer media at elevated temperature levels are used, a regenerator-type heat storage is a particularly cost-effective solution. A large-scale design based on a packed bed inventory can further reduce investment costs, but is fraught with the risk of mechanical failures caused by the punctiform particle contacts. To be able to reduce such risks in a careful design, a simulation tool has been developed and successfully validated. It allows to predict the thermally induced mechanical loads during charge and discharge operation. As a calculation result, the model provides the time varying forces and displacements for each individual particle. The present paper outlines the underlying model equations and, by means of an illustrative example application, summarises the characteristic behaviour of such a setup.

Keywords: *Regenerator storage, packed bed storage, heat storage, thermo-mechanical model.*

1. Introduction

Many novel types of power plants use gaseous heat transfer media in a temperature range between 600 °C and 1000 °C. With increasing requirements on efficiency as well as temporal imbalances of supply and demand of electrical energy, large-scale heat storage becomes increasingly necessary. For applications with a gaseous heat transfer media, thermal regenerators are a suitable technology option and are used in some industrial processes today. A characteristic property is the direct contact between the fluid and storage inventory, allowing a charge temperature of up to 1300 °C.

Typical applications are concentrating solar power (CSP) plants [1, 2], adiabatic compressed air energy storage (ACAES) [3], fossil CHP power plants with improved operational flexibility [4] or industrial waste heat applications.

Today, the storage inventory is arranged as a stack of regularly shaped bricks of various shapes with bed height of up to 50 m [5, 6]. However, to reduce the inventory costs and to improve the discharge dynamics, a significant improvement is necessary. Thermal regenerators based on packed beds have the potential for such improvements. They offer a high thermal efficiency due the large specific heat transfer area as well as the potential to use low-cost materials, such as natural stones.

However, such a design of large-scale implementations is fraught with technical uncertainties with respect to mechanical aspects: The punctiform particle contacts may lead to high mechanical loads. This in particular during thermo-cyclic operation, when cyclic periods of bed expansion and shrinking tend to continuously increase the mechanical forces on the particles and the containment walls. As a result, material lifetime may be substantially reduced, eventually provoking a premature plant failure.

To tackle these risks, a suitable design tool considering the thermo-mechanical implications is needed. The following sections outline the model basis of such a tool and summarise the results of a calculation example.

2. Thermo-Mechanical Implications and Modelling

Thermo-mechanical models for packed beds fall into the categories of macroscopic and microscopic approaches. The former consider the packed bed as a continuum, described through constitutive equations. The model parameterisation depends on experimental investigations to derive the required continuum parameters, such as measured stress-strain curves [7].

In contrast, the microscopic approach as used in this work describes the mechanical behaviour of packed beds as an assembly of individual particles. Such a “discrete” model approach is given by the “discrete element method” (DEM) [8] and has gained interests in diverse applications, from molecular dynamics to particle processing [9]. As an advantage the stochastic nature of packed beds, such as randomly caused rearrangements, local force maxima, etc. can be reproduced. Coupled with a thermal model, the particle-discrete approach allows to calculate the thermally induced forces and the motion of individual particles during thermal operation.

In the following, the governing equations for the thermally extended DEM are outlined. Subsequently, a sample data set of specifications for power plant application is used for a large-scale dimensioning of a packed bed heat storage regarding thermal and thermo-mechanical aspects.

3.1. Mechanical Particle Model and a Thermal Extension

The thermo-mechanical approach describes the motions and displacements for each single particle over time and space applying a sequential calculation procedure of the thermal model followed by the discrete mechanical model. The model parts are coupled through an equation for the linear expansion of the particles.

