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Experimental study of the interaction of ceramic breeder pebble beds with structural materials under thermo-mechanical loads

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Abstract

This paper presents the first results obtained in a facility constructed at the University of California, Los Angeles to study the interaction of ceramic breeder pebble beds with structural materials in conditions relevant to fusion energy power plant blanket operations. The experiments study the thermo-mechanical performance of lithium *meta*-titanate oxide (Li_2TiO_3) pebbles and silicon carbide clad constrained by a low thermal expansion alloy in vacuum and He atmosphere. The results show that large deformations due to induced thermal stresses are present during the first heat cycle but afterward are accommodated by a combination of pebble re-arrangement within the bed and thermally induced creep deformation. Initial results of a numerical simulation of the experiments using a finite element code that includes creep deformation is also presented. Planned operation of the UCLA thermo-mechanics test facility is summarized to conclude the paper.

Keywords: Fusion energy; Gas-cooled blanket; Lithium *meta*-titanate; Silicon carbide; Creep deformation; Finite elements

1. Introduction

The thermo-mechanical performance of lithium-based ceramic materials is a critical issue for assessing the reliability of solid breeder blanket concepts over the lifetime of the component. The investigation of the effect of the thermal cycling typical of a fusion energy power plant on the blanket components is complicated by the coupling of the thermal and structural behavior intrinsically related to the use of pebble beds as breeding material. The pebble bed as a whole can be described as an intermediate phase between solid and liquid, with properties depending on the fraction of voids present in the bed volume. The void fraction initially depends on the porosity and the initial packing of the pebbles, but can vary locally through the component lifetime due to the cycling variation of the applied stresses and to irradiation. For example, the formation of a void between the pebble bed and the structure due to creep relaxation would lead to a local deterioration of the interface heat transfer and the creation of a hot spot. The effect of thermal cycling is further

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aggravated by the degradation of materials mechanical properties due to neutron irradiation, and final assessment of blanket component reliability will only come from an integrated experiment such as ITER.

The focus of the experimental work initiated at the University of California, Los Angeles is the investigation of the combined thermal and structural response of blanket candidate materials exposed to thermal cycles that are representative of fusion energy power plant conditions. In particular, the study is aimed at the characterization of the cumulative effect of the plastic behavior of the pebbles resulting from thermal cycling on various assemblies that integrate all the components of different blanket concepts: breeding material, structure and coolant. The integrated tests will generate comparative data on various candidate materials and guide the design of more complex experimental facilities such as the ITER Test Blanket Module. This paper specifically reports on the results obtained with a test article that integrates lithium *meta*-titanate oxide (Li_2TiO_3) as breeder, silicon carbide as cladding and a low thermal expansion alloy (Kovar) as the structure. The choice is motivated in part by the ongoing research effort under the JUPITER II collaborative program that is aimed at the development of high temperature gas-cooled blanket systems with coolant output temperature as high as 900 °C [1,2]. The experimental data available on the thermo-mechanical properties of Li_2TiO_3 are not as extensive as for other ceramic breeder candidate materials and even fewer data are available on compatibility with silicon carbide.

2. Thermo-mechanic response of Li_2TiO_3 pebble beds and silicon carbide

The thermo-mechanic tests described in this paper have been performed in a cylindrical vacuum vessel 0.4 m in diameter and 0.46 m high. The vessel houses a second stainless steel enclosure that is designed as a radiative shield as well as a support for the heating filaments. The enclosure is formed by two hemispherical halves plus a top and bottom plate. Fig. 1 shows one of the hemispherical halves mounted on the vessel base while the other is removed to access the test article. Eight pairs of tungsten filaments mounted around the test article are used as radiative heating elements with a peak power of 3.6 kW. The filaments are mounted over a molybdenum shield insulated by ceramic posts that serves as primary radiative and thermal shield. The test article is shown in Fig. 2 as a map of the finite element mesh used in the simulation that is described in more details at the end of this paper. It is formed by two 0.15 m Kovar flanges and a sandwiched assembly of two commercial graded CVD silicon carbide discs

