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Thermo-mechanical test rig for experimental evaluation of thermal conductivity of ceramic pebble beds

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HIGHLIGHTS

- Thermal conductivity values of bed as function of a material of known conductivity.
- Minimizing the error caused by radial heat transfer.
- Experimental evaluation of thermal conductivity of alumina pebble at different temperatures.
- Experimental test with/without compression load.

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ABSTRACT

The experimental determination of mechanical and thermal properties of ceramic pebble beds, such as the lithium orthosilicate or lithium metatitanate, is a key issue in the framework of fusion power technology, for the reason that they are possible candidates in the design of breeder blankets.

The paper deals with an experimental method for the evaluation of the thermal conductivity of ceramic pebble beds versus the temperature and compressive strain, based on a steady state heat flux through a material (alumina) of known conductivity. The alumina thermal conductivity is determined by means of the hot wire method. To assess the experimental method, a thermo-mechanical characterization of alumina pebble beds (a material largely available), having different diameters, considering a wide range of temperatures and compression forces has been carried out.

Moreover preliminary tests have been performed on lithium orthosilicate and lithium metatitanate pebble beds.

1. Introduction

As widely known in the scientific literature [1–4], the breeders blanket is of meaningful importance in fusion reactor since it allows to produce, by neutron capture, the tritium necessary for the fusion reaction, slow down neutrons and extract thermal power. The lithium ceramic blanket, specifically in form of solid breeders, is a promising blanket concept for the fusion reactors that received a significant interest in the last years with worldwide efforts dedicated to its R&D [5,6].

The potential tritium breeding materials, such as lithium orthosilicate (Li_4SiO_4) and lithium metatitanate (Li_2TiO_3) in the form of pebble beds, are required to have good thermal properties as well as satisfactory breeding characteristics.

The mechanical and thermal properties, in particular the knowledge of thermal conductivity versus temperature and compressive strain, are considered essential key issues to be investigated for a proper blanket design [4] and assessment of the heat transfer processes.

This paper describes the research activity developed at the Department of Civil and Industrial Engineering (DICI) of the University of Pisa for a thorough understanding and characterization of the mechanical and thermal properties of pebble beds. In particular, the thermal conductivity, at different values of temperature, compression forces and pressure of interstitial gas, was determined by means of an appropriate and dedicated experimental facility [6]. In addition, numerical analysis (by FEM code) were also carried out to evaluate the structural response of a pebble lattice and examine the different mechanisms of heat transfer. The obtained results, described in [7], indicated that, for lithium orthosilicate pebble bed (with helium gas and at 200–700 °C), the effective thermal conductivity is almost independent from the temperature and small dependent on strains [7].

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The present paper illustrates:

- the experimental device used for the experimental determination of pebble bed thermal conductivity;
- the methodology used to determine the effective thermal conductivity of pebbles bed based on a steady state heat flux through a material (alumina) of known conductivity;
- the experimental campaign to assess the accuracy of the method determining the thermal conductivity of alumina pebble beds (a material largely available) of different diameters, considering a wide range of temperatures and compression forces
- preliminary tests on lithium orthosilicate and lithium metatitanate pebble beds.

2. Evaluation of the effective pebble beds thermal conductivity

The pebble bed thermal conductivity depends on many parameters such as temperature, strain and packing factor of the bed, and interstitial gas.

The packing factor is also dependent on the pebble size. Small pebbles have higher packing factors. Therefore, the pebble size has to be chosen in manner that to ensure a packing factor upper than 60%. Strains, caused by stresses due to the different thermal expansions between beds and other structural materials, may result in variations of the effective thermal conductivity of the beds. The temperature instead may influence both the deformation and the packing fraction, and, in turn, the effective thermal conductivity of pebbles.

In the present study, the thermal conductivity was evaluated as function of a known conductivity of an alumina disc (used as reference value) experimentally determined with the hot wire method (furnace temperature from 20 °C to 400 °C) [8].

The experimental rig is based on the "hot plate with guardian ring method", according to the UNI EN 12664 requirements. This method allows to determine the bed conductivity, in steady state condition, by measuring the thermal gradient through the alumina disc and the pebble bed, by means of the following relation:

$$\lambda_{PB} = \lambda_A \frac{\Delta T_A}{\Delta x_A} \cdot \frac{\Delta x_{PB}}{\Delta T_{PB}} \quad (1)$$

where λ_A and λ_B are respectively the thermal conductivity of the alumina disc and the pebble bed; ΔT_A and ΔT_{PB}, the temperature differences through the alumina disc and the pebble bed; Δx_A and Δx_B the thickness of the alumina disc and pebble bed.

