Parametric study of the influence of double-walled tubes layout on the DEMO WCLL breeding blanket thermal performances

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Within the framework of the EUROfusion activities regarding the EU-DEMO Breeding Blanket (BB) concept, the University of Palermo is long-time involved, in close cooperation with ENEA, in the design of the Water Cooled Lithium Lead (WCLL) BB, that is one of the two concepts under consideration for the DEMO reactor. It is mainly characterized by a liquid lithium-lead eutectic alloy acting as breeder and neutron multiplier, as well as by subcooled pressurized water flowing as coolant under PWR-like conditions (pressure of 15.5 MPa and inlet/outlet temperatures of 295 °C/328 °C). A research campaign has been recently carried out to study the potential influence of the Breeding Zone cooling circuit layout, composed of bundles of Double Walled Tubes (DWTs), on the blanket thermo-mechanical behaviour. In the first phase, a parametric study has been performed to investigate the effects of some geometrical DWT parameters onto the blanket thermal response in order to identify the best tubes layout, in case arranged along toroidal-radial planes. In the second phase, the thermo-mechanical performances of the blanket equatorial region, equipped with the optimized DWTs layout, have been assessed. The study has been carried out following a theoretical-numerical approach based on the Finite Element Method and adopting the ABAQUS v. 6.14 commercial code. Model, assumptions and results obtained are herewith presented and critically discussed.

Keywords: DEMO, WCLL breeding blanket, DWT, FEM.

1. Introduction

Aiming at the exploitation of fusion energy for electric power generation [1], EUROfusion consortium is leading the European research activities towards the development of the "first generation" of thermo-nuclear fusion power plants. Among the several milestones to be reached along such a tough and long-term path, the construction of DEMO reactor plays a relevant role, having to demonstrate the commercial feasibility and economic competitiveness of the future fusion power plants in the world energy market. Pivotal to this project is the design of the Breeding Blanket (BB) [2], which represents the biggest directly plasma facing component covering the vacuum vessel, deputed to three main functions: heat power removal, radiation shielding and tritium production. Currently, two breeding blanket concepts are being investigated for the selection of the driver concept to be adopted for the European DEMO reactor. In particular, the Helium-Cooled Pebble Bed (HCPB) BB concept [3], which relies on the use of helium as coolant and pebble beds composed of Be and Li_4SiO_4 acting respectively as neutron multiplier and breeder material, and the Water-Cooled Lithium Lead (WCLL) BB concept [4], which foresees the adoption of water acting as coolant and a liquid eutectic alloy of Pb and Li (Pb-15.7Li) as neutron multiplier and breeder material, respectively. The latter stands out in the use of pressurized sub-cooled water as working fluid undergoing a thermal cycle very similar to the one adopted in the well-known PWR fission power plants (pressure of 15.5 MPa and inlet/outlet temperatures of 295 °C/328 °C). Nevertheless, its design results particularly demanding since several aspects need to be taken into account, mainly concerning neutronics [5][6], thermomechanics [7][8] and thermal-hydraulics [9][10][11]. The research activities carried out so far show the need for this kind of component of a multi-physics approach able to improve its design by means of optimization methods while complying with all the prescribed requirements [4] regarding performances, integration, materials and safety. Accordingly, the herein presented research activity has concerned the study of the impact of the Breeding Zone (BZ) cooling circuit layout on the thermal behaviour of the WCLL BB by means of parametric thermal analyses aiming at the identification of the best configuration in terms of cooling performances. Furthermore, a final thermo-mechanical assessment of the equatorial region of the central outboard blanket segment, equipped with the optimized tubes layout, has been carried out. The study has been carried out following a theoretical-numerical approach based on the Finite Element Method (FEM) and adopting the quoted ABAQUS v. 6.14 commercial code [12].

2. WCLL BB architecture

The current configuration of the WCLL BB foresees a toroidal segmentation of the whole torus in 16 sectors, each one composed of 2 inboard segments and 3 outboard segments [4]. Recent studies [4][13] have demonstrated the advantages of the adoption of a Single

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Module Segment (SMS) architecture with respect to the Multi Module Segment (MMS) one. Such architecture relies on the adoption of several "banana-shaped" segments [14], whose design consists of a pressurized steel structure named "Segment Box" (SB), composed of the First Wall (FW) covered by a 2mm-thick W-armour, the Side Walls (SWs), the caps and the back plate, housing the BZ, containing the liquid breeder and a grid of Stiffening Plates (SPs). A structure composed of both cooling water and breeder manifolds and the Back Supporting Structure (BSS) is finally attached to the BP. According to such design, each segment can be conceived as made of a poloidal repetition of elementary "cells", delimited by two consecutive toroidal-radial SPs (SPs_{tr}), with except of Cap regions whose design might be determined "ad hoc". The architecture of the outboard central segment of the WCLL BB is shown in Fig. 1.

