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Ceramic breeder pebble bed packing stability under cyclic loads

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HIGHLIGHTS

- The feasibility of obtaining packing stability for pebble beds is studied.
- The responses of pebble bed to cyclic loads have been presented and analyzed in details.
- Pebble bed packing saturation and its applications are discussed.
- A suggestion is made regarding the improvement of pebbles filling technique.

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ABSTRACT

Considering the optimization of blanket performance, it is desired that the bed morphology and packing state during reactor operation are stable and predictable. Both experimental and numerical work are performed to explore the stability of pebble beds, in particular under pulsed loading conditions. Uniaxial compaction tests have been performed for both KIT's Li_4SiO_4 and NFRI's Li_2TiO_3 pebble beds at elevated temperatures (up to 750 °C) under cyclic loads (up to 6 MPa). The obtained data shows the stress-strain loop initially moves towards the larger strain and nearly saturates after a certain number of cyclic loading cycles. The characterized FEM CAP material models for a Li_4SiO_4 pebble bed with an edge-on configuration are used to simulate the thermomechanical behavior of pebble bed under ITER pulsed operations. Simulation results have shown the cyclic variation of temperature/stress/strain/gap and also the same saturation trend with experiments under cyclic loads. Therefore, it is feasible for pebble bed to maintain its packing stability during operation when disregarding pebbles' breakage and irradiation.

1. Introduction

Previous research on ceramic breeder pebble beds has revealed that thermally induced stress can cause packing changes and volume reduction of pebble beds, and thereafter allow pebble bed/wall separation [1–4]. Gan and Kamlah reported that gap formation is found at the interface of the FW in the middle sub-cell of the ceramic pebble layer, and the widths of the gaps are mainly in the range of 0.25–0.38 mm [3]. A deteriorated pebble bed/wall contact due to bed packing change may result in a significant decrease of heat transfer between pebble bed and wall, and increased temperatures in regions of the pebble bed [4].

However, very little work on the packing stability of pebble beds is available. Therefore, both experimental and numerical studies are performed to explore the packing stability for pebble beds, in particular under ITER-like pulsed operating conditions. This preliminary work identifies the stable regimes of pebble bed's packing with respect to operating temperature and compressive stress levels when ignoring the effects of pebbles' breakage and irradiation.

2. Uniaxial compaction tests

Since ITER operating condition has a pattern of pulsed plasma-on/–off, the pebble bed mechanical behavior has been experimentally explored as a function of uniaxial loading-unloading cycles. Cyclic uniaxial compaction tests are performed on both KIT's Li_4SiO_4 (d = 0.25–0.6 mm; 3% porosity; 61% P.F.) and NFRI's Li_2TiO_3 (d = 1.0 mm; 10% porosity; 63% P.F.) pebble beds at elevated temperatures (up to 750 °C) under cyclic loads (up to 6 MPa). The initial height of pebble bed is about 15 mm. The axial stress/strain loops have been obtained and analyzed in details.

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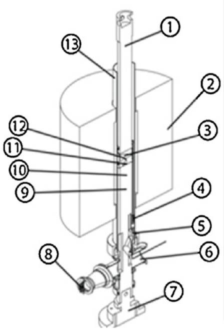

Number	Item Name
1	Upper piston
2	Heater
3	Sample
4	LVDT probe tip
5	LVDT sensor
6	Vacuum inlet
7	50kN load cell
8	Sensor cable vacuum seal
9	Lower piston
10	Thermocouple #1
11	Thermocouple #2
12	Thermocouple #3
13	Quartz tube

Fig. 1. Diagram of UCLA's uniaxial compaction/creep testing facility.

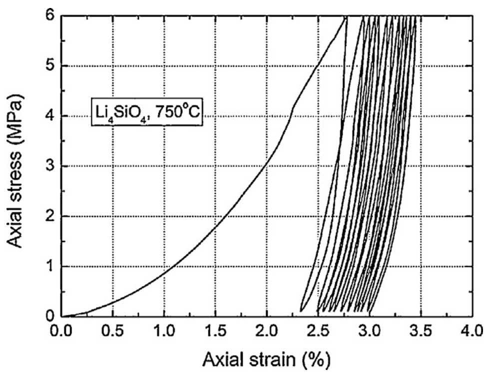

Fig. 2. Axial stress-strain loops of Li_4SiO_4 pebble bed at 750 °C, 6 MPa and 12 cycles.