The mechanical part of the coupled model treats the packed bed as an assembly of individual particles and is based on the fundamental correlations of the DEM [8]. Basic quantities are the particle coordinates $\vec{x}$, the particle velocities $\vec{v}$ and its rotational speed $\vec{\omega}$. The idea of the DEM is to sum up the acting forces over all contacts on each particle decomposed in normal and tangential direction, to obtain the velocities and positions at distinct time steps after integration Newton´s equations of motion. The contact forces are described by recoil, dashpot, friction models and a virtual compression at the contact location and constitute the right hand side of Newton's equations of motion.

$$m_i \frac{\partial^2 \vec{x}_i}{\partial t^2} = \vec{F}_i \tag{1}$$

$$J_i \frac{\partial \vec{\omega}_i}{\partial t} = \vec{M}_i \tag{2}$$

$$\vec{F}_i = \sum_{j=1,\, j\neq i}^{N} \left[\vec{F}_n^{ij}\left(\vec{x}_i, \vec{\omega}_i\right) + \vec{F}_t^{ij}\left(\vec{x}_i, \vec{\omega}_i\right) \right] + m_i \vec{g} \tag{3}$$

$$\vec{M}_i = \sum_{j=1,\, j\neq i}^{N} \left[r_i \vec{n}_{ij}\left(\vec{x}_i\right) \times \vec{F}_t^{(ij)}\left(\vec{x}_i, \vec{\omega}_i\right) \right] \cdot \tag{4}$$

Further details on the model, the model implementation as well as the experimental model validations can be found in [10, 11].

The time varying temperature field during thermal cyclic operation is calculated with a thermal model considering the packed bed as a heterogeneous porous medium [12]. With some simplifications and a normalisation of time and space, the one dimensional heat balances for the fluid and solid phase in axial direction can be written as:

$$\frac{\partial T_S}{\partial t^*} = \Pi \cdot \left(T_F - T_S\right) + \Psi \cdot \left(T_S - T_U\right) \tag{5}$$

$$\frac{\partial T_F}{\partial z^*} = \Lambda \cdot \left(T_S - T_F\right) \tag{6}$$

$$\Pi = \frac{k \cdot a_P \cdot \tau}{\left(1 - \varepsilon\right) \cdot \rho_S \cdot c_S} \tag{7}$$

$$\Psi = \frac{k_{Ins} \cdot a_{Ins} \cdot \tau}{\left(1 - \varepsilon\right) \cdot \rho_S \cdot c_S} \tag{8}$$

$$\Lambda = \frac{k \cdot a_P \cdot V_{ges}}{\dot{m}_F \cdot c_F} \tag{9}$$

This expression describes the temporal and spatial temperature distribution with only three dimensionless parameters and allows an efficient thermal calculation for identifying suitable design options. The total heat transfer coefficient k is defined by [13,14].

As a computational result, the time series of the thermally induced particle forces and particle displacements are obtained for each individual particle. However, a design process depends on calculated material stresses rather than forces. Therefore, as an additional step the material loads are determined with the help of a continuum-based mechanical contact model, using FEM techniques and the previously calculated forces as an input. Exemplarily, figure 1 below illustrates the tensile stress distribution inside the insulation layer and a contacting particle.

Figure 1. Spatial tensile stress distribution (rotational symmetry condition).

The maximum tensile stress is located at the surface of contact region due to the highest deformation. A comparison with material strength level then allows to elaborate and to assess options for critical design aspects, such as the interface of the particles with the thermal insulation.

3.2. Practical Application Example

For the dimensioning of a large-scale packed bed heat storage, a set of thermal specifications for a power plant is defined. It includes a maximum decrease of the storage outlet temperature during discharge, a maximum heat loss rate and a maximum pressure drop level. Dry air is assumed as the heat transfer medium and the inventory properties assume oxide ceramics in a spherical shape for the spherical inventory, and lightweight refractory for the insulation. Table 1 and 2 list the operating conditions and thermal specifications. Here, the packed bed porosity is set to a value of 0.4, the insulation total heat transfer coefficient to 0.5 W/m^{2}K, the particle density to 2400 kg/m^3 and the specific heat capacity to 950 J/kg K.

