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Progress in the benchmark exercise for analyzing the lithiate breeder pebble bed thermo-mechanical behaviour

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Abstract

The Helium Cooled Pebble Bed (HCPB) Blanket is one of the reference concepts for the European Breeding Blanket Programme for DEMO. In the reference blanket module, alternate layers of lithiated ceramics and beryllium pebbles act, respectively, as tritium breeder and neutron multiplier. The thermo-mechanical behaviour of both the pebble beds and their performances in reactor relevant conditions are also dependent on the pebble size and cell geometries (bed thickness, pebble packing factor, bed thermal conductivity). Therefore, in the EU Fusion Technology Programme, several out-of-pile experimental test campaigns have been performed to determine these behaviours. Theoretical calculations have been also launched for the prediction of the thermal and mechanical performances of the pebble beds under different testing conditions. More recently, among the EU Associations involved in the ceramic breeder qualification, a benchmark exercise has been launched to select the pebble bed thermal mechanical constitutive models to be implemented in a FEM computer code. This paper describes the activities, carried out by ENEA and DIN, University of Palermo (I), for the first comparison with the results of the experiments carried out at HE-FUS 3 facility of ENEA Brasimone on the HELICA mock-up. The paper describes the test conditions and also presents the main experimental results and its first comparison with the theoretical calculations.

Keywords: Thermo-mechanical behaviour; Lithiated ceramics; Breeder

1. Introduction

The prediction of thermo-mechanical behaviours of the breeder and multiplier pebble beds, in reactor relevant conditions, is one of the main concern of the design of the Helium Cooled Pebble Bed (HCPB) Blanket

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for DEMO and its Test Blanket Module (TBM) to be tested in ITER. In fact, the bulk thermal conductivity of these beds are dependent on both the bed local temperatures and strains. In the interface regions of the steel containment walls, the heat transfer is dominated by a pressure-dependent thermal conductance. Furthermore, the thermal cycles due to the plasma pulses and the high design temperatures of both materials could also affected these dependencies due to pebble relocations during the pulses and creep effects at high temperatures. Therefore, several out-of-pile experimental test campaigns were launched at FZK (D) and ENEA (I) to determine these behaviours in small scale mock-ups with cylindrical [1] or prismatic geometries [2,3]. The trial to adapt a FEM commercial code to have a tool for the estimation of the pebble bed behaviour has given good results only for the first thermal–mechanical cycle [4]. Therefore, the EU Associations involved in the ceramic breeder qualification and modelling have agreed on the EFDA proposal to compare the experimental results of the out-of-pile experiments, carried out by ENEA on the mock-up HELICA with the theoretical calculations performed adapting the available constitutive models of the pebble beds in the nonlinear elasticity, in the plasticity and in the creep regions.

2. Test objectives

In 2001–2003, ENEA has carried-out three test campaigns on both Li_4SiO_4 and Li_2TiO_3 breeder pebble beds in a prismatic mock-up. These tests have demonstrated that, after several cyclical step increases of the bed temperature from 200 to 800 °C, the overall bed thermal conductivity is almost univocally dependent on the bed average temperature. The pebble thermal expansions up to 800 °C have procured negligible deformations (±0.1 mm for Li_4SiO_4 and ±0.2 mm for Li_2TiO_3) on the lateral cooling plates (CP) of the breeder containment cell, without further increasing of their lateral stiffness [2], and negligible pressure loads (0.21 MPa for Li_4SiO_4 and 0.36 MPa for Li_2TiO_3) when, on the contrary, the lateral stiffness is artificially increased by inserting load cells [3]. The pebble filling and packing of the beds, even if performed by high frequency mechanical vibrations, were not able, in any case, to avoid both the relocation of the pebbles and the bed height reduction due to its compaction under the cycling thermal sequences [2,3]. The aim of the HELICA test campaigns is to furnish experimental results to be compared in the first benchmark exercise with the theoretical computation of the breeder pebble bed thermo-mechanical behaviour. The main experimental data are the pebble bed height reductions, the breeder and cell temperatures and the lateral deformations of the cell under the pressure loads operated by the beds.

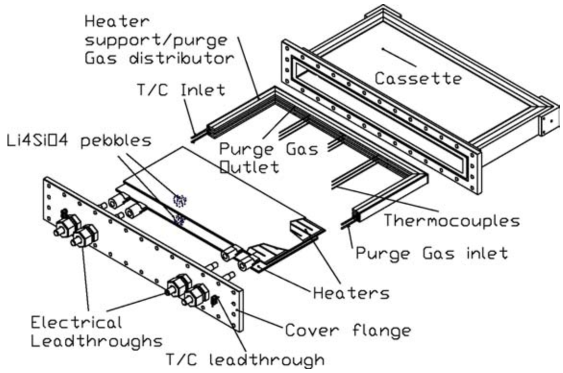

Fig. 1. HELICA mock-up scheme.

3. HELICA mock-up

The HELICA mock-up, shown in Figs. 1 and 2, consists of a single welded cell made in ferritic–martensitic steel ASME SA 387 grade T91. The breeder cell, provided with two flat electrical heaters designed to reproduce the reference pebble temperature increase, is divided into three sub-cells 446 mm in width, 192 mm in depth and 4.6 mm in thickness. The total cell volume is 2012 cm^3 (1197 cm^3 in heated zone, 747 cm^3 in the superior dead space and 68 cm^3 in the level monitoring tube). The pebble bed temperature gradient is controlled by two external helium-cooled plates. The mechanical constraint on the lateral plates of the cell is obtained by using stack of SCHNORR springs set at variable preload. The test cell is closed by a flanged plug provided with the power supply and instrumentation leadthroughs. The pouring of the pebbles inside the cells is operated via a proper filling tube also used for the monitoring of the pebble level during the tests (Fig. 2). The bed level is also measured by a