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Experimental and numerical analyses on $LiSO_4$ and Li_2TiO_3 pebble beds used in a ITER test blanket module

Donato Aquaro *, Nicola Zaccari

Dipartimento di Ingegneria Meccanica Nucleare e della Produzione, University of Pisa Via Diotisalvi n.2 – 56100 Pisa, Italy

Abstract

One of the possible configurations of test blanket module (TBM) which will be tested during the ITER operation phase is made up of neutron multiplier and breeder as pebble beds. This paper describes an experimental device for the determination of the pebble bed conductivity in presence of interstitial air. The tests were performed with a simultaneous compression of the bed in order to obtain the effective bed conductivity versus the axial deformation for several values of the temperature. The effective conductivities of $LiSiO_4$ and Li_2TiO_3 pebble beds, both in air and in vacuum, were determined. The packing factors of the beds were measured by means an ad hoc built instrumentation, based on the gamma ray back-scattering. The experimental results have been compared with those of a theoretical model developed by the authors, obtaining a good agreement in terms of bed conductivity and stiffness.

1. Introduction

The helium cooled pebble bed (HCPB) test blanket module designed for ITER is characterized by the use of ceramic breeder materials in the form of pebbles. Lithium-orthosilicate (Li_4SiO_4) and lithium-metatitanate (Li_2TiO_3) are among the candidates proposed as ceramic breeder materials. Their thermo-mechanical properties need to be known in detail for designing the test modules. At the Department of Mechanical and Nuclear Engineering of the University of Pisa (Italy), the heat transfer and the stress distribution in the pebble beds have been analyzed from a theoretical point of view by considering a medium composed of regular lattices of spheres (i.e. simple cubic, body centred cubic and face centred cubic lattices) characterized by means of a packing factor value (that is, the ratio between the pebble bed density and the homogeneous material density). This theoretical model has permitted the effective conductivity and the effective stiffness of the pebble bed to be determined in simple configurations from the geometrical and applied load point of view. The model has been assessed by performing numerical simulations using finite element method (FEM) computer codes and comparing the results with theoretical results. Moreover, a comparison has been made with experimental data found in the literature [1–3]. However, the geometry of the TBMs and the distribution of the thermal and mechanical loads are very complex and the theoretical model can not be applied in the form which has been developed. The model could be used in conjunction with a FEM code developing a new finite

* Corresponding author. Tel.: +39 050 836631; fax: +39 050 836665.
E-mail address: aquaro@ing.unipi.it (D. Aquaro).

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element which describes pebble bed behaviour. The thermal and mechanical behaviour of pebble beds needs further experimental investigation in order to verify the validity of the model assumptions. In fact, the experimental results found in the literature [8] define the macroscopic behaviour of the pebble bed (i.e. the whole effective conductivity or stiffness of the bed), but little information is given about the contact between the pebbles on which the model is based. Recent work [9] tries to experimentally determine the topology of the pebbles in the bed as well as the position and extension of the contacts. Nevertheless, the results are not immediately usable since the pebbles are made of metallic material (aluminium) and the pebble diameters are larger than those of the breeder material. An experimental set up has been built for testing ceramic pebble beds under axial compression in order to directly determine the data necessary to assess the theoretical model and to implement a finite element able to describe the pebble bed behaviour. The device permits the determination of the bed stiffness and thermal conductivity at the same time.

Several tests have been performed on pebble beds of lithium-metatitanate (Li_2TiO_3) and lithium-orthosilicate (Li_4SiO_4) in air at atmospheric pressure and in vacuum conditions. The method used for determining the effective thermal conductivity of the bed is a steady-state method (guarded hot plate), namely a heat source and a heat sink generate a temperature gradient in the bed and in a homogeneous material of known conductivity located above the bed. When the steady-state condition is reached, the temperature gradients in the bed and in the homogeneous material, measured by means of thermocouples, allow the determination of the effective thermal conductivity of the bed. The effective conductivity is determined at different values of the bed compression.

