Fusion Engineering and Design 116 (2017) 73–80

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Effective thermal conductivity of advanced ceramic breeder pebble beds

S. Pupeschi*, R. Knitter, M. Kamlah

Institute for Applied Materials (IAM), Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form
20 December 2016
Accepted 17 January 2017

Keywords:
Effective thermal conductivity
Ceramic breeder
Pebble beds
Hot wire method
Advanced breeder material
Lithium orthosilicate

ABSTRACT

As the knowledge of the effective thermal conductivity of ceramic breeder pebble beds under fusion relevant conditions is essential for the development of solid breeder blanket concepts, the EU advanced and reference lithium orthosilicate material were investigated with a newly developed experimental setup based on the transient hot wire method. The effective thermal conductivity was investigated in the temperature range RT–700 °C. Experiments were performed in helium and air atmospheres in the pressure range 0.12–0.4 MPa (abs.) under a compressive load up to 6 MPa. Results show a negligible influence of the chemical composition of the solid material on the bed's effective thermal conductivity. A severe reduction of the effective thermal conductivity was observed in air. In both atmospheres an increase of the effective thermal conductivity with the temperature was detected, while the influence of the compressive load was found to be small. A clear dependence of the effective thermal conductivity on the pressure of the filling gas was observed in helium in contrast to air, where the pressure dependence was drastically reduced.

1. Introduction

Lithium-based ceramics, in the form of pebble-packed beds, are selected as tritium breeder in the solid breeder blanket concepts. In the fusion environment the pebble beds are subjected to severe conditions such as neutron irradiation, cyclic mechanical compression and high thermal flux. A thorough knowledge of the thermal properties of the ceramic pebble beds under fusion relevant conditions is essential for the design of the breeder blanket modules of a future fusion reactor. A pebble bed is a multiphase material consisting of a solid phase and a gas phase that fills the voids between pebbles. For that reason the thermal conductivity of a packed bed, called effective thermal conductivity, depends on the thermal conductivities of the constituent phases. Furthermore, due to their granular nature, pebble bed materials show a dependence of thermal conductivity on the mechanical state (packing factor, stress/strain state). Pebble beds were proposed due to their intrinsic resistance to thermal loads. Complex geometries can be filled with pebble beds, while the generated tritium can be recovered by a purge gas flowing between pebbles. Moreover, the parameters of the bed such as the packing factor, the filling gas type/pressure, the pebble material and the size distribution, can be tailored to obtain the optimal thermo-mechanical properties. In the breeder blanket the ceramic beds have no structural function; however they have to withstand the compressive stress arising from the mismatching of the thermal expansion coefficients between the beds and the structural materials.

Several experimental investigations were previously performed to study the effective thermal conductivity of the candidate ceramic breeder materials. A reasonable literature regarding the investigation of the effective thermal conductivities of lithium orthosilicate [1–6] (Li_4SiO_4), lithium metazirconate [4,7–9] (Li_2ZrO_3), lithium metatitanate [4,10–12] (Li_2TiO_3) and lithium oxide [4,13] (Li_2O) materials exists. Both transient [4–6,10,11] and steady state [1–3,7–9,12,13] methods were utilized. The thermal conductivity was found to be mainly influenced by the temperature, the thermal conductivity of the solid material, the bed strain, the packing factor and by the filling gas type and pressure. All studies, except for [12], reported an increase of the effective thermal conductivity with the temperature. For some material the increase was more pronounced while other material, such as Li_2O, showed poor temperature dependence. Only few reports on the measurement of the effective thermal conductivity of compressed bed exist [5,8,10,11]. These reports detect a moderate increase of the thermal conductivity with the increase of the strain of the pebble bed. Li_2O beds showed the highest thermal conductivity compared to the other

---

* Corresponding author.
E-mail address: simone.pupeschi@kit.edu (S. Pupeschi).

http://dx.doi.org/10.1016/j.fusengdes.2017.01.026

breeder materials investigated in [4], due to the inherently higher thermal conductivity of Li_2O. All reports in which the effect of the filling gas pressure was assessed [4,7,9], agree that the effective thermal conductivity of the bed is strongly influenced by the filling gas pressure in the pressure range 0.0001–0.1 MPa. For pressures above 0.1 MPa the pressure dependence, although still present, was found to be drastically reduced. Only in [3], the influence on the helium pressure was reported to be negligible for pressures higher than 1 bar.

The current European reference breeding material consists of a two-phase material fabricated by the melt-spraying method [14]. It consists of about 90 mol% lithium orthosilicate (Li_4SiO_4) and 10 mol% lithium metasilicate (Li_2SiO_3) [15]. Due to the fabrication process these pebbles exhibit pores that influence rupture strength. To improve the mechanical performances by reducing the process related defects, a new experimental facility based on a melt-based method was put into operation at KIT for the production of Advanced Ceramic Breeder (ACB) pebbles [16]. To further enhance the mechanical properties, lithium metatitanate (Li_2TiO_3) was introduced as a second phase [17].

Aim of the present work is the experimental investigation of the effective thermal conductivity of the advanced and the reference breeder pebble beds under fusion relevant conditions. The influences of temperature, compressive load and filling gas type/pressure on the effective thermal conductivity pebble beds were investigated. The influence of the lithium metatitanate (LMT) content was examined as well.

