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Cyclic behavior of ceramic pebble beds under mechanical loading

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ABSTRACT

Uniaxial compression test (UCT) experiments were conducted along with Discrete Element Method (DEM) simulations. The objective was to investigate the effect of the material properties and of the blanket operational parameters (in terms of packing factor, pebble material/size, compressive load and bed height) on the mechanical response of breeder beds subjected to cyclic loading. UCTs were performed with the EU advanced and reference ceramic breeder materials. To investigate the wall effects on the cyclic response of packed beds, a parametric study was performed varying the bed height to pebble size ratio (H/d). To this end monosized commercial zirconia pebbles with different sizes were also used. The numerical experiments were carried out with the KIT-DEM code on pebble assemblies using mixed boundary conditions (periodic and rigid planes). The influence of the bed height, pebble size and pebble material were systematically evaluated to gain an insight about their influence on the macro and micro response of the beds. Thanks to the microscale numerical modelling the macroscale response is presented together with the micro response at the pebble scale. Good agreement was found between experiments and simulations and thus, the KIT-DEM was confirmed to be a reliable predictive tool for the study breeder bed related problems.

1. Introduction and review of the state of the art

Lithium-based ceramics, in the form of packed-pebble beds, were selected as tritium breeder in the solid breeder blanket concepts [1,2]. The qualification of the breeder material for blanket application is required to demonstrate acceptable performances under fusion relevant conditions, this includes the characterization of their thermo-mechanical behavior. A blanket module will experience a cyclic loading due to the burn pulses of the plasma, temperature gradients and a mismatch of the thermal expansion coefficients between the beds and the structural materials results in a cyclic compressive load acting on the breeder beds. Pebble beds show a rather complex thermo-mechanical behavior due to the discrete nature of the individual pebbles. Laboratory investigations along with microscale numerical modelling, e.g. using Discrete Element Method (DEM), can produce full insight into the complex mechanical behavior of the packed beds relating the macroscopic response with the microscopic interactions at the pebble scale.

The Uniaxial Compression Test (UCT, or oedometric compression test) was extensively used to characterize the mechanical response of breeder beds. Several UCT experiments have been carried out by using different facilities and types of pebbles [3–11]. The mechanical behavior of the pebble beds is characterized by nonlinear elasticity accompanied by an irreversible residual strain after the first unloading. This is caused by a significant pebble rearrangement during the first cycle that leads to a densification of the bed. When the bed is subjected to cyclic loading, the largest part of the irreversible residual strain is generated during the first few cycles [11]. Then the compaction of the bed is still progressing, but with smaller increments as the cycling proceeds. This progressive compaction behavior should be quantified in order to effectively control and manage the gap formation that may result in isolated heating zones of breeding zones during operation.

The mechanical behavior of pebble beds can be modelled by either the Discrete Element Method (DEM) or a continuum approach. In the continuum approach a set of phenomenological constitutive equations, based on the effective properties of the beds, are implemented in a Finite Element code to simulate the mechanical behavior of the beds [12]. In the DEM approach, introduced by Cundall and Strack [13], each particle defined by its radius (for spherical particles), mass, physical and mechanical properties, is considered individually. The contact law between particles defines the inter-particle normal and tangential forces. By solving the equations of motion for each single particle composing the assembly and homogenizing the microscopic interactions between the constituent particles, the macroscopic behavior of the granular assembly is derived. DEM has been widely adopted to study the thermomechanical response of breeder pebble bed assemblies. A

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comprehensive survey about the status of ceramic breeder materials thermomechanics R&D can be found [1,14]. The use of DEM for fusion related applications was started by the researchers of University of California Los Angeles (UCLA), who firstly used a DEM approach to study the micromechanics of breeder beds [4,15]. In their following works [16,17], pebbles were packed in cuboidal and cylindrical assemblies confined by elastic walls made of steel and compressed in the axial direction, the stress strain response as well as the internal contact forces were investigated. Assemblies consisting of monosized spherical pebbles (diameter of 1 mm) with an initial packing factor (PF) of 60 ± 0.5% were studied. In their more recent works an open-source DEM code was employed to study the uniaxial compression of monosized packed assemblies with periodic boundary conditions [18] and the thermomechanics of breeder beds experiencing pebble failure [19]. In [18] a modified and randomly distributed young modulus was assigned to the pebbles according to experimental outcomes. An estimation of the percentage of crushed pebbles has also been made.

At Karlsruhe Institute of Technology (KIT) an in-house DEM code was developed by Gan and Kamlah [20]. The original KIT-DEM code was extended by Zhao et al. and Annabattula et al., who implemented the possibility to simulate polydispersed [21] and crushable [22–24] assemblies. Recently the development of the KIT-DEM code has been restarted. The code was further extended to study the bulk behavior of assemblies composed of ellipsoidal particles [25]. The KIT approach [20,21,24,25] was to simulate periodic cubic assemblies of randomly packed pebbles in periodic configuration and under periodic boundary conditions. Doing that, the mechanical response of the bulk of the assembly is represented and wall effects are avoided. The assemblies were generated using a Random Close Packing (RCP) algorithm [26]. The KIT-DEM code was successfully used in previous studies [20,21] to investigate the mechanical behavior of monosized, binary and polydispersed pebble assemblies. The influence of the initial PF [20] and the friction coefficient [21] were investigated as well. Since the previous studies were focused on the first loading/unloading cycle, no repeated cycles were simulated. The characteristic mechanical behavior of granular assemblies subjected to uniaxial compression was accurately reproduced by the DEM simulations. The initial PF as well as the friction coefficient was found to have a profound influence on the mechanical response of the assembly. The monosized assemblies were characterized by a stiffer behavior than binary and polydispersed assemblies. In particular, for an initial PF of approx. 64%, a negligible residual strain was found for monosized assemblies while a residual strain was observed for polydispersed beds.

