Preliminary experimental evaluation of thermal conductivity of ceramic pebble beds

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Preliminary experimental evaluation of thermal conductivity of ceramic pebble beds

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Abstract.
This paper illustrates the preliminary experimental tests for determining the effective thermal conductivity of ceramic pebble beds versus temperature and compression strains.
Ceramic pebble beds are promising candidates to be used in breeding blankets for nuclear fusion reactor as breeder and neutron multiplier.
The tests were performed with an experimental rig, built at the DICI-University of Pisa, which permits to determine the thermal conductivity of pebble beds in steady state conditions, at several temperatures and compression forces. The values of thermal conductivity of pebble beds are obtained as function of a known conductivity of an alumina disc.
The assessment of the method has been performed determining the effective thermal conductivity of alumina pebbles beds of different diameters. Void fraction and compression strains are the parameters that mainly influence the variability of the thermal conductivity of the beds.

1. Introduction

The breeding blanket of nuclear fusion reactor produces, by means of neutron capture, the tritium necessary for the fusion reaction, slows down the neutrons and permits to extract the thermal power.

Compounds of lithium (lithium orthosilicate (Li4SiO4), lithium metatitanate (Li2TiO3)) in form of ceramic pebbles are breeder candidates in the design of breeding blankets for nuclear fusion power technology.

These breeders, packed in the form of pebble beds into a box-like structure, are characterized by strong mechanical loading arising from the differential thermal expansion between breeder pebbles and the containing structure.

The knowledge of the effective thermal conductivity of pebble beds is important for a proper thermo-mechanical blanket design [1] and assessment of the heat transfer processes.

The available measurements (in the literature) of the thermal conductivity of ceramic pebbles bed are concentrated mainly on the uncompressed pebble beds [2-3], while very few researches has been performed [1],[4-6] considering the bed subjected to compression forces.

The research program, developed at the Department of Civil and Industrial Engineering (DICI) of the University of Pisa, aims to characterize the thermo-mechanics behavior of ceramic pebble beds. Specifically the thermal conductivity, at several temperatures and values of compression forces (up to 100 kN), was determined experimentally [7].

The experimental tests look like oedometric tests from a mechanical point of view and were carried out on a thin layer of pebbles.

The approach used to evaluate the thermal conductivity is based on the thermal conductivity of an alumina disc (used a reference value) experimentally determined with the hot wire method carried out in a furnace (in the 20 °C-200 °C range) [8].

Numerical simulations were also performed in order to determine the accuracy and consistency of the envisaged method for the evaluation of the pebble bed conductivity.

2. Assessment of thermal conductivity of pebble beds

The pebble bed conductivity depends on the temperature, strain and interstitial gas. Deformations, caused by stresses due to different thermal expansions between beds and other structural materials, may result in variations of the effective thermal conductivity of the beds. The thermal conductivity of pebble beds is determined without any compressive load (zero strain tests) or loading the bed with increasing loads (tests at strain steps). In this latter case, the pebble bed is submitted at progressive strain in correspondence of which the thermal conductivity is evaluated.

Experimental methods for determining the thermal conductivity are the following:

- Pulsed Hot Wire Method (HWM);
- Hot Plate with guard rings Method.

J.Reimann et al. [1] have determined the thermal conductivity of Li4SiO4 and Li2TiO3 pebble beds with different interstitial gas (air and helium) using the pulsed hot wire method. Aquaro et al. [9] applied the ‘hot plate method with guard rings’ for determining the thermal conductivity of Li4SiO4 and Li2TiO3 pebble beds at room temperature.

In this study a modified ‘hot plate method with guardian rings’ is used (according to UNI EN 12664 [10]) to evaluate the thermal conductivity of pebble bed in a steady state condition.

A heat flux, q, produced by an electrical resistance, is transmitted to a cylindrical specimen (thick s) of unknown thermal conductivity (λ) reaching a steady state thermal gradient (T_c, T_f upper and lower specimen temperature, respectively). In steady state conditions, the thermal conductivity may be calculated as:

$$\lambda = \frac{qs}{T_C - T_f} \tag{1}$$

One or more resistances (called ‘guard resistances’) compensate the heat flux dispersion to the environment during the test execution.

The hot plate method has high accuracy if the heat loss to the environment is minimized; a drawback is, instead, the long duration of the test, necessary to reach steady state conditions.

The experimental device, available at University of Pisa, measures the effective thermal conductivity of ceramic pebbles beds by comparison with a known conductivity of a disc of Alumina. Therefore the experimental measurements are restricted to the temperature gradients through the bed and Alumina.