4. Results and Discussion

4.1. Thermal Design Results

Prior to the mechanical computations, an initial thermal design is needed. Table 3 lists the resulting design values of two sample design solution meeting the specifications defined in Table 2 above. The thermal results based on the numerical integration of equations (5) and (6) with (7) to (9) as input parameter are valid for a cyclic equilibrium, i.e. for the operation after repeated charge and discharge periods. The resulting spatial and temporal temperature curves are illustrated in figure 2 and 3 below.

Table 1. Thermal Operating Conditions.

p [bar]	1
T_{ch} [°C]	700
T_{dis} [°C]	120
T_U [°C]	20
τ_{ch} [h]	8
τ_{dis} [h]	8
$\dot{Q}_{th}$ [MW]	16

Table 2. Thermal Specifications.

Permitted temperature drop during discharging at the outlet [°C]	85
Heat lost relating to the cyclic stored thermal energy [%]	< 3
Pressure drop [mbar]	< 10

Table 3. Packed Bed Design Options.

Design option	#1	#2
d_P [m]	0.1	0.055
a_P [m^2/m^3]	36	65.1
H [m]	19.6	13.3
D [m]	10.5	11.5
m_S [t]	2500	1970
Δp [mbar]	6.9	6.2

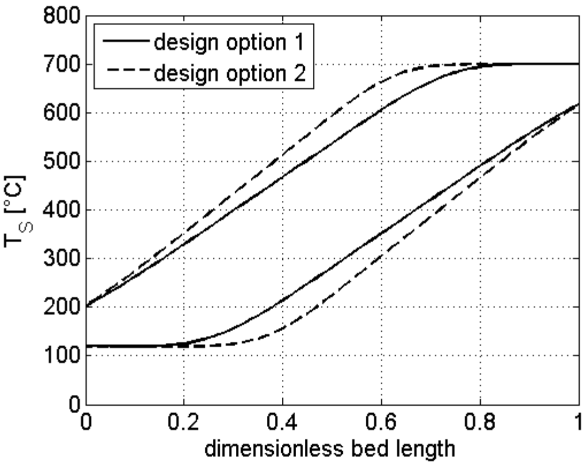

Figure 2. Spatial temperature profile at the end of charge and discharge.

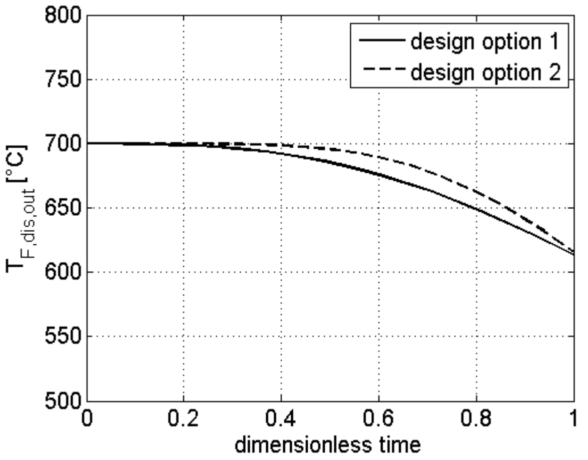

Figure 3. Temporal discharge outlet temperature.

Figures 2 shows the temperature profile at the end of charge and discharge for design option #1 and #2 in a cyclic equilibrium. The curve indicate a better thermal utilization of the storage mass with design option #2. This is due to the larger specific surface of the packed bed particles. Accordingly, a smaller inventory mass is needed to provide the specified storage capacity (see Table 3). Figure 3 shows the time variation of the outlet temperature during discharge for both designs. The curves confirm the permitted temperature drop of 85 °C with an outlet temperature of 615 °C at the end of discharge. Here, the increased thermal efficiency of design option #2 becomes visible as a slightly improved uniformity of the outlet temperature.

