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Thermo-mechanical analysis of pebble beds in HELICA mock-up experiments

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ABSTRACT

In this investigation, a thermo-mechanical model for pebble beds and a method for the identification of the material parameters, recently developed in Forschungszentrum Karlsruhe, are adopted for the analysis of HE-FUS3 Lithium Cassette (HELICA) mock-up. A pressure-dependent thermal contact conductance model to represent the pebble–wall interactions has been implemented in the FE code ABAQUS. First, the current material model has been verified by uniaxial compression and creep experiments under a wide range of temperature fields, and good agreement between experiments and theory has been achieved. The HELICA mock-up has been modelled by 2D generalized plane strain elements, and analyzed in ABAQUS. The results show that the temperature and mechanical fields obtained in FE analysis agree well with the measurements by thermo-couples and LVDTs located at different positions.

1. Introduction

In helium cooled pebble bed (HCPB) blankets, pebble beds work as breeder (i.e. lithium orthosilicate) and neutron multiplier (beryllium) materials. The pebble beds are not only subjected to extreme conditions, such as neutron irradiation and high heat flux, but also have complex behaviour due to their discrete nature. Therefore, a constitutive model is necessary for predicting the thermo-mechanical behaviour of pebble beds [1] and the pebble bed–container interfaces under fusion-relevant conditions. As a benchmark exercise for validating different models proposed by different EU parties (ENEA [2], NRG [3] and FZK), HELICA mock-up experiment has been carried out at HE-FUS3 facility in ENEA Brasimone [4].

In the framework of continuum mechanics, there are different material models describing the thermo-mechanical behaviour of granular materials, among which, the modified Drucker–Prager–Cap model, consisting of a shear failure surface and a cap surface, can be adopted in fusion-relevant analyses of pebble beds [5–7]. For interface regions, friction between pebbles and the container wall can be taken into account by the Coulomb law, and the heat transfer coefficient can be determined as a function of local temperature and pressure [8–10]. With the appropriate constitutive model of both bulk materials and interfacial regions, it is possible to study the thermo-mechanical behaviour of pebble beds by the finite element method.

This paper has been organized as following. The constitutive model of pebble beds, describing behaviour of the bulk material and interfacial regions, is briefly introduced in Section 2. In Section 3, HELICA mock-up experiment has been simulated as a thermo-mechanically coupled problem. The finite element results are compared with the experimental data. And a few conclusions are drawn in Section 4.

2. Constitutive modelling of pebble beds

2.1. Material model

The present material model is mainly based on the modified Drucker–Prager–Cap theory, which is one of the most popular constitutive models for granular materials. The yielding surfaces in Drucker–Prager–Cap theory are sketched in Fig. 1, being composed of a shear failure surface and cap surface [11]. Details about the material parameters can be found in [6]. In Fig. 1, a unit cell of pebbles has been schematically drawn for demonstrating the behaviour of the material while the yield/failure mechanism is active. The recoverable deformations have been described by a non-linear elasticity law, depending on hydrostatic compressive stress p and von Mises stress q. Time-dependent behaviour has been accounted for by a consolidation creep law. The material parameters can be identified from uniaxial compression and creep experiments by a method proposed in our previous work [6].

The material model and the identification method have been implemented in commercial finite element package ABAQUS by user-subroutines. For the ceramic pebbles filled into HELICA (with diameters between 0.2 and 0.4 mm [12]), uniaxial compression and

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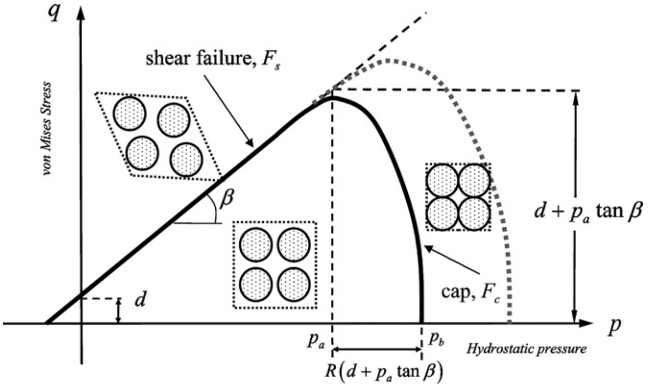

Fig. 1. Modified Drucker–Prager–Cap model. A unit cell shows the schematic configurations under different loading conditions.

