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Thermo-hydraulic analysis of EU DEMO WCLL breeding blanket

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ABSTRACT

In the frame of EUROfusion Work Package Breeding Blanket, thermal-hydraulic engineering analyses were carried out at ENEA Brasimone, in close cooperation with Sapienza University of Rome, to investigate thermal and fluid-dynamic behavior of the Water Cooled Lithium Lead Breeding Blanket, which is a candidate option for the European DEMO nuclear fusion reactor.

The research activity focused on the equatorial elementary cell of an outboard segment with the aim of obtaining a temperature map of breeding blanket domains and to evaluate breeding zone and first wall systems cooling ability. A three-dimensional finite volume model of the breeding unit was developed, adopting the commercial CFD code ANSYS CFX 15.0. Steady state simulations were carried out considering a heat flux of 0.5 MW m^{-2}, a radial power density distribution applied to all domains, and buoyancies forces activated in PbLi region. Results show that FW and BZ systems have good cooling efficiency, maintaining the maximum temperature in PbLi and solid structures well below 500 °C. The thermal-hydraulic results are discussed, highlighting open issues and suggesting pertinent modifications to DEMO WCLL coolant system layout aimed at optimizing the design.

1. Introduction

The breeding blanket is a key component in a fusion power plant in charge of ensuring tritium breeding self-sufficiency, adequate neutron shielding and energy extraction for an efficient power conversion cycle.

The Water Cooled Lithium-Lead (WCLL) blanket has been identified as a feasible blanket candidate for DEMO fusion power plant and it is investigated in the EUROfusion Breeding Blanket Project [1] by ENEA and its linked third parties [2].

The WCLL blanket uses reduced activation ferritic-martensitic steel (Eurofer) as structural material, Lithium-Lead (PbLi) as breeder, neutron multiplier and tritium carrier, and water at typical Pressurized Water Reactor (PWR) conditions as coolant.

Thermal and fluid-dynamic analyses have been carried out to obtain a complete temperature map of WCLL breeding blanket, to investigate PbLi flow path in breeding zone and to evaluate thermal-hydraulic efficiency of Breeding Zone (BZ) and First Wall (FW) cooling systems, verifying that maximum temperature of Eurofer structures is below 550 °C. The analyses focused on the equatorial breeding unit of an outboard segment [2]. A detailed three-dimensional finite volume model of the breeding unit is developed, adopting the commercial CFD code ANSYS CFX 15.0. This approach allows obtaining a temperature distribution in solid and fluid domains. Some steady state simulations are carried out in order to evaluate the BZ and FW cooling ability and to optimize the temperature distribution changing system layout.

2. WCLL breeding blanket design

The WCLL BB design is based on DEMO 2015 specifications [3] and CAD model, which is characterized by 18 sectors. Each sector (20°) includes two inboard segments and three outboard segments.

Starting from the main outcomes obtained from WCLL 2015 design and analyses [4–6], an advanced and optimized design has been developed in 2016. The WCLL blanket concept [2] is based on the Single Module Segment (SMS) approach. The blanket segment, shown in Fig. 1, consists of an external box, composed by the FW, directly exposed to the plasma, the Side Walls (SWs), the bottom and top caps and the Back Plate (BP).

The blanket segment is reinforced with a set of stiffeners: radial-toroidal stiffeners divide the segment in poloidal direction in slices (i.e. breeding units) illustrated in detail in Figs. 1 and 2. Five radial-poloidal stiffeners divide the breeding units in 6 toroidal channels, where PbLi is distributed. A baffle plate, placed at half between two horizontal stiffeners, ensures the circulation of PbLi in radial-poloidal direction inside the breeding zone (see Fig. 3). The breeding units are filled with PbLi alloy and cooled by means of water, at PWR conditions, flowing in

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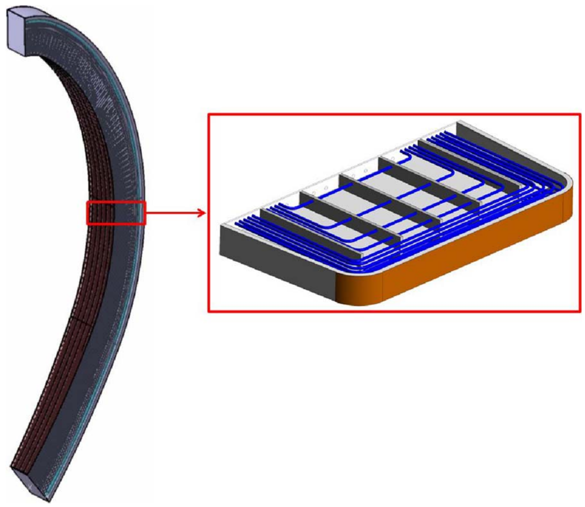

Fig. 1. WCLL BB 2016 design: outboard segment and breeding unit at equatorial plane.

