Fusion Engineering and Design 89 (2014) 1257–1262

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Construction of PREMUX and preliminary experimental results, as preparation for the HCPB breeder unit mock-up testing

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HIGHLIGHTS

- PREMUX has been constructed as preparation for a future out-of-pile thermo-mechanical qualification of a HCPB breeder unit mock-up.
- The rationale and constructive details of PREMUX are reported in this paper.
- PREMUX serves as a test rig for the new heater system developed for the HCPB-BU mock-up.
- PREMUX will be used as benchmark for the thermal and thermo-mechanical models developed in ANSYS for the pebble beds of the HCPB-BU.
- Preliminary results show the functionality of PREMUX and the good agreement of the measured temperatures with the thermal model developed in ANSYS.

ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form 25 March 2014
Accepted 25 March 2014
Available online 24 April 2014

Keywords:
PREMUX
HCPB
Breeder unit
Lithium orthosilicate
ANSYS

ABSTRACT

One of the European blanket designs for ITER is the Helium Cooled Pebble Bed (HCPB) blanket. The core of the HCPB-TBM consists of so-called breeder units (BUs), which encloses beryllium as neutron multiplier and lithium orthosilicate (Li_4SiO_4) as tritium breeder in form of pebble beds. After the design phase of the HCPB-BU, a non-nuclear thermal and thermo-mechanical qualification program for this device is running at the Karlsruhe Institute of Technology.

Before the complex full scale BU testing, a pre-test mock-up experiment (PREMUX) has been constructed, which consists of a slice of the BU containing the Li_4SiO_4 pebble bed. PREMUX is going to be operated under highly ITER-relevant conditions and has the following goals: (1) as a testing rig of new heater concept based on a matrix of wire heaters, (2) as benchmark for the existing finite element method (FEM) codes used for the thermo-mechanical assessment of the Li_4SiO_4 pebble bed, and (3) in situ measurement of thermal conductivity of the Li_4SiO_4 pebble bed during the tests.

This paper describes the construction of PREMUX, its rationale and the experimental campaign planned with the device. Preliminary results testing the algorithm used for the temperature reconstruction of the pebble bed are reported and compared qualitatively with first analyses completed with the FEM codes.

1. Introduction

One of the mid-term goals projected at the Institute of Neutron Physics and Reactor Technology at the Karlsruhe Institute of Technology (KIT-INR) is to test a breeder unit mock-up (BU MU [1]) for the Helium Cooled Pebble Bed Test Blanket Module (HCPB-TBM [2,3]) in a dedicated helium loop named KATHELO [4]. This test will aim at the verification of the thermal and thermo-hydraulic performances of the BU under ITER relevant conditions, as well as to serve as an additional benchmark platform for the finite element (FE) code developed in KIT during the past years [5] for modeling the thermo-mechanics of pebble beds in the BU.

In order to reproduce the volumetric heating due to the neutron irradiation in an out-of-pile experiment with a BU MU, a heater system based on a matrix of wire heaters has been designed and developed [6]. As its implementation in a full scale BU MU is technically challenging, it is desired to check the performance of this heater system in a simplified yet relevant pre-test experiment (PREMUX) before its realization in a full scale BU MU. The main design characteristics of PREMUX have been presented in [6]. The

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http://dx.doi.org/10.1016/j.fusengdes.2014.03.074
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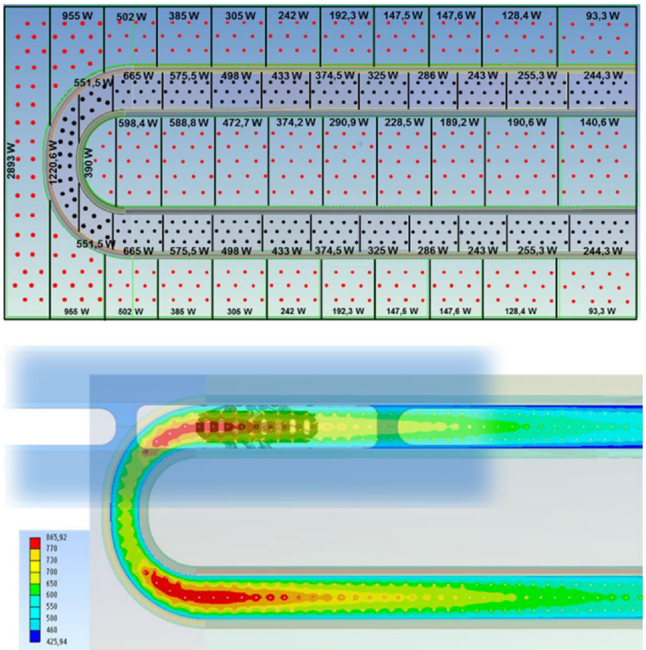

Fig. 1. Top: nuclear heating discretization proposal for a BU MU experiment. Bottom: BU MU thermal analysis with detail of the 21 heating cells and superimposed picture of the PREMUX test box.