4.2. Thermo-Mechanical Results

For both design options, thermo-mechanical simulations have been run with the aim to determine the particle-wall contact loads. Firstly, an initial packed bed arrangement must be calculated for each design option. For this purpose a bulk of particles with randomly initialized locations is defined, and a mechanical simulation calculates the gravity-driven movement down into the containment until all particles have come to a standstill. Subsequently, the model equations in section 3.1 together with the parameters given in section 3.2 are solved numerically for a timespan of three thermal cycles. As a further step the particle-wall forces are used as input data to determine the contact stresses inside the insulation via the continuum based FEM contact model. As a result, the spatial and temporal distribution of the particle contact stresses is obtained.

Figure 4 below illustrates the time variation of the contact tension stresses inside the insulation layer for design option #1.

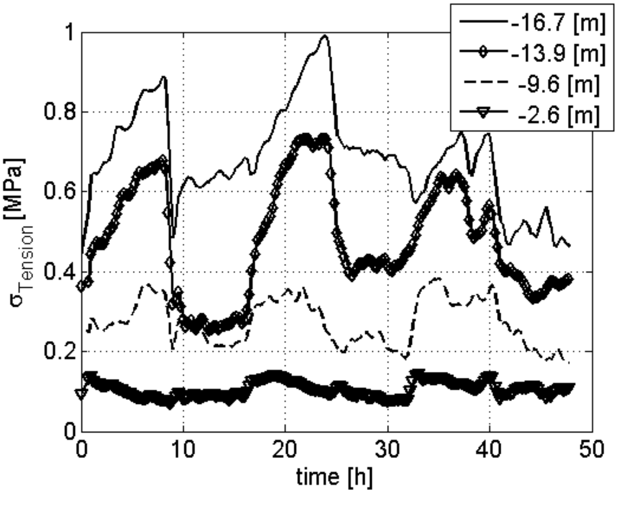

Figure 4. Temporal varying tension stresses for design option #1.

Due to the stochastic nature of the mechanics of the randomly distributed packed bed the curves show a noise-like scatter band. But still, the thermo-cyclic operation becomes well visible. The stress level inside the insulation layer increases during charging and decreases during discharging due to the cyclic expansion and shrinking of the particles. With increasing bed depths and thus higher static pressure, the bed´s ability to reduce thermally forces through particle displacements are increasingly hindered. Accordingly, the results show higher tension stresses towards the bottom of the storage containment. For design option #1 a maximum contact tension stress of 1 MPa is determined for a bed depth of 16.7 m.

Figures 5 and 6 illustrate the maximum values of the contact tension stresses in the insulation before and during thermal cycling for both design options.

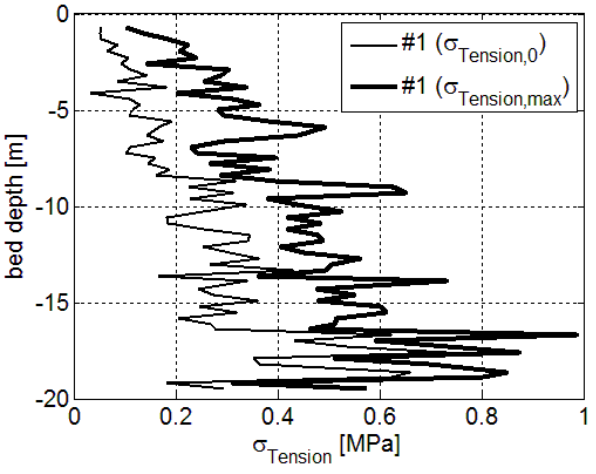

Figure 5. Spatial distribution of the tension stresses before (index 0) and the maximum (index max) during thermal operation for design option #1.

