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Thermo-mechanical analyses and assessment with respect to the design codes and standards of the HCPB-TBM Breeder Unit

Francisco Hernández [a,*], Fabio Cismondi [a], Béla Kiss [b]

[a] Karlsruhe Institute of Technology (KIT), Germany
[b] Budapest University of Technology and Economics, Hungary

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ABSTRACT

The Helium Cooled Pebble Bed-Test Blanket Module (HCPB-TBM) is one of the two breeding blanket concepts currently under development in Europe. Key component of the HCPB-TBM, the Breeder Unit (BU), has entered the detailed engineering design phase. After establishing a base design, thermal and thermo-mechanical analyses have been performed under typical ITER operational conditions: the results are presented and discussed in this paper.

A full scaled finite element model of the base design of the HCPB-TBM BU has been built to run thermal analyses of the beryllium and Li_4SO_4 pebble beds and thermo-mechanical analyses of the BU structure, both in steady state and in a typical transient regime during a pulse of the ITER D–T phase. The temperatures reached in the Li_4SO_4 and beryllium pebble beds in the BU base design are 930.8 °C and 712.9 °C, respectively, which are above the recommended values of 920 °C for Li_4SO_4 and 650 °C for the beryllium pebbles. The maximum temperature in the structural steel is 548.4 °C, which remains under the design limit defined for the TBM studies (550 °C). In order to decrease the temperature in the hot spots identified in the pebble beds, a reduction of the Li_4SO_4 and beryllium bed volumes has been adopted. As for the structural material, the thermo-mechanical analyses have been assessed with respect the RCC-MR design code (completed for irradiation damages with ITER SDC-IC). The results reveal some problematic points in the base design, concentrated in the coolant inlet and outlet pipes and in the connection region of the BU cooling plates with the BU backplate. Submodeling technique has been used to improve the design in these regions. An increase in the thickness of the coolant inlet and outlet pipes and a redesign of the BU backplate have led to a fulfillment of the codes and standards. The design modifications of pebble bed region and structural material have been implemented in the final design of the BU that is presently used as reference for the design and test of a BU mockup in KIT.

1. Introduction

One of the major technical objectives in ITER will be to "Test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat, and electricity production" [1]. The HCPB-TBM is one of the 2 European TBM concepts to be tested in ITER. The role of the BU in the TBM is to breed tritium, and extract heat produced in structural and functional materials.

The design and functionality of the HCPB-TBM box and BU are described in detail in [2,3]. The BU (Fig. 1 down) consists of 2 parallel U-shaped *cooling plates*. 2 thin *wrap plates* are welded to connect the cooling plates on their side. The 2 cooling plates connected define the volume where the breeder material (in form of lithium orthosilicate–Li_4SO_4–pebble bed) is contained. The *manifold front* and *backplate* close the volume of the breeder material and are designed to distribute the helium coolant (8 MPa) in the cooling plates. The cooling plates and the manifold front/backplates are welded in cantilever position to the *BU backplate*, which acts as structural interface between the TBM Box and the BU. The BU volume between the external part of the cooling plates and the TBM box structure is occupied by the beryllium pebbles (neutron multiplier). The high pressure (8 MPa) helium coolant enters/exits the BU by the *inlet/outlet pipes* which are welded to the manifold backplate, and is distributed in the cooling plates. The low pressure (0.4 MPa) purge gas helium enters the BU through the BU backplate and sweeps first the beryllium pebble then the Li_4SO_4 pebble bed in order to extract the tritium bred. The structural material is the reduced activation ferritic–martensitic steel, EUROFER 97-3 (9% CrWVTa).

The relevant design parameters identified for the HCPB-TBM considered in the D–T high duty phase are: EUROFER maximum

* Corresponding author. Tel.: +49 (0)721 608 2 2562.
E-mail address: francisco.hernandez@kit.edu (F. Hernández).