In order to estimate the radial distribution of the bed packing factor, a gamma ray device has been built which is able to measure the material density before and after the test. In the following sections the experimental tests performed are described and the results are compared with those of the theoretical model developed by the authors.

2. Experimental tests

The main items of the experimental set up [3] are shown in Fig. 1: a hydraulic actuator (a), a heat source plate, connected to the piston, (b); a cylinder

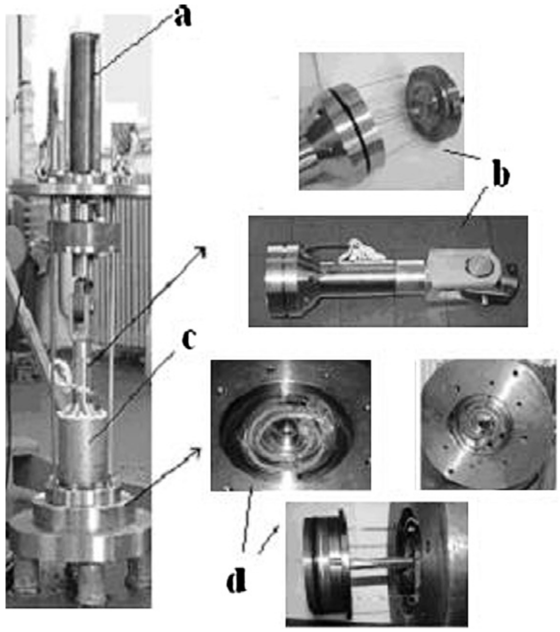

Fig. 1. Experimental equipment for thermal–mechanical tests on the pebble bed.

that contains the pebble bed (100 mm of diameter) (c) and a water cooled heat sink lower plate (d). The heat source plate contains a central electric resistance and a peripheral one which works like a guard ring. Moreover, electric resistance heaters are coiled around the cylinder that contains the pebbles in order to heat the bed to the test temperature. It is possible, through the heat sink lower plate, to pressurize the pebble bed with a particular gas or to establish vacuum conditions. The load acting on the pebble bed is measured by means of a piezoelectric load cell, while a laser transducer records the vertical deformation.

The gamma ray device for measurement of packing factor is made up of a lead cylinder that supports a scintillator detector and the gamma source (Co^{60} with an activity of 10 μCi). The lead cylinder is put on the pebble bed by means of a circular plate (with a buttonhole) connected to the container of the pebble bed. Experimental tests were performed on 1 mm diameter pebble bed of lithium-metatitanate (Li_2TiO_3) and on 0.5 mm diameter pebble bed of lithium-orthosilicate (Li_4SiO_4). The properties of the two materials were obtained from [4–7]. The average packing factor of the pebble bed was 0.635 for Li_2TiO_3 and 0.628 for Li_4SiO_4. Several loading and unloading cycles, at a maximum compression pressure equal to 6.6 MPa, were performed in each test. The load, increased or decreased step by step, was held for a time interval needed to reach a steady-state heat transfer condition in order to determine the thermal conductivity versus axial deformation.

The tests on the pebble beds were carried out at 25 °C, in air at 1 atm and at 5 mm of Hg. Fig. 2 shows the curves of pressure versus vertical deformation obtained in the tests on Li_2TiO_3 and Li_4SiO_4 25 mm high pebble beds, respectively. In the first cycle, the curve is initially characterized by small values of the pressure and high values of deformation. This corresponds to a phenomenon characteristic of the oedometric test related to the arrangement of the pebbles. The following cycles reduce this phase (see Fig. 8). After the initial arrangement, an increase of the contact area of the pebbles caused by the yielding strains occurs and this is the most interesting phase of the deformation from the pebble bed thermal and mechanical point of view.