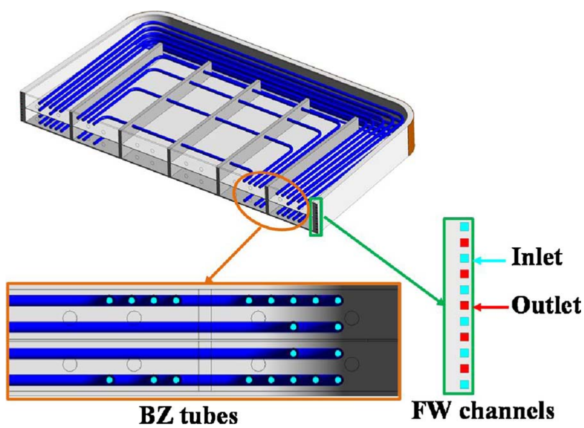

Fig. 2. WCLL breeding unit: detail of FW and BZ coolant systems.

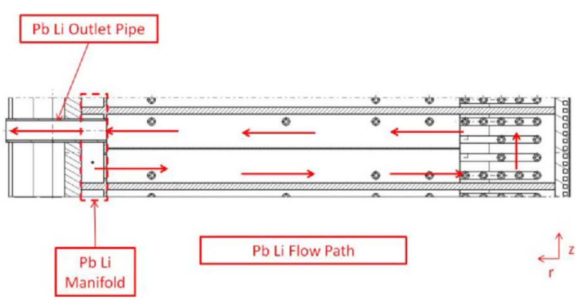

Fig. 3. WCLL breeding unit: PbLi flow path.

radial-toroidal Double Wall Tubes (DWTs) crossing vertical stiffeners. The FW and SWs are cooled by means of square channels, where water flows in counter-current direction at PWR conditions.

In order to transfer the thermal power to the Power Conversion System (PCS) [7], the WCLL blanket is linked and integrated with the Primary Heat Transfer System (PHTS) [2] through the in-vessel piping system, which is formed by the feeding and collecting pipes of the in-board and outboard segments.

3. Computational model

3.1. Geometry

A three-dimensional finite volume model of the breeding unit of DEMO WCLL blanket was set-up, using ANSYS CFX v15.0 code. The model includes solid domains (i.e. stiffeners, DWTs, FW, and Tungsten layer) and fluid domains (i.e. PbLi and water coolant), schematized in Fig. 4.

The breeding unit has an average toroidal distance of 1300 mm, the radial dimension is 827 mm and the total height is 135 mm. The model is developed considering half height of radial-toroidal stiffeners, as the periodic condition is applied. The BZ coolant system consists of 21 DWTs with hydraulic diameter of 8 mm and an external diameter of 13.5 mm. The gap of DWT is not modelled. The breeding unit includes 10 square channels in the FW of 7 × 7 mm.

3.2. Mesh

A mesh independency analysis, described in Ref. [8], is performed for the finite volume model to select optimized spatial discretization, allowing accurate results and reasonable calculation time. A first preliminary independent analysis is conducted on BZ and FW fluid domains. For this purpose, simulations are carried out for one BZ tube and one FW single channel, using meshes with different degree of detail. Pressure drops between inlet and outlet and the bulk temperature are evaluated for each case and compared with the others, as reported in Tables 1 and 2.

The analysis demonstrated that a good comprise between accuracy and computational cost is achieved with 1.43×10^6 nodes in one FW channel and 1.78×10^6 nodes in one BZ tube.

Once selected the mesh for BZ and FW water domains, a sensitivity analysis is conducted using the complete computational model. Three meshes are set-up which differ for the level of detail in the PbLi domain as well as in the solid structures. The parameters used for the comparison are the maximum and the outlet temperature of PbLi domain. The results, reported in Table 3, showed that a good compromise between degree of detail and the computational time efforts is achieved with a minimum of 10.3×10^6 nodes.

The selected mesh, used for the simulations, is characterized by 14×10^6 nodes and 28×10^6 elements. Hexahedral and tetrahedral elements are adopted to discretize the model, considering the

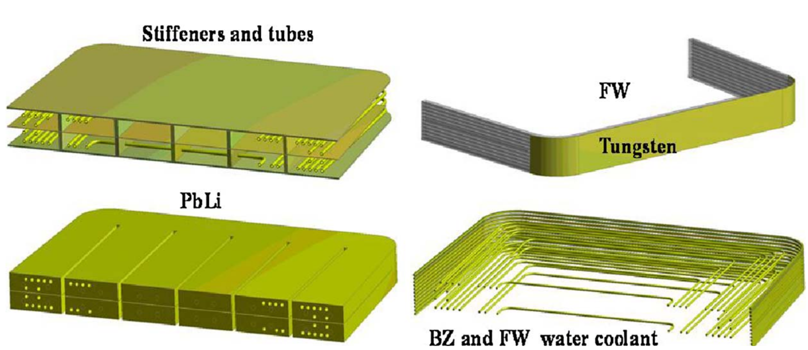

Fig. 4. CFX solid domains (i.e. stiffeners, DWTs, FW and tungsten layer) and fluid domains (i.e. PbLi, FW and BZ coolant).