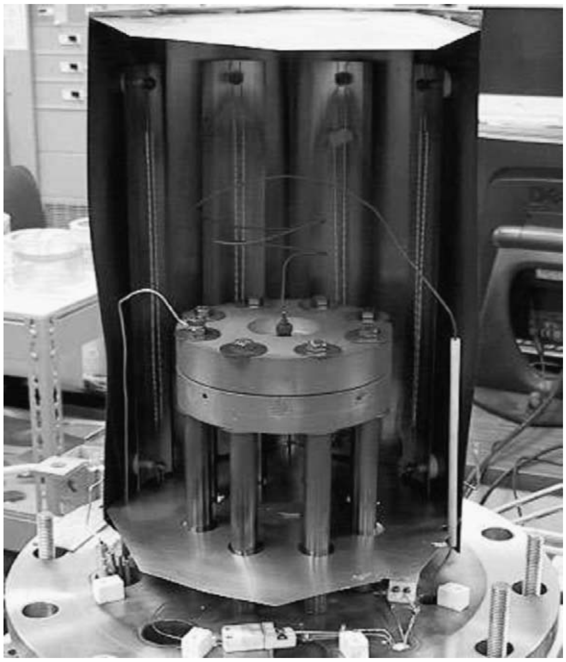

Fig. 1. Test article inside high temperature furnace.

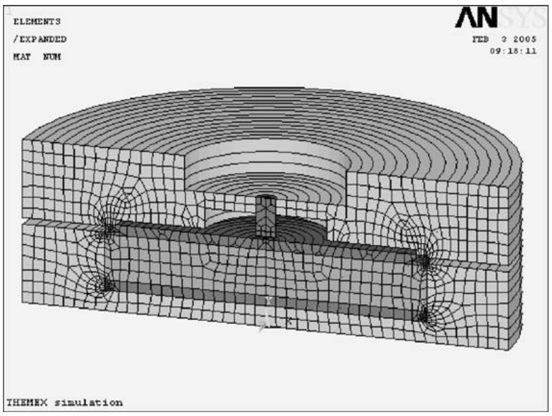

Fig. 2. Test article schematic and finite element meshing.

Table 1
Properties of test article materials

	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)	Young modulus (Pa)	Poisson ratio
Kovar[a]	8360	502.4	16.8	137.9×10^9	0.3
Li_2TiO_3[a]	2000	1080.3	0.93	0.262×10^9	0.3
CVD SiC[b]	3210	574	333	460×10^9	0.21
SS 316L[b]	8040	456.28	13.28	200.4×10^9	0.29

[a] At 20 C.
[b] At 0 C.

and Li_2TiO_3 pebbles supplied by C.E.A. Saclay and fabricated with the extrusion–spheronisation–sintering process [3]. The discs are 0.10 m in diameter and 3.2×10^{-3} m thick, while the average diameter of the pebbles is 7×10^{-4} m. The initial bed height is 15.3×10^{-3} m. The temperature is measured at the center of the bottom SiC disc and on two diametrically opposite locations of the upper disc side. The properties of the materials are summarized in Table 1. The listed properties of Li_2TiO_3 are the "effective" properties of the pebble bed used for the finite element analysis [4]. The temperature dependence of the thermal expansion coefficient of the materials is separately plotted in Fig. 3. Measured densities of the bed obtained on a vibration table range from 1997 to 2023 kg/m^3, which corresponds to packing fractions ranging between 58 and 59% of the theoretical density of Li_2TiO_3 (3440 kg/m^3) or 67.5 and 68.4% of the effective density of the pebbles (86% of TD due to material porosity). The pebbles color changes slightly after each cycle, turning from white to a light color between blue and gray. The change has been previously observed and explained as a phase transformation during annealing in an oxygen-free atmosphere that leads to the formation of different Ti oxides on the pebbles surface [5,6]. The function of the flanges is to establish an initial known compression on the silicon carbide and pebble bed assembly and to ensure an adequate mechanical constrain through the thermal cycle. Eight equally spaced bolts initially compress the flanges with a measured force of about 1300 N each. They are machined from the same low thermal expansion material of the flanges to ensure the same response to the thermal cycle. The force is transferred from the upper flange to a small section at the edge of the silicon carbide disc, constraining the edge of the disc but allowing the center to expand during the heat cycle. If the compressive load is assumed to be uniform on the whole pebble bed contact area the resulting precompression is 1.32×10^6 Pa. The large dimension of the flanges ensures that the load is distributed relatively uniformly across the pebbles, allowing high compressive stresses but local contact forces below the failing threshold of the ceramic material. The drawback is that the current test article has a large thermal inertia with typical thermal cycles are of a few hours. As the temperature increases the pebbles act on the SiC disc because of the higher thermal expansion. As a result the disc bends, and the capacitive sensor embedded in the upper flange reads the maximum displacement at the plate center. The analysis of the experimental results is complicated by the fact that the sensor is not an absolute reference, since it is mounted on a structure also subject to deformation. The effect of the expansion of