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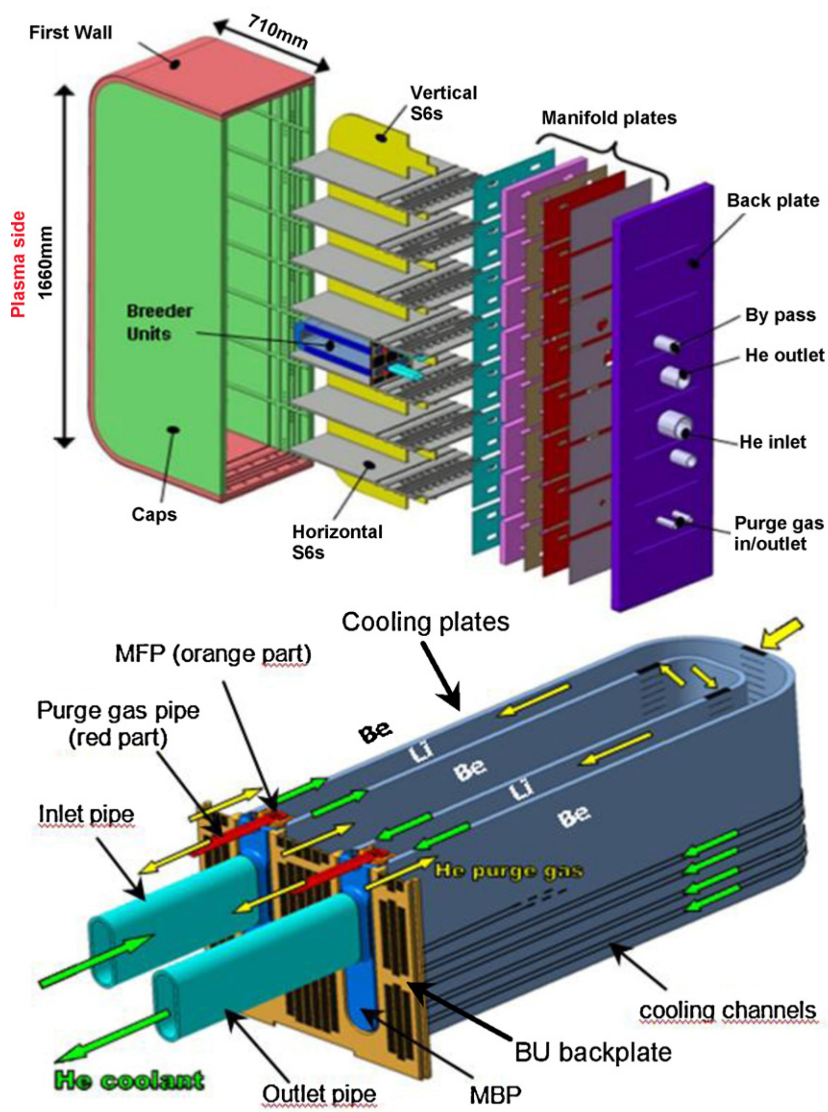

Fig. 1. HCPB-TBM box (up) and sliced BU (down).

operational temperature 550 °C, ceramic breeder Li_4SO_4 maximum temperature (920 °C), beryllium multiplier maximum temperature (650 °C). EUROFER temperature upper limit of 550 °C is set by the creep strength [4]. The maximum temperature of 920 °C for the Li_4SO_4 is strongly linked to its thermo-mechanical behavior, tritium release, and thermal expansion. In particular the value of 920 °C is based on avoiding sintering, which could inhibit the tritium release [15]. As for beryllium, its lifetime is limited by the accumulated amount of transmutation helium. Swelling of beryllium at temperatures below 500 °C is roughly proportional to the accumulated helium concentration. However, beryllium swelling increases exponentially with further increase of temperature until it reaches saturation at ∼40%: maximum beryllium pebble operation temperature is thus strictly restricted below 650 °C [15].

Starting from a preliminary design of the BU based on the one proposed in [3], detailed fluid dynamic analyses of the helium coolant have been presented in [5], in order to optimize the mass flow distribution in the cooling plates and define a BU base design. Preliminary thermal analysis of the BU base design presented in [3], confirmed its suitability to be used for further studies. In this paper the detailed thermal and thermo-mechanical performances of the base design have been evaluated and the problematic points identified. Solutions to solve the thermo mechanical design issues in the problematic areas have been studied and successfully implemented in the final design.

2. Thermal analysis

The temperature field in the structural and functional components of the BU has to be monitored with respect the design limits and is necessary as boundary condition for the thermo-mechanical analyses. Two finite element (FE) analyses have been performed with Ansys (Workbench 13) code: steady state and transient under a typical ITER pulse.

The model used in both analyses is shown in Fig. 2. It consists in a 1/16 of the TBM box, corresponding to the left side BU cell in the equatorial plane of the TBM box (the one exhibiting the highest nuclear heating, according to the neutronic analyses performed in [6]). The model includes the Li_4SO_4 and beryllium pebble beds. In order to calculate helium temperature variations during a transient analysis, helium coolant is modeled by fluid lines (FLUID116 elements in Ansys). A material database [7] is used to define the properties of the EUROFER 97 structural components. A continuum dummy material is used to model the pebble beds and appropriate properties are affected to simulate their discrete nature. Data on the thermal conductivities of the pebble beds have been obtained