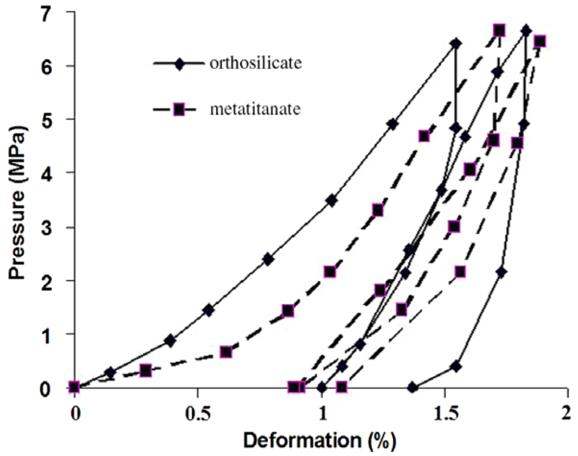

Fig. 2. Experimental curves of the pressure versus axial deformation for lithium-metatitanate and lithium-orthosilicate pebble beds.

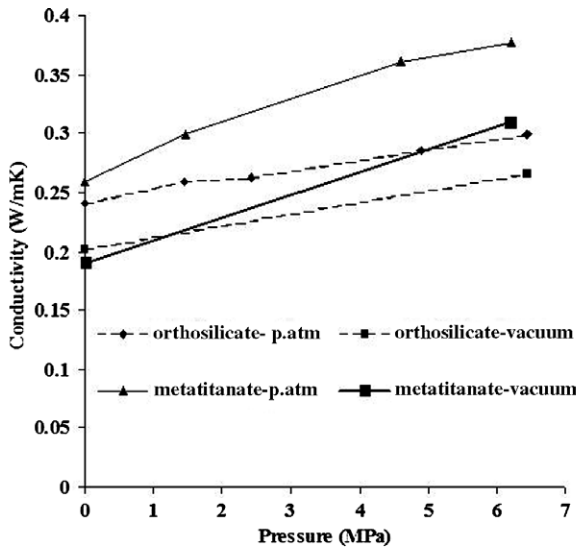

Fig. 3. Experimental curves of the thermal conductivity versus pressure for lithium-metatitanate and lithium-orthosilicate pebble beds.

Fig. 3 shows the effective thermal conductivity of the bed versus the pressure for the Li_2TiO_3 and Li_4SiO_4 pebble beds, respectively. The conductivity increases in proportion to the pressure because the contact area of the pebbles increases.

The histograms in Figs. 4 and 5 illustrate the percentage of the pebble bed volume which has a particular value of packing factor and the modification due to the compression test for the two materials taken into consideration. The central part has a greater packing factor than that of the boundary and the distribution amplitude before the test is larger for the pebbles of greater diameter (metatitanate pebbles). After the test, the radial distribution of the packing factor is almost uniform.

Fig. 6 shows the deformation of the Li_2TiO_3 pebbles. Several pebbles agglomerated in the central part of the bed to a greater extent than the rest. The contact area looks like a cracked cylinder. The cracks are due to residual tensile stresses which develop during the unloading. These tensile stresses are due to the action of elastic zones on those plastically deformed in compression during the loading. The material in the cylindrical zone was analyzed and it proved to have the same composition as the pebble material.

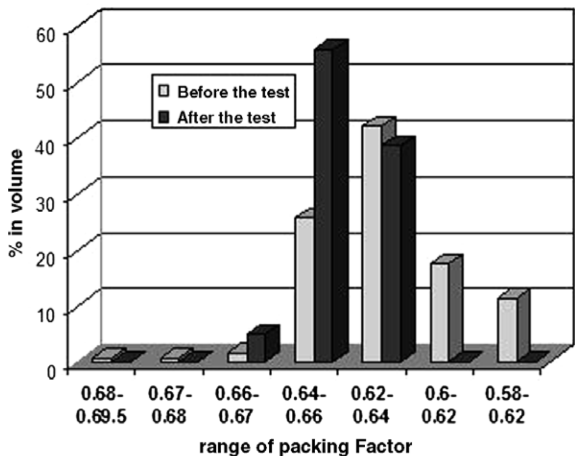

Fig. 4. Distribution of the packing factor of the lithium-metatitanate pebble bed.