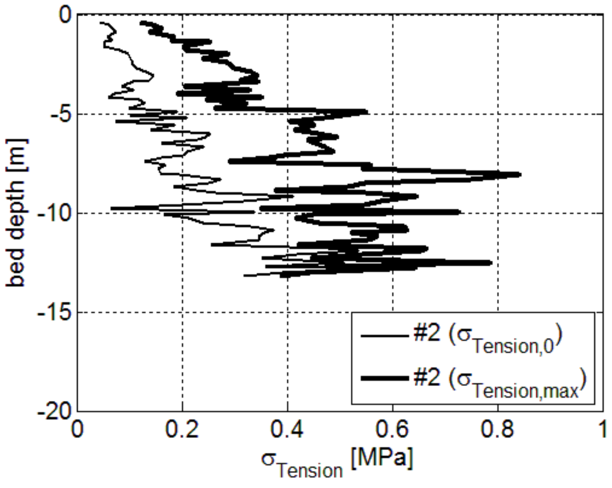

Figure 6. Spatial distribution of the tension stresses before (index 0) and the maximum (index max) during thermal operation for design option #2.

The graphs show similar curves and stress levels for both cases. After three thermal cycles, the contact tension stresses for design option #1 increase to values up to 1 MPa in a bed depth of 16.7 m, whereas for design option #2 up to 0.8 MPa in a packed bed depth of 5 m are reached. Compared to the initial stress values, this is an averaged increase by a factor of 2 for design option #1 and 2.5 for design option #2.

This higher ratio of increase is attributed to a larger temperature spread of the particles during the thermal cycling, favoured by their relatively larger specific surface, see figure 2. As in figure 4, the irregular shape of the curves reflects the stochastic nature of the underlying process.

For the considered cases, the resulting maximal tensile stresses fall below typical strength levels of clay-based refractories - in spite of their low tensile strength of about 1.5 MPa - 15 MPa [15]. Still, this relatively small stress level can be critical: these cycling mechanical loads may lead to the propagation of cracks inside the insulation and can be the cause for a decreased material lifetime. A lifetime analysis using the above results as an input is therefore a helpful further design step.

5. Conclusions

Regenerator storage based on packed has good prospects for a deployment in various novel power plant applications. The present paper tackles the challenges regarding a reliable mechanical design of a thermally cycled packed bed.

To this end, the model basis for a suitable simulation tool was developed. Previous experimental work has confirmed the validity of the results. The underlying particle-discrete model equations describe gravity-induced and thermally induced motions of each single particle, as well as the contact forces inside the packed bed and to the surrounding insulation and containment. A thermal extension of the mechanical model allows to predict the thermally induced particle forces. Further processing the results in a FEM-based contact model provides the material stresses.

The computational results of an illustrative example show varying contact stresses inside the insulation layer due to the cyclic expansion and shrinking of the particles during thermal operation. Here, for the considered cases with bed depths of up to 20 m, the maximal tensile stresses fall below typical strength levels. However, propagation of cracks inside the insulation layers as well as inside the particles caused by thermally induced loads may lead do decreasing durabilities and will be investigated in further design steps via suitable life time models.

Not only does the model allow an accurate prediction of the temporal and spatial behaviour of thermally cycled packed beds, but also gives a valuable insights into the underlying phenomena, including the stochastic nature of the process, such as local force maxima and minima, local rearrangements of particles etc. Hence, this modelling approach is considered an important step towards a reliable design basis for utility-scale implementations of packed bed storage.

The thermo-mechanical simulation tool will be used to design low stress packed bed design options in continuing works. Therefore, metallic liners as protection methods to homogenise the punctiform contacts forces on the insulation as well as particle size distributions to allow an increased bed deformation - thus lower bed stiffness - are two examples in further investigations. Additional thermo-mechanical simulation variations regarding material properties and containment shapes open up the potential to identify thermal efficient and durable packed bed arrangements.