The main concept of the method is to generate a temperature gradient across the pebble bed and the disc of Alumina. In steady state heat transfer, the heat flux flowing through the alumina disc and pebble bed is the same, for zero heat losses (this is surely true in a region around the centreline).

The thermal conductivity of the pebble bed (λ_{PB}) is calculated as function of that of the alumina (λ_A), by applying the following equation:

$$\lambda_{PB} = \lambda_A \frac{\Delta T_A}{\Delta x_A} \cdot \frac{\Delta x_{PB}}{\Delta T_{PB}} \tag{2}$$

Where ΔT_A and ΔT_{PB} are the temperature differences across the alumina and the bed. The thickness of the alumina and of the pebble bed are indicated respectively as Δx_A and Δx_{PB}.

3. Description of the experimental device

The experimental equipment, shown in figure 1, consists of the following main parts: measurement cell (containing the pebbles), hydraulic jack, piston, load cell, heating source, heat sink, thermocouples, displacement transducers.

The measurement cell, containing a maximum useful height of 20 mm of the pebble beds, is a cylindrical component, made of stainless steel, having 100 mm inner diameter and 170 mm height.

A disc of alumina, of known conductivity (the value of which was experimentally evaluated by means of hot wire test, as forward illustrated), is directly placed on the upper surface of the pebble bed and it is connected to a copper plate, 20 mm thick, that allows to obtain a uniform radial distribution of the temperature.

The heating source is made of two mica armoured electrical resistances connected to the upper surface of the copper plate, while the heat sink is placed under the bed in order to generate an axial heat flux through the pebble bed.

The pebble bed is resting on 35 mm of thick copper plate, the lower part of which is cooled by air or water. A small duct allows to void the pebble bed or to inject into it pressurized air or different interstitial gases (nitrogen, helium).

Thermocouples are positioned in a similar arrangement on the lower and upper copper plates. In the upper copper plate, five K type thermocouples measure the radial distribution of the temperature: four of them are located on two diameters at 90° each other and at a distance of 36 mm from the fifth one, located in correspondence of the plate centreline.

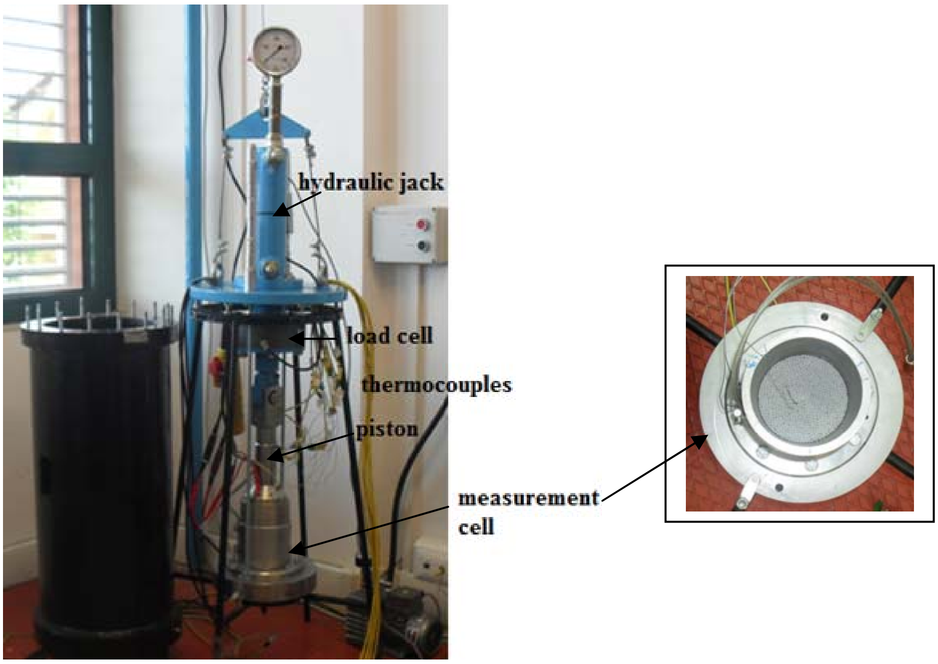


Figure 1. Experimental device: main components and measurement cell with pebbles

Another thermocouple crosses almost all the thickness of the alumina plate and provides a temperature measurement close to the pebble bed upper surface. Furthermore two O-Ring gaskets (capable to withstand temperatures up to 500° C) are mounted on the two mentioned copper plates in order to ensure the cell leak tightness.