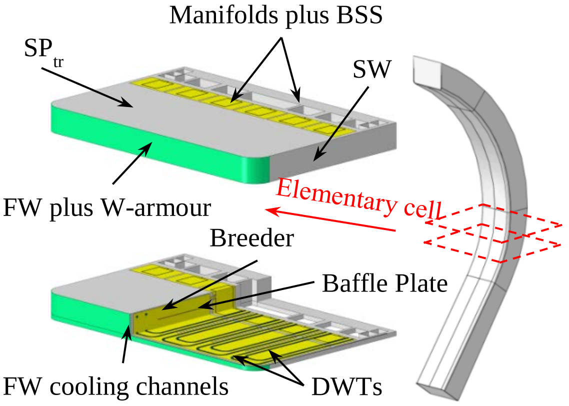

Fig. 1. WCLL BB outboard central segment architecture.

Inside each elementary cell, the presence of a steel Baffle Plate (BP) able to drive the liquid metal flow along its radial-poloidal-radial path is foreseen, but without playing any structural role. Two separate circuits are deputed to cool down the SB and the BZ. The former consists in a system of radial-toroidal C-shaped squared cooling channels (maximum 10 per cell), where countercurrent water flow occurs, whereas the latter relies on the use of bundles of Double-Walled Tubes (DWTs) submerged within the breeder. The structural material proposed for this component is EUROFER [15], a reduced activation ferritic/martensitic steel developed within the R&D activities on fusion reactor materials.

3. DWT layout optimization

Breeding blanket optimization relies basically on the enhancement of its tritium breeding and heat removal performances, while complying with safety, structural and manufacturing requirements. Since both nuclear and thermal behavior of the WCLL BB are strictly related to the total amount and distribution of both steel and water within the BZ, a parametric analysis aiming at the optimization of the DWTs layout has been carried out, taking into account the following requirements [4].

- Maximum temperature of EUROFER structural components below 550 °C [15]
- DWTs external diameter (D_o) and internal diameter (D_i) equal to 13.5 mm and 8 mm, respectively
- DWTs minimum bend radius equal to 3 times D_o
- Minimum distance between DWTs axes of 26 mm
- Maximum number of DWTs bends limited to 2
- Toroidal symmetry of the thermal field
- No intersection with SPs

3.1 Parametric model

As already adopted in [9], the parametric model of a novel DWTs concept layout has been set-up considering only a Central Unit (CU) of the equatorial elementary cell (Fig. 2), delimited by two consecutive poloidal radial SPs (SPs_{pr}). In particular, a set of 4 toroidal-radial DWTs (2 external and 2 internal) has been conceived for each unit of the elementary cell, following the idea that DWTs have to be placed nearby those steel surfaces whose temperature has to be kept below the prescribed limit (i.e. FW back surface and SPs).

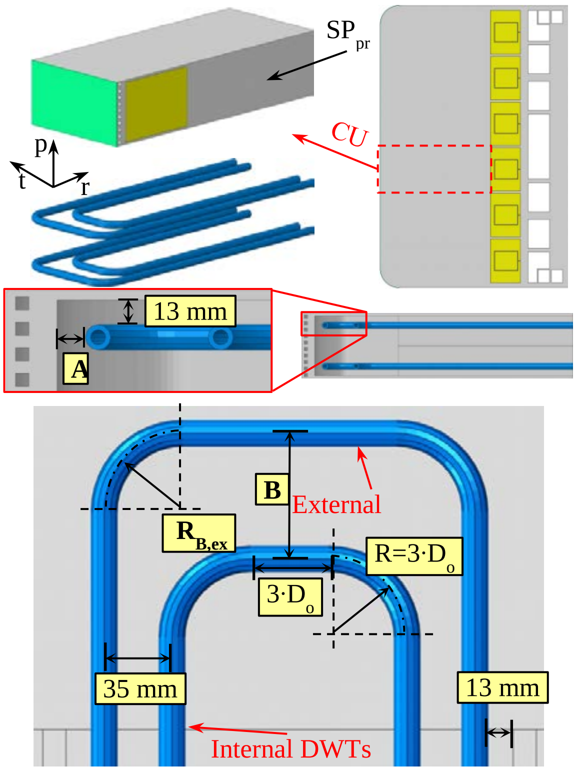

Fig. 2. DWTs concept parametric model.