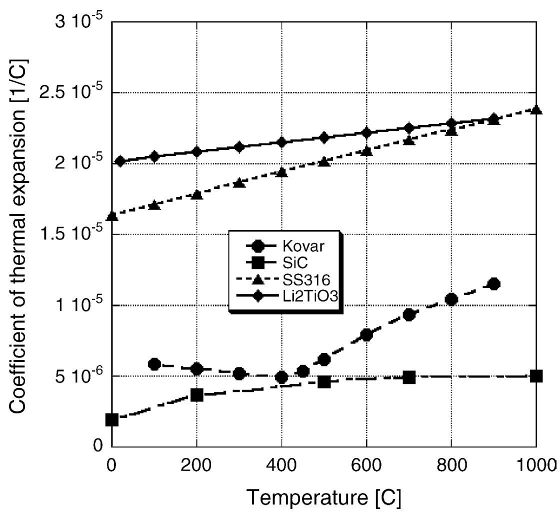

Fig. 3. Temperature dependence of test article materials coefficient of thermal expansion.

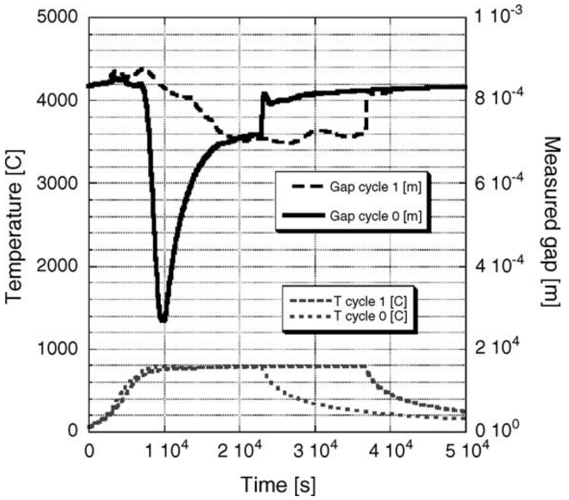

Fig. 4. Displacement and temperature data from two heat cycles of test # 4.

the sensor (which has a stainless steel enclosure) and the alloy structure in which is embedded was evaluated by testing the assembly without a compressive force, and the resulting deformation was measured to be less then 40 μm and constant after 600 °C. This effect is responsible for the initial increase of the measured gap observed in the data. Fig. 4 shows a representative set of data from the first (# 0) and second (# 1) thermal cycle of a thermo-mechanics experiment with the described test article. At low temperatures the expansion of the pebbles is countered by that of the flange on which the measuring sensor is embedded. During the first cycle at temperatures above 700 °C, the gap is gradually reduced by about 580 μm due to a combined effect of thermal expansion and pebble re-arrangement in the bed. After about 3 h from the start of the heating cycle and 30 min at a constant temperature of 800 °C the effect of the stress relaxation due to the thermally induced creep in the ceramic material becomes visible and the gap increases logarithmically at constant temperature to an asymptotic value 120 μm smaller than the initial value, which is completely recovered after cooling indicating that the disc is again straight. It is to be noted here that the uniform plastic deformation of the pebbles induced by the creep as well as the compacting of the bed due to re-arrangement during the thermal cycle cannot be recorded by the sensor, which measure only the displacement of the SiC disc center. However, the bed height after the second cycle was measured to be about 200 μm smaller than its initial value, accounting for an effective residual volumetric deformation of about 1.3%. Future experiments will include absolutely referenced LVDT sensors to accurately measure the accumulated plastic strain. During the second cycle showed the pebbles have already been compacted and the gap reaches the same asymptotic value without the initial swelling. Further consecutive thermal cycles of the same materials have been performed after re-arranging the pebble bed to recover the initial compressive load. The results are similar to the second cycle showed in Fig. 4, with the exception that the asymptotic value is lower due to the higher initial stress, ranging between 250 and 150 μm lower than the initial value.