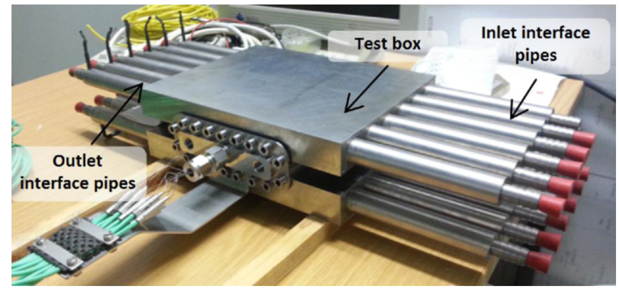

Fig. 3. PREMUX test box.

construction of this experiment, its rationale, the methods that are used and future steps are reported in this paper.

2. Experiment design, engineering and construction

2.1. PREMUX heater system and test box

The nuclear heating occurring in the HCPB BU has been discretized into volume cells of uniform power: 23 cells for the Li_4SiO_4 and 10 cells for the beryllium multiplier (Fig. 1, top). As it has been shown in [6], PREMUX reproduces two cells where the temperature will reach its maximum. Each cell contains a heater block that provides the corresponding discretized power. A central heater between both heater blocks is used for the determination of the thermal conductivity of the breeder material by hot wire method (HWM) [7].

These two cells reproduced in PREMUX are relevant in thickness (22 mm) and width (189.5 mm) to a BU MU. The length of the pebble bed corresponds to the length of two cells plus an extra length (118 mm) needed for purging the bed with helium gas.

The heater system composed by the two heater blocks and the central wire for HWM measurements has been designed in KIT-INR and developed by the company Thermocoax (Fig. 2). Each heater block can develop up to 700 W. The design details can be found in [6]. The positioning of thermocouples permits a temperature reconstruction of the section under study by means of biharmonic spline interpolation in a Control Tool program implemented with the software LabVIEW (explained in Section 2.4). The power of the heater blocks is regulated by two independent power supplies (EA PS8360-15 2U) with LabVIEW through Ethernet.

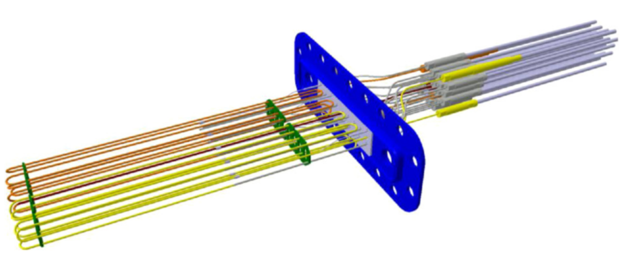

Fig. 2. Heater system developed for PREMUX.

The pebble bed is enclosed in a box made out of P92 (X10CrWMoVNb9-2) ferritic steel grade (Fig. 3). This steel is currently used as substitution of EUROFER in many experimental and fabrication activities because of its similar composition and characteristics to EUROFER, yet more accessible and economic. In PREMUX is particularly important its similar thermal conductivity. The upper and lower walls in contact to the breeder material have 1.2 mm thickness (relevant to that in the cooling plates of a HCPB BU) and they are cooled by air at 0.2 MPa flowing through six squared channels of 25 mm side length. The air is coming from the air loop L-STAR Large Loop (L-STAR/LL) at the KIT-INR [8].

The geometry of the channels and its dimensions corresponds to a tradeoff between relevant thermal performance to a BU MU and manufacturability. First, it was decided to minimize the number of welds in the test box to reduce the distortion. Due to the small thickness of the pebble bed and the high thermal gradient in-between, a low tolerance (0.1 mm) is imposed for this dimension, thus the need for a reduced distortion. Therefore, the test box is fabricated by just welding together 2 quasi-symmetric parts (Fig. 3) with electron beam. Each half is fabricated out of a 50 mm thick P92 plate, where the 6 cooling channels and half of the volume of the pebble bed are cut off with spark erosion.

The length of the cooling channels is important for two reasons: (1) the longer, the more developed will be the flow and less pronounced the entrance region effects in the heat transfer region of the pebble bed and (2) the shorter, the easier the spark erosion process is. A spark erosion process around 300 mm long is standard in the industry. Several analyses performed with ANSYS CFX concerning the length of the channels showed that an air flow at 5 g/s (initial estimation for the cooling rate) needs a length of about 80 mm before it reattach (Fig. 4, top). Therefore, the length of the test box has been set-up to 250 mm, which lets the flow to develop while keeping a standard spark erosion process.

Considering the 50 mm thick P92 plates, the height left for the cooling channels is about 25 mm. Past studies with just 5 cooling channels and rectangular shape (36 mm × 12 mm) show unsteady flow patterns due to the creation of a Karman vortex street at the considered flow regime (Fig. 4, bottom). This is due to the transition from the circular cross section of the interface pipes that connect the test box to the air loop to the rectangular one at the test box. What is more, a reduced number of channels make the structure less stiff against the secondary stresses coming from thermal expansion of the box, so it has been decided to keep the configuration with 6 + 6 cooling channels of 25 mm of side length.

A first guess of the coolant mass flow has been imposed to study the fluid dynamics of the air in the channels. However, a more precise value is needed in PREMUX so that the coolant is relevant (physically similar) to the helium cooling in the BU MU. The