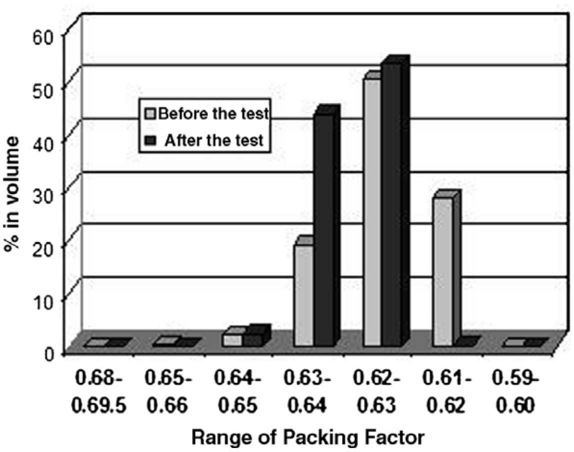

Fig. 5. Distribution of the packing factor of the lithium-orthosilicate pebble bed.

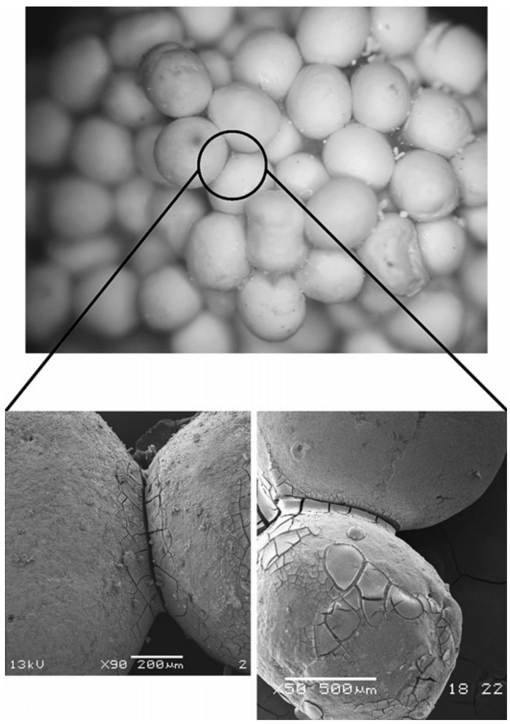

Fig. 6. Deformation of the lithium-metatitanate pebbles.

3. Comparison between the theoretical and experimental results

The theoretical model developed by the authors describes the thermo-mechanical behaviour of two compressed spheres and extends the results to a pebble bed assuming that it is made up of a mixture of regular lattices [1–3]. The mechanical stiffness is determined by considering two half spheres as variable cross-section beams and assuming the behaviour of the material to be elastic-perfectly plastic under compressive stresses and elastic under tensile stresses. Materials which have low tensile resistance (such as ceramic materials) crack when the tensile stress reaches a cracking stress. In the model it is assumed that the spheres radius decreases, discarding the cracked part of the material. The conductivity is determined considering the series of two thermal resistances: that of the contact zone and that of the rest of the pebble.

Fig. 7 shows the comparison between the experimental and theoretical values of the effective conductivity of the lithium-metatitanate and orthosilicate pebble bed. The average values are similar but the theoretical values show a stronger dependence on the pressure. This depends on the influence of the air in the heat transfer between pebbles. In the theoretical model, the heat flux is assumed to be only transmitted by conduction through the pebble contact area. Therefore, the thermal conductivity increases in proportion to the contact area. The presence of the air is important above all for small contact area between the spheres (Hertzian contact). In this case the conductivity is due to the