Two electrical resistances (both peripherally and centrally positioned, as illustrated in figure 2) are designed to guarantee a minimum thermal gradient of 5 °C between the upper and lower surface of the pebble bed.

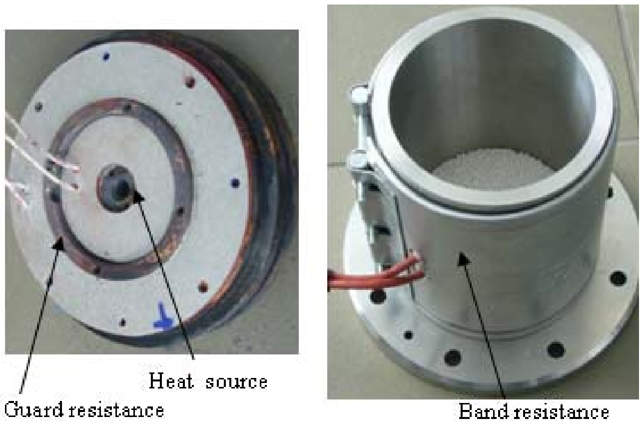


Figure 2. Heating source: electrical resistances.

The peripheral or guard resistance allows to compensate for heat flux radial losses. Around the cylindrical measurement cell a band shaped electric resistance (figure 2), 105 mm height, allows to heat the pebble bed up to 500°C. Moreover a hydraulic jack, connected to a load cell and a stainless steel piston, applies progressively the mechanical load (up to 100 kN) on the bed.

The piston is, in turn, connected through a coupling sleeve (50 mm height and 5 mm thick) to the upper copper plate (shaped in such a way to reduce the heat flux toward the hydraulic jack).

The piston displacement (corresponding to the pebble bed deformation) is measured by means of displacement laser transducer. The measurements of the load, displacement and temperatures were recorded by means of a Data Acquisition System made by National Instrument.

The uncertainty in the measurement of the thermal conductivity of the pebble bed is strictly dependent, in this type of tests, on the accuracy of the alumina conductivity values as well as on the accuracy of temperature measurements. Another source of uncertainty may be also the loss of heat flux in radial direction (reduced because the gradient of temperature is measured on the centerline).

The values of the alumina thermal conductivity, to be used in the equation 2, were determined by an experimental test campaign on an alumina specimen, shown in figures 3, having the same composition of that used in the experimental device.

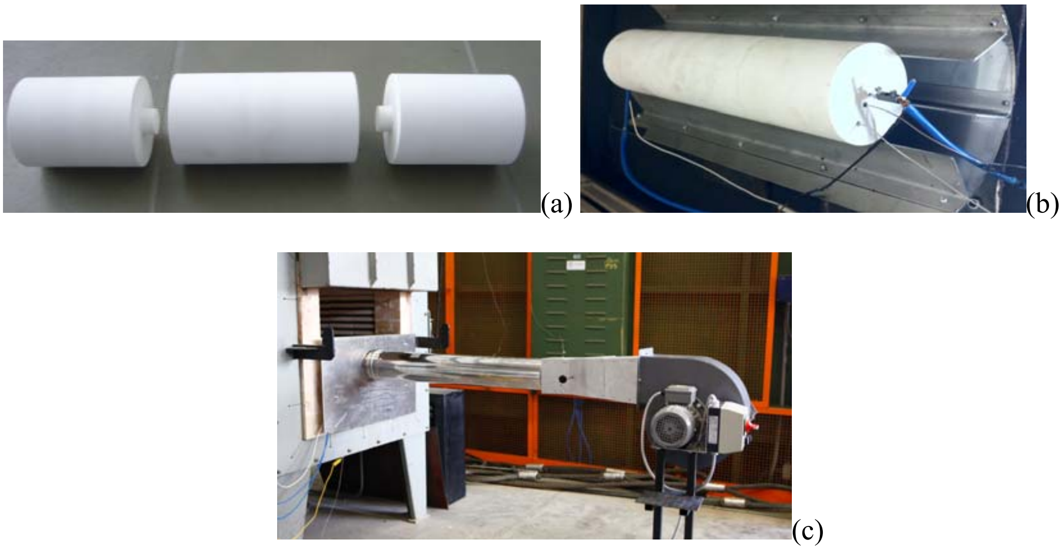


Figure 3. Alumina sample (a) used in 'hot wire test' (b, c) for determining the thermal conductivity.