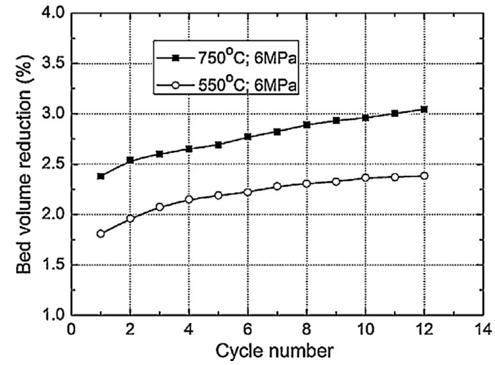

Fig. 3. The volume reduction of Li_4SiO_4 pebble bed varying with cycle number at 750/550 °C and 6 MPa.

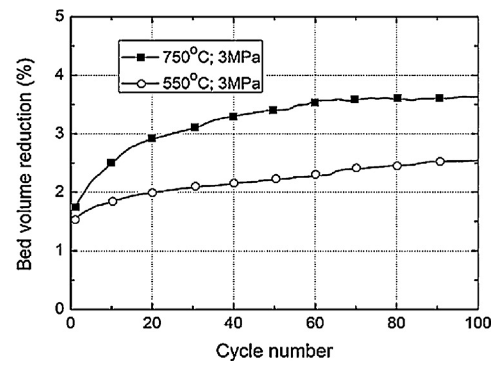

Fig. 4. The volume reduction of Li_4SiO_4 pebble bed varying with cycle number at 750/550 °C and 3 MPa.

2.1. Experimental setup

UCLA's facility, shown in Fig. 1, employs a uniaxial/creep test stand (Zwick, Kappa 50 DS) and 3-zone furnace (Max. 1200 °C) for pebble bed mechanical testing. A 50 kN load cell is used for force measurement. A high-temperature LVDT sensor (Max. 230 °C operation temperature) is used to measure the sample region deformation. To eliminate the error from piston's thermal expansion, the LVDT sensor and probe are mounted at the cup containing the pebble bed and bottom of the top piston. Pebbles are packed in a cup with 46.5 mm internal diameter, which sits on the lower piston and are compressed/decompressed by the upper piston with a constant rate of 1 MPa/min. Both the cup and pistons are made of Inconel 718 due to its excellent mechanical strength at high temperatures. Thermocouples are placed underneath the cup and on the lower piston to monitor temperature profile and distribution. A quartz tube is sealed on the top and bottom pistons to provide a vacuum environment.

2.2. Experimental results

Fig. 2 illustrates the typical pebble bed stress-strain behavior under cyclic uniaxial compressive loads. The axial strain value represents the permanent volume reduction of pebble bed when the unloading process is completed. Major volume reduction is generated during the initial few cycles, e.g., 2.5% for the first 2 cycles at 750 °C/6 MPa, which is attributed to pebble rearrangements. Subsequent cycles continue to result in bed volume reduction with smaller increments, e.g., only 0.5% more for the next 10 cycles combined. For the test at 550 °C/6 MPa, pebble bed has a smaller volume reduction of 2.0% after the 2nd cycle and 0.4% more for the rest of 10 cycles, shown in Fig. 3. Since pebbles' creep has been observed at 750 °C, the bed volume reduction during these subsequence cycles may be dominated by creep. Under the cyclic stress of 6 MPa, the bed volume continues to decrease after 12 cycles.

In Figs. 3 and 4, the evolution of Li_4SiO_4 pebble bed volume reduction with cycle number has been plotted for different temperature/stress conditions. We observe that bed volume decreases fast in the beginning and tends to saturate afterwards with continuous cycles. The tests conducted under the conditions of 550 & 750 °C/3 MPa show that Li_4SiO_4 pebble bed volume becomes stable after ~85 cycles. When other conditions remain the same, higher stress and temperature generate both a larger reduction and increased rate of pebble bed volume reduction. Since pebbles have more tendencies to creep at higher temperature, more cycles are needed for pebble bed to reach its steady state, in which the bed's packing has almost no further change under the same cyclic loads. The maximum compressive load of the cycle also affects the cycle number required for steady-state, depending on temperature level. Generally speaking, neglecting the influence of creep (i.e., beds at temperatures less than 650 °C), higher pressure speeds up pebble arrangements and requires fewer cycles for bed volume reduction to saturate. However, higher pressure also causes more creep deformation of pebble beds for a higher temperature, i.e., 750 °C, which requires more cycles to saturate.

Similar tests were performed on Li_2TiO_3 pebble bed at an elevated pressure of 2 MPa (3-step loading-unloading) and temperature of 750 °C for 48 cycles, shown in Fig. 5 (1st run). There is again very little bed volume reduction from one cycle to the next after the initial volume reduction is removed by compression. A volume reduction of 1.6% is resulted after the 2nd cycle, and 0.9% more is found for the rest of 46 cycles. After the 1st run, pebble bed total volume reduction was zeroed out and run through the same 3-step loading-unloading sequence (Fig. 5, 2nd run). It is observed that pebble bed shows a higher stiffness and much smaller packing change under the same testing condition.