2. Experimental

The developed experimental setup for the measurement of pebble beds' thermal conductivity is shown in Fig. 1a. The experimental setup was designed for the investigation of ceramic pebble beds' thermal conductivity as a function of temperature, mechanical load and filling gas type and pressure. The Hot Wire Method (HWM) was selected to measure the thermal conductivity [18]. The HWM is a transient technique, where a linear heat source (thin heater) is embedded in the material to be investigated. A modification of the HWM for granular materials employs a more robust probe instead of a wire. Both methods are based on a very similar theory. In practical applications several factors contribute to the definition of the sample and probe dimensions. Aim of this work is the investigation of the effective thermal conductivity of ceramic pebble beds under severe conditions (mechanical compression and high temperatures). This has influenced the design of the probe in order to withstand such conditions. Due to theoretical approximation and practical considerations the probe method deviates from the ideal linear heat theory. Great efforts were made to design a suitable probe, the design was based on the analysis of error sources reported in [19–21]. In Fig. 1b a schematic drawing of the thermal probe and an image of the installed probe are shown. The diameter of the probe was kept as small as possible according to the requirements of the linear heat source theory. In this sense, a 40 mm long probe with an outer diameter of 1.9 mm was used as linear heat source. The thermal probe consists of a heating element and a type K thermocouple enclosed in a thin Inconel clad. The thermocouple junction is located at the probe middle length. A nickel-chromium wire, 0.18 mm in diameter, was used as heating element surrounded by aluminum oxide as electrical insulator. The sample dimensions, in particular the bed height (equal to the probe length), was the result of a compromise for a reliable measurement of the thermal conductivity with a uniform compressed bed along its axis. A higher value of the bed height would be beneficial for the thermal conductivity measurement, but detrimental to the uniformity of the mechanical compression due to wall friction and arching of pebbles. The uniformity of the mechanical compression is influenced by the ratio H/D [22], where H and D are the bed height and diameter, respectively. The H/D ratio should be kept much less than 1 to have a uniform compressed bed. The chosen radial dimension of the sample is 27.5 mm resulting in a H/D ratio of 0.73. The experimental setup was conceived to generate a purely radial heat flow around the probe. To this end, a cylindrical measuring cell of 55 mm inner diameter with the probe placed along its axis was manufactured to be filled with ceramic pebbles. Pebbles were packed into the measuring cell by mechanical vibration. The initial Packing Factor (PF) of the bed was approx. 64% with an initial height of approx. 40 mm. Ceramic disks made of MACOR were placed below and above the pebble bed to thermally insulate it in the axial direction. The experimental setup was placed axially in a universal testing machine. By this, the pebble bed was compressed in the axial direction by a piston connected to the movable crossbar of the testing machine. The bed strain was measured by means of three Linear Variable Displacement Transducers (LVDT) equally spaced along 360°, while the compressive load was measured by a load cell. The LVDTs are placed outside the heated zone of the facility thanks to a displacement measuring system that transfers the displacement of the piston outside of the facility. The measuring system consists of six bars going through the cap. Three of them are connected with the piston, while the other three are connected to the test cell. The LVDT body is fastened to one of the three rods connected to the test cell, while the LVDT plunger is fastened to the one of the three rods connected to the piston. In this way the differential displacement between the piston and measuring cell is measured by the LVDTs working at ambient temperature. A three zone furnace surrounding the experimental setup was used to heat up the bed. Four type K thermocouples, equally spaced along 360° at four different heights, were used to monitor the temperature of the measuring cell. The thermocouples were placed in holes radially drilled in the measuring cell. The sealing was assured by a flat high temperature gasket between the measuring cell and the pressure pipe and by o-rings in the upper part. A high temperature fitting was used to hold the thermal probe in position and to ensure the sealing. Heat exchangers were designed to cool down the components where o-rings are used. Furthermore in order to thermally disconnect the experimental setup and the testing machine; two additional heat exchangers were placed around the lower and the upper rods. The test cell as well as all other components exposed to high temperatures were made of high temperature/low creep materials like Hastelloy X and Nimonic 80A alloys.

After the assembling of the experimental setup, the bed was first evacuated and then filled with the selected gas at the desired pressure. For each investigated material the first experiment was conducted at RT with the initial packing factor reported before. Then the measurements were performed at increased temperatures up to 700 °C. During the heating up process helium or air atmosphere was kept in the facility. At every investigated temperature the gas pressure was adjusted at the desired level. The facility was allowed to come to the thermal equilibrium, at the selected testing temperature, for several hours. When the difference in temperature measured by all thermocouples during a 30 min period was negligible, i.e. $\Delta T_{30\mathrm{min}} \ll 1\,^{\circ}\mathrm{C}$, the probe was heated by feeding a constant current to the heating element and the temperature rise of the probe was measured by the enclosed thermocouple. The experimental setup was monitored and controlled by a dedicated LabVIEW program. The current was kept constant by means of a high precision power supply.

To obtain a well-defined mechanical state of the bed, at each investigated temperature it was mechanically conditioned prior to measure the thermal conductivity. The mechanical conditioning consisted of 3 loading/unloading cycles up to 6 MPa with a loading rate of 1 MPa/min. The effective thermal conductivity at a