The alumina thermal conductivity (h in table 1) has been determined at stationary conditions: the temperature gradient arisen across the longitudinal direction of the specimen was measured by two thermocouples by applying the ‘hot wire test’ method, like represented in figure 3 (b).

The preliminary results obtained (the test campaign is still on-going), summarized in table 1, are considered of meaningful importance to study, analyse and characterize the thermo-mechanical behaviour of the alumina. This phase is necessary and important in the setting up a methodological approach capable, in turn, to determine the thermal conductivity of Li4SiO4 and Li2TiO3 pebbles bed.

Table 1. Experimental values of the alumina thermal conductivity.

h [W/m^{2}K]	**T** [°C]	$\boldsymbol{\lambda_A}$ [W/mK]
34.71	36.4	13.82
34.67	39.6	14.71
34.62	44.8	15.53

In previous table 1, h is the heat transfer coefficient between the external surface of Alumina sample and the furnace ambient; T, the average temperature of Alumina; λ_A, the thermal conductivity of Alumina.

The assessment of the experimental method has been done performing tests on Alumina pebble beds. In these tests, the material of disc and pebbles is the same. Therefore the results will depend only on the geometrical characteristics of pebbles.

Preliminarily, two types of pebbles, having average diameter of 1.275 mm and 2.05 mm, respectively, were used. For the first type of pebble, the diameter ranges from 0.75 to 1.8 mm (tests TC1), while for the second ones it ranges from 1.8 and 2.3 mm (tests TC2). Moreover both two TC1 and TC2 were carried out without and with compression load and considering different temperatures.

The test procedure may be summarized as follows:

a) Heating of the pebble bed until an average temperature is reached;

b) Switching on the cooling system in order to generate an axial heat flow through the bed;

c) Start-up of the guard resistance to compensate for heat flux radial losses (depending on the radial distribution of temperature);

d) Application or not (depending on the type of tests) of the compression load;

e) Measurement of the reference temperatures;

f) Calculation of the value of the thermal conductivity of the bed.

4. Numerical simulations

Numerical pre-test simulations were also performed in order to optimize the operating test conditions and to evaluate the accuracy of the thermal conductivity measurements [6].

In this study only a brief description of FEM simulations of the hot plate method (used in the experimental tests) is reported, since it was extensively treated in [6]. The FEM model (implemented by using four nodes axial-symmetric elements) of the experimental device is shown in figure 4.

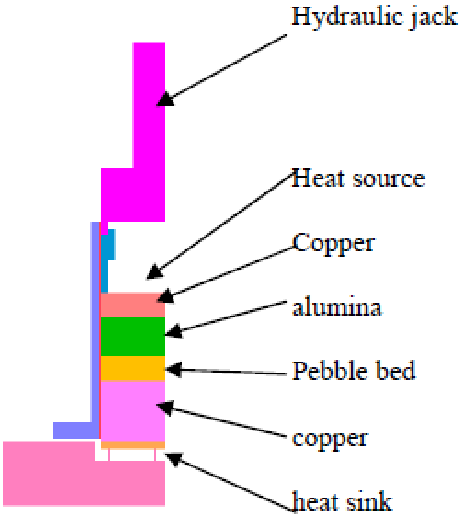


Figure 4. FEM model of the experimental device.

As indicated in [6], the bed was assumed to behave like an isotropic material having the real properties of the pebble bed. The heating sources (simulating the electric resistances shaped as disc, annular disc or band) were represented by means of heat fluxes applied on the correspondent surfaces.

The convection heat transfer in the heat sink was simulated through a suitable heat transfer coefficient (h = 10÷40 W/m^2 °C) and a bulk temperature (T_b), which depends on the cooling conditions. Two boundary conditions were also considered for the remaining surfaces: adiabatic surface (zero heat flux if insulated) or surface cooled by air at 20°C and heat transfer coefficient equal to 10 W/m^2°C (stagnant air).

The results of the numerical simulations, presented in [7], permitted to estimate the accuracy/discrepancy between the values of the thermal conductivity given in input [11-12] in the analyses and those obtained by the method described from the equation (2). As an example, the results, obtained in terms of pebble bed conductivity, highlighted that the discrepancies between the reference conductivity of Li2TiO3 (1 mm diameter)[11] and the values calculated with equations (1) and (2) resulted respectively about 24 % and about 12%. In the case of alumina (1 mm diameter) this discrepancy resulted about 1.26%. Furthermore the heat flux losses in the radial direction resulted higher (about 20%, as shown in figure 5) for the lithium metatitanate than for the alumina (about 4.5% as shown in figure 6).