With application to breeder beds, an ample literature regarding the micromechanics of ceramic beds subjected to a single loading/unloading cycle exist. However, numerical and experimental studies on granular beds undergoing cyclic mechanical loading are comparatively rare. The available experimental and numerical studies [11,16,27] and very recently [28–30] show that cyclic loading leads to a progressive compaction of the bed, resulting in an increase of the effective bed stiffness [16,28,29]. Initially a large volume reduction occurs during the first few cycles, then the compaction saturates as the cycling proceeds. The average and maximum normal contact forces were found to decrease to some extent with cycling, while the coordination number and effective elastic moduli increased [29,30]. In [11], beside the UTC experiments, FEM simulations were carried out as well to study the coupled thermomechanical problem of the HELICA mock-up experiment. A main outcome was that the cyclic thermal stress peaks acting on breeder pebble beds are relaxed, to then saturate after few thermal cycles, due to the pebble bed volume reduction. The DEM numerical studies [16,28] refer to monosized pebble assemblies bounded by elastic walls with an initial packing factor of about 60%. The number of compressive load cycles was limited to few cycles. In the recently published studies [29,30], a commercial DEM code was used to study the cyclic behavior of packed assemblies subjected to uniaxial compression with a considerable number of cycles (about 80). In [29] the influence of sphericity, size distribution and friction coefficient between pebbles on the cyclic behavior of packed beds was assed. The assemblies were uniaxially compressed with both target stress [29,30] and strain [30]. Mixed boundary conditions were used and the initial packing factors varied in the range 60–62%. The simulated pebble size was 1 mm while, when simulated, a very narrow Gaussian size distribution (0.9–1.1 mm) and high sphericity (0.95) were used. The numerical studies [16] [28–30], refer to packing factors actually below the reference value for the solid breeder blanket (BB) concept. Furthermore, in the EU solid BB concept in view of the production process [31], polydispersed beds are used.

This present paper extends an earlier study [32] where DEM simulations were compared with laboratory experiments to gain a preliminary insight on the influence of the cyclic compressive load. In the present study dedicated UCT experiments were performed with both breeder materials and commercial zirconia pebbles to investigate their mechanical response under cyclic loading. To study the wall effect on the cyclic response of packed beds a parametric study was performed varying the bed height to pebble size ratio (H/d). In parallel, numerical simulations were carried out with the KIT-DEM code on pebble assemblies using mixed boundary conditions (periodic and rigid planes). The results of the two approaches, experimental and numerical, were compared. The influence of the bed height, pebble size and pebble material was systematically evaluated to gain insight on the effect of the pebble properties and the blanket operational parameters on the mechanical response of breeder beds subjected to cyclic loading. To provide a representative result for the EU BB, blanket relevant conditions in terms of PF, pebble size, compressive load, bed height and boundary conditions were used. Besides the comparisons between DEM simulations and experiments, rarely reported in literature, this work expands the very limited existing literature about cyclic behavior of breeder beds subjected to mechanical loading.

2. Experiments

The Uniaxial Compression Test (UCT) is one of the few experimental options to get representative parameters of compressed granular materials. Even if differences between the UCT experiment and the real use of the breeder material in the blanket exist, the UCT experiment is one of the very few opportunities to investigate the complex mechanical behavior of granular beds. In UCTs the pebbles, contained in a cylindrical container, are compressed in the axial direction. The bed axially deforms under the applied load while the lateral deformation is inhibited by the container. The stress strain response of the bed is used to characterize its mechanical behavior. Fig. 1 shows a schematic view of the employed oedometer test cell. It consists of a cylindrical measuring cell ①, made of Hastelloy X, of 55 mm inner diameter with a stainless steel disk ② placed in the bottom part. The thickness of the disk can be varied to change the experimental H/D ratio, where H and D are the bed height and diameter, respectively. In the UCT, in order to assure that the mechanical response of the bed is governed by the bulk behavior of the bed, the dimensions of the cylindrical container should be much larger than the diameter of the single pebbles, d. In this study the diameter of the container was kept constant (55 mm) while the bed height was varied to study the influence of the wall effects on the cyclic behavior of ceramic pebble beds. A diameter of 55 mm was considered to be large enough in relation to the maximum diameter of the studied pebbles of 1.2 mm.

Both the EU reference (EU Ref.) and advanced (ACB) tritium breeding materials were investigated. The two materials differ in the chemical composition of the bulk material, the production process and the pebble size distribution. The EU Ref. material consists of about 90 mol% lithium orthosilicate (Li_4SiO_4) and 10 mol% lithium metasilicate (Li_2SiO_3) while the ACB material consist of about 70 mol% Li_4SiO_4 and 30 mol% lithium metatitanate (Li_2TiO_3). The EU Ref. and ACB materials were produced by the melt-spraying process [33] and a melt-based method [34,35], respectively. This results in a difference of the