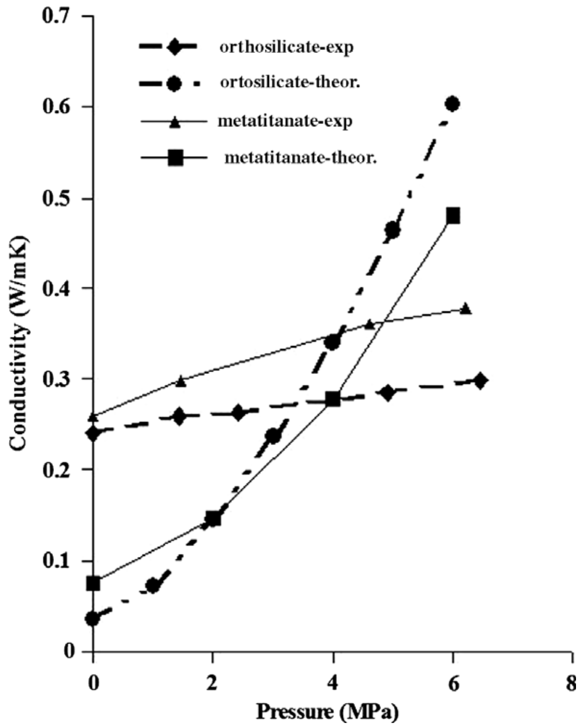

Fig. 7. Theoretical and experimental curves of the thermal conductivity versus pressure for lithium-metatitanate and orthosilicate pebble beds.

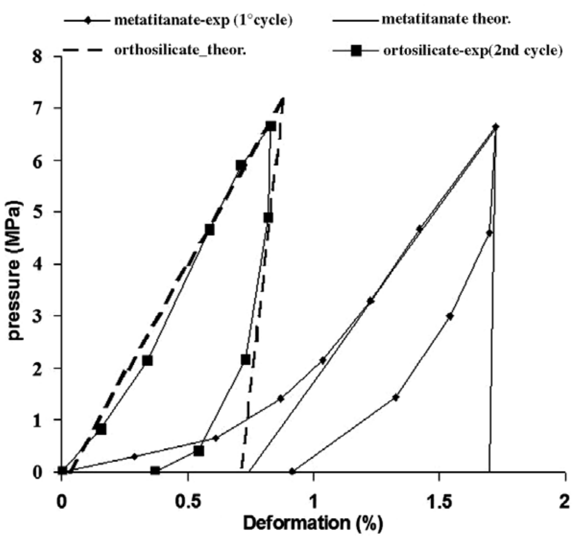

Fig. 8. Theoretical and experimental curves of the pressure versus axial displacement for lithium-metatitanate and orthosilicate pebble beds (for illustration purpose, considered zero the residual deformation after the 1st cycle).

convection between air and pebbles. Fig. 8 illustrates the comparison of the pressure versus axial deformation as obtained from the model and the experimental tests on lithium-metatitanate and orthosilicate pebble beds. The model considers only the elastic–plastic deformation of the pebble and this phase agrees well with the experimental curve. The pebble arrangement in the initial part of the first loading cycle and in the final part of the unloading cycle is not described by the model. The aspect of the experimental contact zone (a cylindrical part plastically deformed) corresponds perfectly to the evolution of the plasticity assumed in the model (see [1–3]).

4. Conclusions

Experimental tests on Li_2TiO_3 and Li_4SiO_4 pebble bed have permitted the effective stiffness and conductivity versus axial deformation to be determined. The radial distribution of the packing factor has been determined by means of a gamma ray device. The bed compression produces a more uniform distribution of the packing factor. The presence of air between the pebbles increases the effective conductivity of the bed. In the case of the lithium-metatitanate this increase is equal to 36% at atmospheric pressure and to 22% at 6.6 MPa. For the lithium-orthosilicate the increase is equal to the 20% for every pressure.

The comparison with the theoretical model shows good agreement with the experimental effective thermal conductivity and stiffness of the bed above all in the elastic–plastic deformation. The aspect of the experimental contact zone (a cylindrical part plastically deformed) corresponds perfectly to the evolution of the plasticity assumed in the model.

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