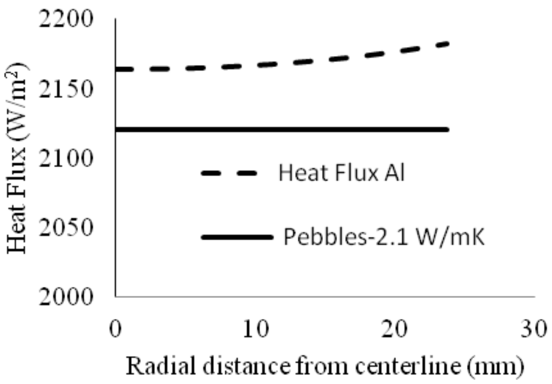


Figure 5. Radial distribution of heat flux for alumina pebble bed.

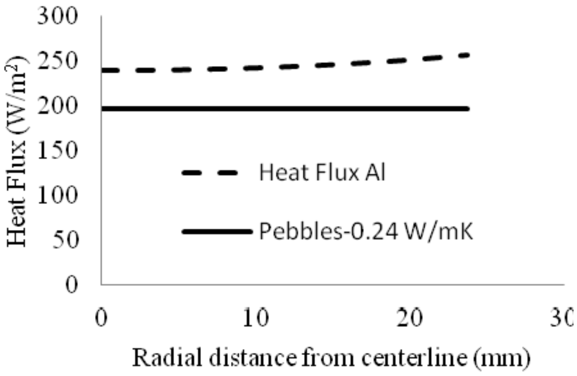


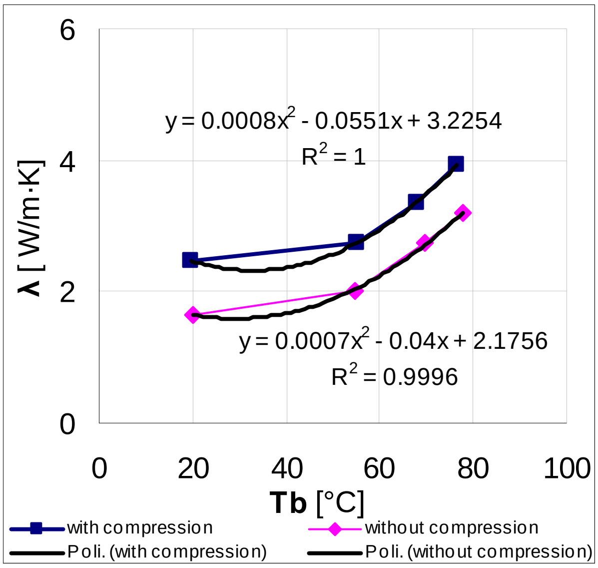
Figure 6. Radial distribution of heat flux in lithium metatinate pebble bed.

5. Experimental results and discussion

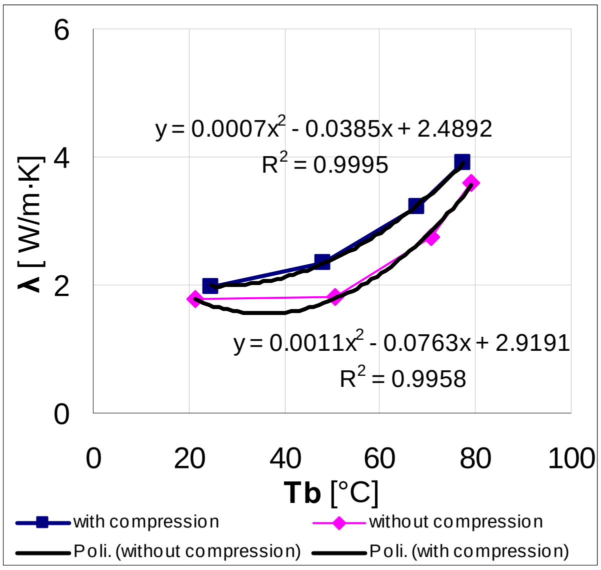
The temperature values measured in the alumina and in the bed, were analysed, by applying the equation (2). The results obtained, in terms of thermal conductivity versus temperature, are showed in figures 6 for both two test campaigns TC1 and TC2 (with and without compression load). The tests were performed with air as interstitial gas, while the theoretical packaging factor measured resulted about 92%. The compression force, as already indicated along the text, was 100 kN.