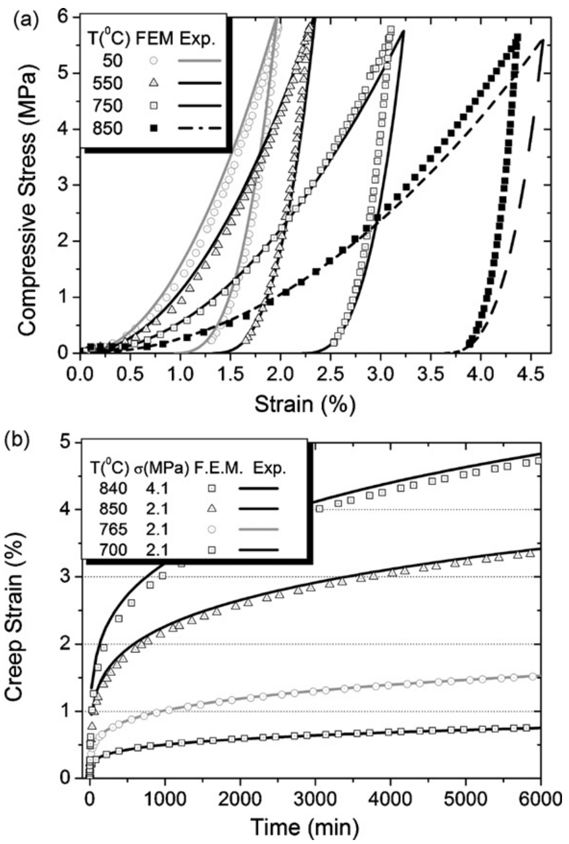

Fig. 2. (a) Uniaxial compression of lithium orthosilicate under 50–850 °C: dots, prediction of FEA; lines, empirical curves. (b) Creep tests of lithium orthosilicate under different compressive stress and temperature, comparison between FEA (dotted lines) and empirical curves (solid lines).

creep experiments have been simulated for validation purposes, see Fig. 2. The comparison shows that the prediction of the present material model coincides well with the empirical curves [12] over a wide temperature range. In the framework of the present material, the temperature effects on plasticity are represented, by introducing temperature-dependent empirical relations instead of tuning the material parameters, i.e. hardening data, at different temperature levels on a trial and error basis.

2.2. Interface model

In the interfacial regions at the container wall, the mechanical interaction can be modelled by the Coulomb friction law, assuming the pebble beds to be a continuous medium. The friction forces present near the wall regions have a significant effect on the overall behaviour of the pebble layer, due to the fact that the pebbles behave irreversibly under certain shear stresses.

The interfacial heat transfer includes the solid contact heat transfer, as well as gas gap conduction and thermal radiation. Since radiation is ignorable compared with the other factors, the heat transfer coefficient (HTC) depends on both contact area and the gas gap features. These two mechanisms for heat transfer are in parallel, and the overall HTC can be expressed as $h = h_s + h_g$. The first term on the right-hand side is the solid spot thermal conductance [9], depending on the contact pressure of the interface

$$h_s = 2nak.$$

Here, a is the radius of each contact spot and can be calculated by Hertzian solution as a function of contact pressure, n is the density of the contact spots at the interface, and $k = 2k_1k_2/(k_1 + k_2)$ is the harmonic mean of the conductivities, where subscripts 1 and 2 stand for wall and pebble's bulk materials. The second term h_g is the effect of the gas gap, which depends on the type of the interstitial gas (purged helium in this study), the topology of the near wall packing [13] and the temperature of the gas.

3. Thermo-mechanical analysis and results

3.1. Description of the FE model

The HELICA mock-up is filled with breeder ceramic pebbles (Li_4SiO_4) and heated by two electric heaters located inside the breeder cell to reproduce the designed temperature increase of pebble beds. The breeder cell filled with the pebbles is divided into three sub-cells, 446 mm in width, 192 mm in depth and 4.6 mm in thickness [4]. Thermo-couples (TCs) are placed at different positions, 55/100/150 mm to the first wall (FW), and six LVDTs measure the deformation of the steel cassette during operation. Considering not only the ratio of the width to the thickness of the cassette, but also the similar loading conditions along the width, a 2D generalized plain strain model has been used in this investigation. The out-of-plane deformation is set to be identical to the one caused by

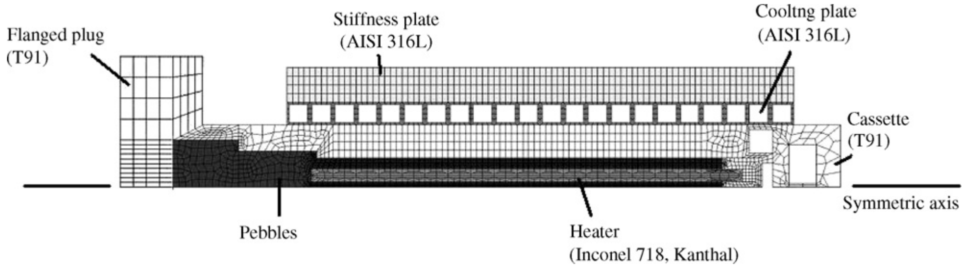

Fig. 3. FE model of HELICA mock-up. The components are shown in different parts.