Nomenclature

a	volume specific surface (m^2/m^3)
c	specific heat capacity (J/kg K)
d	particle diameter (m)
F	force (N)
g	gravitational acceleration (m/s^2)
J	moment of inertia (kg m^2)
k	total heat transfer coefficient (W/m^2 K)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
M	torque (N/m)
N	number of particles

r	particle radius (m)
t	time (s)
T	temperature (K)
V_{ges}	heat storage volume (m^3)
x	particle coordinates (m)
z	space (m)

Greek:

ε	void fraction
τ	charge/discharge duration (s)
ω	rotational speed (s^{-1})
Λ	reduced regenerator length
Π	reduced period duration
Ψ	reduced heat lost

Index:

F	fluid
i	particle i
Ins	insulation
j	particle j
n	normal direction
P	particle
S	solid
t	tangential direction
U	ambience

References

[1] S. Zunft, M. Hänel, M. Krüger, V. Dreißigacker, F. Göhring, E. Wahl, Jülich solar power tower – Experimental evaluation of the storage subsystem and performance calculation. *Journal of Solar Energy Engineering*, *133*, 1019-1023, 2011.

[2] S. Zunft, M. Hänel, M. Krüger, V. Dreißigacker, A design study for regenerator-type heat storage in solar tower plants – Results and conclusions of the HOTSPOT project. Energy Procedia, Elsevier, 19th SolarPACES Conference, Las Vegas (NV) USA, Sep. 2013.

[3] S. Zunft, M. Krüger, V. Dreißigacker, P. M. Mayer, C. Niklasch, C. Bertsch, Adiabate Druckluftspeicher für die Elektrizitätsversorgung – der ADELE-Wärmespeicher. Kraftwerkstechnik, Bd. 4, Seiten 749-757. TK Verlag. 44. Kraftwerkstechnisches Kolloquium, Dresden Deutschland, Oktober 2012.

[4] K. Stahl, S. Zunft, Entwicklung eines Hochtemperatur-Wärmespeichers zur Flexibilisierung von GuD-Kraftwerken. Kraftwerkstechnik, Bd. 4, Bd. 4, Seiten 777-784. TK Verlag. 44. Kraftwerkstechnisches Kolloquium, Dresden, Deutschland, Oktober 2012

[5] R. H. Turner, High temperature thermal energy storage. Philadelphia, Pa.: Franklin, 1978.

[6] R. L. Carl-Jochen, L. L. Sizmann, Vant-Hull: Solar Power Plants. Fundamentals, Technology, Systems, Economics, Springer-Verlag Springer, Berlin, 1991.

[7] J. Reimann, E. Arbogast, M. Behnke, S. Müller, K. Thomauske, Thermomechanical behaviour of ceramic breeder and beryllium pebble beds. *Fusion Engineering and Desgin*, *49-50*, 643-649, 2000.

[8] P. A. Cundall, O. D. L. Strack, A discrete numerical model for granular assemblies. *Géotechnique, 29*, 47–65, 1979.

[9] S. Masson, J. Martinez, Effect of particle mechanical properties on silo flow and stresses from distinct element simulations. *Powder Technology*, *109*, 164–178, 2000.

[10] V. Dreißigacker, H. Müller-Steinhagen, S. Zunft, Thermo-mechanical analysis of packed beds for large-scale storage of high temperature heat. *Heat Mass Transfer, 46*, 1199-1207, 2010.

[11] V. Dreißigacker, S. Zunft, H. Müller-Steinhagen, A thermo-mechanical model of packed bed storage and experimental validation. *Applied Energy, 111*, 1120-1125, 2013.

[12] I. KAR, Stuginsky R. A parametric study on possible fixed bed models for pcm and sensible heat storage. *Applied Thermal Engineering*, *19*, 757-788, 1999.

[13] H. Hausen, Wärmeübertragung im Gegenstrom, Gleichstrom und Kreuzstrom. Springer, Heidelberg, Berlin, 1950.

[14] F. W. Schmidt, A. J. Willmott, Thermal Energy Storage and Regeneration, New York: McGraw-Hill, 1981.

[15] W. Schulle, Feuerfeste Werkstoffe. Deutscher Verlag für Grundstoffindustrie, 1990.