The thermal conductivity, in both two cases, increases along with the temperature of the bed. Moreover in the absence of compression load, the thermal conductivity value seemed to be less influenced by the dimension of pebble, although varying its diameter almost of a factor 2.

In fact Figure 7 (a) shows the ratio of the conductivities for the pebbles TC1 and TC2 versus the temperature. The ratio is almost independent of the temperature in the case of zero axial load, while it increases with the temperature if the bed is compressed.



(a)



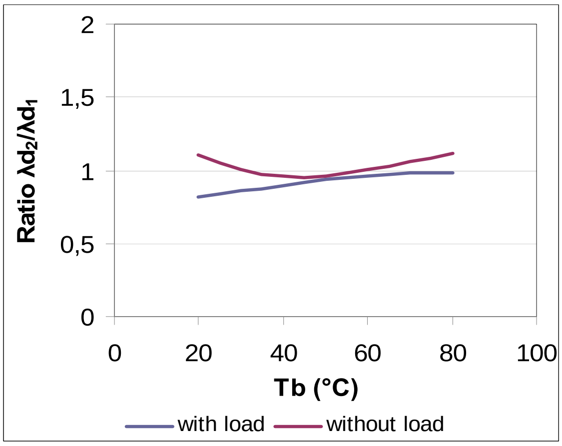
(b)

Figure 6. Thermal conductivity vs. temperature: TC1 (a) and TC2 (b) tests.

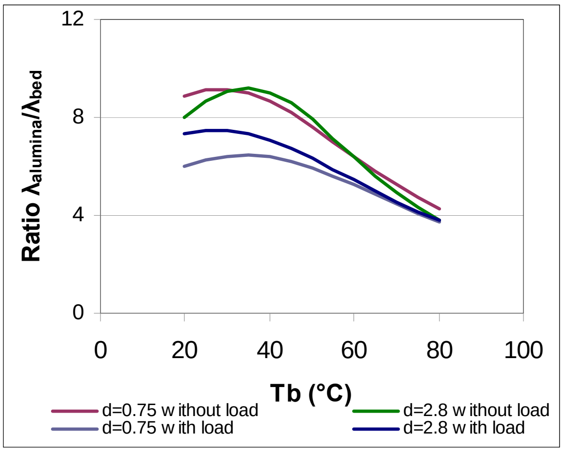
The void fraction and the strain (characterizing mainly the experimental data, as also widely addressed in literature) resulted the parameters that mainly influenced the increase of the thermal conductivity of bed. The increase of the temperature is responsible for a pebble deformation that, reducing the void, seemed to induce a compaction of bed.

Figure 7 (b) illustrates the influence of the compression load on the bed conductivity. In this figure the ratio between the Alumina conductivity and that of the beds of different diameters versus temperature is shown.

The compaction of the pebble bed, due to the temperature, determines the decrease of the influence of the diameter as well as of the compression strain on the conductivity of the bed. At 80 °C of temperature, the bed conductivity is 4 times lower than that of the homogeneous material.



(a)



(b)

Figure 7. Thermal conductivity ratio vs. temperature:
TC1 (a) and TC2 (b) tests.

6. Conclusion

In this paper the thermal conductivity of ceramic pebble beds, which are one of the candidates in the design of breeding blankets for nuclear fusion reactor has been evaluated. To the aim, the thermo-mechanical characterization of alumina pebble beds was done performing experimental tests at different temperatures and varying the compression force (up to 100 kN). Air was, at this first stage, the interstitial gas. The theoretical packaging factor measured resulted about 92%.

Numerical (pre-test) simulations were also carried out to optimize the operating test conditions: the uncertainty associated to the measurements of the alumina thermal conductivity (of 1 mm diameter) resulted about 1.26%.

The preliminary experimental results, since the test campaign is still ongoing, indicated that:

1) the thermal conductivity increases along with the bed temperature;

2) in the absence of compression load, the thermal conductivity seems to be less influenced by the dimension of pebble even if the diameter of pebbles is greater by, almost, a factor 2;

3) the void fraction and the strain are the parameters that mainly influence the variability of the thermal conductivity of bed;

4) the increase of temperature induces a pebble deformation and, in turn, a compaction of bed, which decreases the influence of the diameter and the compression strain.

The conductivity values increase when the bed is subjected to the compression load highlighting that the compaction phenomenon may induce a further increase of thermal conductivity (caused by the void reduction), even if a saturation effect could be foreseen.

Finally it is worthy to note that the results obtained may contribute to the creation of a database of the thermal conductivity of pebble beds which can be used for the design and analysis of fusion breeding blankets.

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