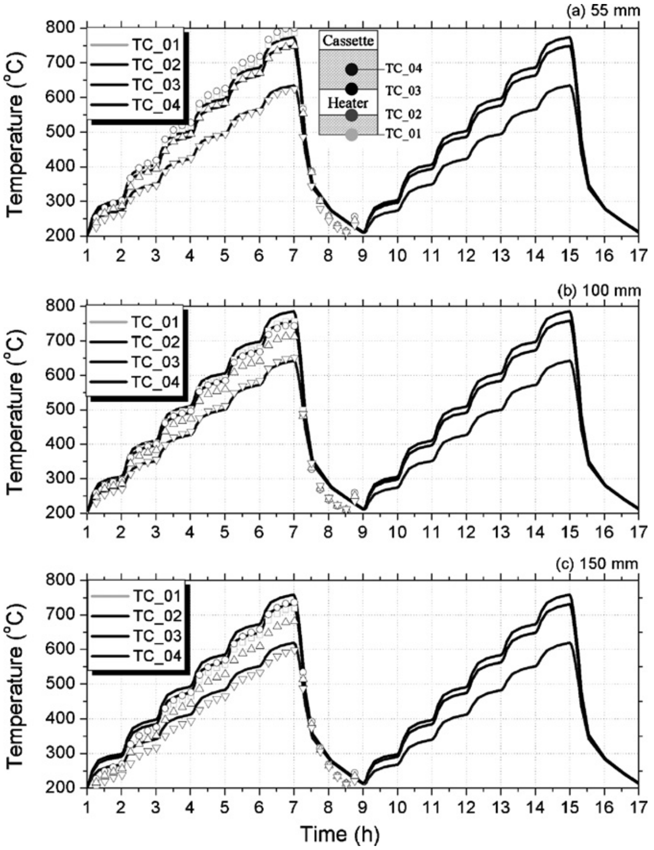

Fig. 4. Temperature over time during two loading cycles: (a) 55 mm; (b) 100 mm; (c) 150 mm. Dots, experimental data; solid lines, FE calculation (unit: °C).

thermal expansion of the cassette. Despite the fact that the helium temperature varies along the cooling channel, here we take the helium temperature at the middle cross-section as the reference value, since the structural materials have higher thermal conductivities than the one of helium and hence are less sensitive to the variation of the helium temperature. Furthermore, the geometric symmetry of the model has been taken into account for reducing the size of the FE model, by applying the symmetry mechanical and thermal boundary conditions to this plane. Fig. 3 shows the geometric model of HELICA with the finite element meshes, based on the IGES-file provided by ENEA, and different components and materials are shown in different parts. The materials database used in this analysis is provided by NRG [14] and the data of ceramic breeder pebble beds are taken from experiments in FZK [12]. The electrical heater generates a surface heat flux of 42 kW/m^2 in six 1-hour subsequent steps. The stiffness plate is pressed with the magnitude of 0.09 MPa. A forced helium flow in the channels of the cooling plate has an initial inlet temperature of 200 °C. The helium temperature increases in the range of 200–300 °C during the heat-up operation. The surface of the mock-up is surrounded by air at the room temperature.

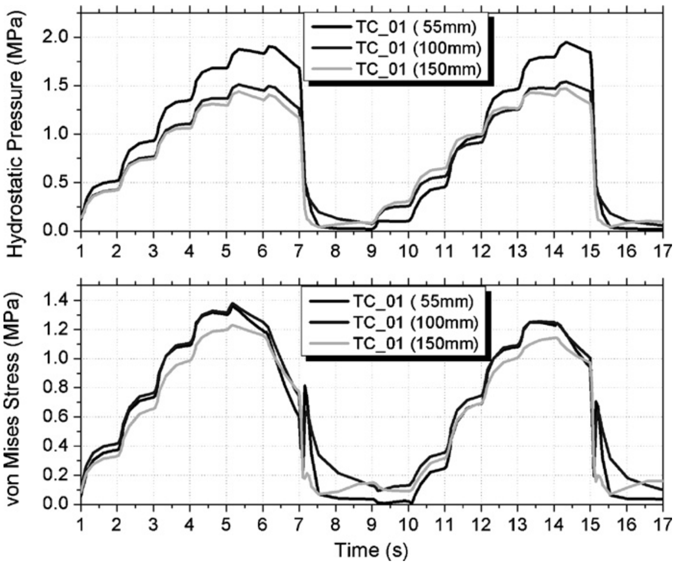

Fig. 6. Stresses over time during two cycles: top, hydrostatic pressure; bottom, von Mises stress (unit: MPa).