3. Finite element method numerical simulation

There has been a wide research effort recently aimed at quantifying the properties of lithium-based ceramic pebble beds [7,8]. The simplest models rely on the continuum material assumption and are derived by fitting a generalized expression with data collected from simplified experiments with a limited number of variables, such as the uni-axial compressive tests at FZK [9,10]. As mentioned in Section 1, the thermo-mechanic tests described in this paper offer an opportunity to compare different models against experimental data obtained in an integrated experiment. The modeling effort here presented was carried on using the finite element code ANSYS [11]. The code was chosen because UCLA already has the capability of running it on parallel processors, which could allow for future modeling of large three-dimensional blanket structures. ANSYS contains a graphical user interface which allows the generation of complex, adaptable meshes once a geometrical model and a set of loads are defined (Fig. 2). The model assumes axi-symmetrical geometry and loads, as well as simplified interface conditions between the various materials (all the degrees of freedom are coupled for adjacent elements) and uniform material properties in all directions (Table 1). The ANSYS thermal analysis tool is first used to derive the nodal temperatures as a function of time. The experimental heat cycle was simulated by imposing a uniform, time-dependent temperature at all nodes corresponding to the locations in the experiment that are exposed to the radiative heat flux. The ANSYS mechanical analysis tool was then used to calculate the stresses and deformations due to the thermal cycle with the additional boundary condition of zero displacement in the vertical directions at the nodes corresponding to the locations in the experiments covered by the bolts washers. The thermally activated creep model derived by Buhler and Reimann [7] was introduced by using the time hardening option of ANSYS where the equivalent creep strain rate is:

$$\dot{\varepsilon}_{\rm cr} = 0.12C\,{\rm e}^{-7576/T}\sigma^{0.65}t^{-0.82}$$

where T is the absolute temperature, σ the equivalent stress, t is time and C a correction factor that accounts for the fact that the measured data from which the constants are derived refer to the volumetric strain rate [4]. The model predicts a swelling of the center of the upper disc of 640 μm after 3 h, which is consistent with the experimental results. However, the few elements in contact with the edge of the disc show unrealistic values of stress and deformation. Furthermore, because of the large local deformation convergence of the non-linear, time-dependent structural solution is obtained only for small time steps, which is incompatible with the simulation of the cumulative effect of multiple heating cycles over extended period of time. Further refinement of the model is needed in the contact regions where the element sizes becomes comparable or smaller than the single pebbles diameter, possibly by using tailored contact elements to better simulate effective interface and experimental load conditions.

4. Conclusions and future plans

The first of a series of integrated experiments aimed at characterizing the thermo-mechanic performance of various structural, cladding and breeding materials for fusion energy blankets has been presented. Lithium *meta*-titanate oxide and silicon carbide were chosen among the material candidates to investigate the feasibility of high temperature gas-cooled blanket concept. The experimental results indicate that high thermal stresses and deformations are present during the initial thermal cycle of the assembled test article, but are successively accommodated due to a combination of pebble re-arrangement within the bed and creep induced deformation. This suggests that a few thermal cycles under controlled atmosphere and a compressive load before final assembling of blanket sections would allow a beneficial reduction of the swelling and related thermal stresses during start-up. Future plans include further experiments with low mass test articles with local active cooling that will allow to reproduce thermal cycles that are more representative of fusion energy power plant operation, as well as controlled thermal gradients across the pebble bed. Different combinations of structural, cladding and breeding materials as well as test article geometries will be tested. The cumulative effect of the plastic deformation of the bed will be studied to investigate the possible formation of gaps between the pebbles and the surrounding structural material. The finite element model will be refined and the results of time hardening due to creep deformation compared to those of the experiments over shorter, multiple heat cycles.

Acknowledgements

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