Several authors (Reimann, Enoeda et al. [1,3,4]) determine the pebble bed thermal conductivity by means of the impulsive hot wire technique. This method has several drawbacks because the geometry has to be axial symmetric, the pebble bed very large and temperatures have to be measured inside the bed.

2.1. Description of the experimental device

The experimental device, shown in Fig. 1, consists of the: measurement cell (pebble container), hydraulic jack connected to the piston, load cell, heating source, heat sink, thermocouples, displacement transducer. The measurement cell (Fig. 2) is a stainless steel cylindrical component, 100 mm of inner diameter and 170 mm height which may contain a pebble bed 45 mm thick.

As indicated in [9], an alumina disc of known thermal conductivity is directly placed on the upper surface of the pebble bed. This disc is connected to a 20 mm thick upper copper disc that allows to obtain a uniform radial distribution of the temperature.

The heat source is made of two mica armoured electrical resistances connected to the upper surface of the upper copper disc, while the heat sink is placed under the lower copper plate. The heat

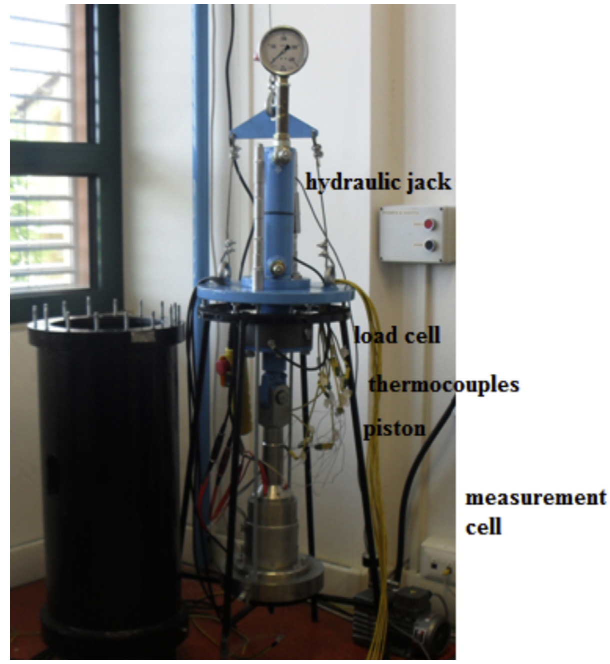

Fig. 1. Experimental device.

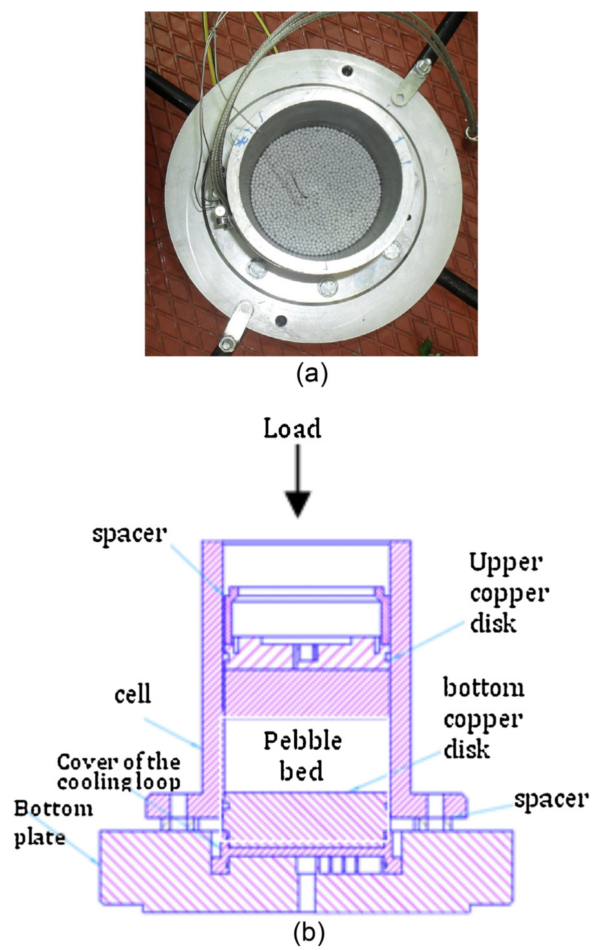

Fig. 2. Measurement cell with pebbles: (a) top view and (b) assembly of main components.