3.2. Temperature field in HELICA

Two cycles of loading have been simulated using the present material model for pebble beds. Fig. 4 shows the comparison between the measured value and the predictions. The experimental data are taken from one typical cycle during the cyclic loading in experiments. The locations of the TCs along the thickness are sketched in a small plot in Fig. 4(a). The prediction underestimates the temperature at 55 mm (the maximum difference within 15 °C), while it overestimates the ones at 100 and 150 mm (the maximum difference within 30 °C). For this simplified FE model, the heat flux generated by the heater and the temperature of the coolant are assumed to be independent of the positions, while in the mock-up experiment they are varied by several factors. For instance, the helium temperature inside the cooling channels could be position-dependent along the width of the cassette. The calculated value of the second cycle has also been plotted out to show cyclic effect. In this investigation, the cyclic effect on the temperature changing is ignorable. The temperature distribution at the maximum heating is shown in Fig. 5, with the deformed configuration. The maximum temperature in the pebbles is located in the middle layer of the breeder cell, and reaches close to 800 °C.

3.3. Mechanical field in HELICA

In the coupled thermo-mechanical analysis, the mechanical field, as well as the temperature field, has been obtained. The mechanical field is important in the analysis of pebble beds, due to the fact that not only thermal and mechanical fields are coupled, e.g. the effective thermal conductivity depends on the average contact area of pebbles and the number of contacts, but also the stress con-

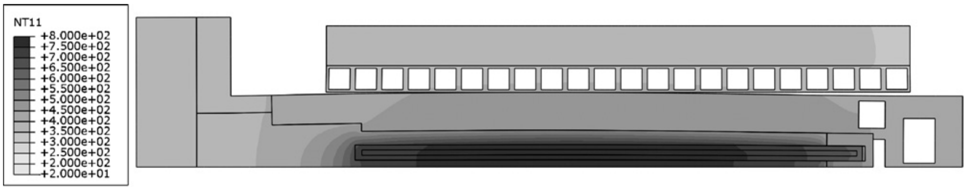

Fig. 5. Calculated temperature distribution at the maximum electrical load (unit: °C), with deformations at a scale factor of 5.

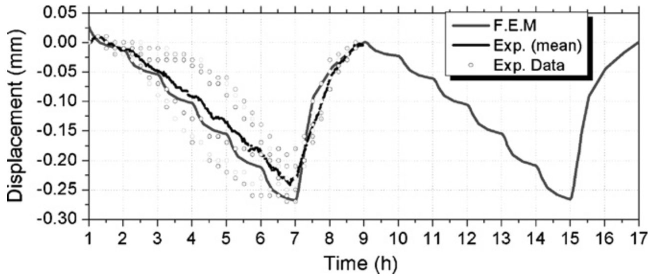

Fig. 7. Displacement of HELICA (unit: mm), comparison between LVDTs' measurements (scattered dots) and calculated value (the solid line).

centration may cause crush of pebbles during the operation. Fig. 6 shows the calculated hydrostatic pressure and von Mises stress at the locations of the TCs along the symmetric axis during the two loading cycles. In each cycle, there are obvious decreases of the stresses at the fifth and sixth loading steps, and this behaviour is caused by the creep at relative high temperature. The main reason for this phenomenon is the re-configuration of the local packing structure of pebbles. The friction forces and the thermal expansion of the heaters are present in this analysis, and it turns out to push the pebbles against the FW. Therefore, the value of hydrostatic pressure at 55 mm to FW is higher than the ones at 100/150 mm. The hydrostatic pressures during unloading reaches almost zero, but no tensile stress is present, which is consistent with the nature of non-cohesive granular materials. Differences between two loading cycles can be observed but they are not notable.

One node of the FE model, where the LVDT is located, is monitored during the calculation. Fig. 7 shows the comparison of the experimental data and predictions. These two sets of data are offset by the displacement obtained at the beginning of the second cycle, in order to provide representative results instead of the irreversible deformation during the first starting cycle. The cyclic effects achieve saturation at the end of the second cycle, in Fig. 7. Considering the scatter of the measurements, the finite element analysis gives a reasonable prediction.

4. Conclusion

In this investigation, the recently developed material model and the parameter identification method have been adopted to the thermo-mechanical analysis of HELICA mock-up. At interfacial regions, a model describing the mechanical and thermal interactions has also been implemented. Using the finite element method, a two-cycle loading has been simulated, in order to investigate not only the response at the maximum loading, but also the cyclic effects. The FE calculation is compared with experimental data, including the temperature and displacement measurements. The reduction of stress increases caused by creep deformation has also been observed at high temperature regions. A 3D analysis will provide more details of this mock-up experiment, but the problem remains mainly in the computational scale, rather than verification of the material model. The present work shows the feasibility of the simulation of large-scale experiments, and the capability of the structural analysis to take into account the special features of pebble beds.

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