Three geometrical parameters have been taken into account in order to set-up the adopted CU parametric model:

- radial distance between the FW back surface and the nearest DWT outer surface (A);
- radial distance between the axes of the external and internal DWTs (B);
- bend radius of external DWTs ($R_{B,ext}$).

The design table of parameters taken into account for the CU parametric model, including 48 configurations, is reported in Table 1.

Table 1. Design table of parameters.

Parameter	min	max	step
A	15 mm	22.5 mm	2.5 mm
B	55 mm	75 mm	10 mm
$R_{B,ext}$	$3 \cdot D_o$	$5 \cdot D_o$	D_o

The other geometrical features have been assumed with the aim of minimizing the distance between DWTs and SPs (which has been kept as half of the minimum distance between axes plus one external diameter), while satisfying the requirements reported above. Moreover, a minimum distance between two consecutive bends equal to 3 times the external diameter has been assumed as good practice in manufacturing. Toroidal distance between internal and external DWTs has been maximized in order to better cover the SP_{tr} surface.

3.2 Parametric thermal analysis and results

A CU parametric FE thermal model has been set up, composed of ~300k nodes connected in ~800k linear elements. Temperature-dependent material properties for EUROFER, Pb-15.7Li and W have been drawn from [16], [17] and [18], respectively. The following set of proper loads and boundary conditions pertinent under the Normal Operation (NO) steady state loading scenario [19] has been adopted:

- heat flux onto FW plasma facing surface equal to 0.32 MW/m²;
- nuclear heating obtained by fully heterogeneous neutronic calculations carried out at the University of Palermo on a previous configuration of the cell [20];
- forced convective heat transfer at coolant/wall interfaces based on Dittus&Bölter correlation [21] using reference the mass flow rates ($\dot{m}_{FW}$=1.0506 kg/s, $\dot{m}_{DWTs}$=1.1040 kg/s) and a bulk temperature of 311.5 °C (average between inlet and outlet temperatures);
- pure diffusive heat transfer within the breeder (assumed as stagnant due to its very low flow velocity) with a contact thermal conductance at steel walls conservatively assumed equal to 100 kW/(m² °C).

Heat transfer inside BZ is strongly dependent upon coolant flow path and, hence, on DWTs distribution. The herein proposed layout has been conceived assuming a water triple-pass flow inside the BZ, with the inlet located at the central region and the outlet at the side ones (Fig. 3). According to that, the total BZ coolant mass flow rate of a single elementary cell is fed to 8 DWTs at the inlet (4 tubes each side), flowing then along multiple radial-toroidal paths.

A total of 48 CU configurations have been analyzed by means of a Python script able to manage the selected geometrical parameters and perform steady state thermal analysis inside ABAQUS code environment.

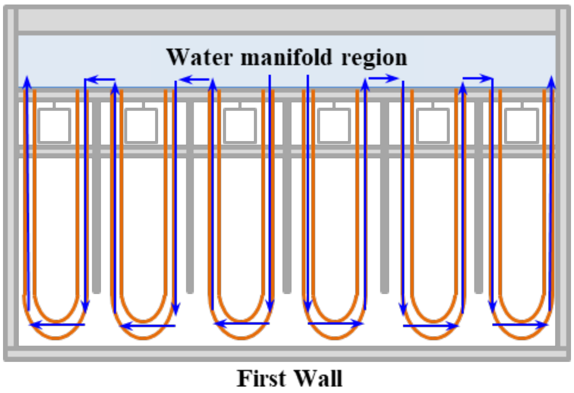

Fig. 3. Coolant flow path inside BZ.

Maximum temperatures in the EUROFER domain and, especially, in the SPs grid, have been considered, as FW is effectively cooled well below the limit. The best layout, characterized by A^*, B^* and $R_{B,ext}^*$ parameters, has been identified by the following criterion:

$$\left\{A^*,B^*,R_{B,ext}^* \;\middle|\; T_E\left(A^*,B^*,R_{B,ext}^*\right) \le 550\ °C \;\wedge\; T_{SP}\left(A^*,B^*,R_{B,ext}^*\right) = \min\left[T_{SP}\left(A,B,R_{B,ext}\right)\right]\right\} \tag{1}$$

where T_E is the EUROFER maximum temperature and T_{SP} is the maximum temperature of the SPs grid domain. The temperature distributions in the best configuration, given by A^*=17.5 mm, B^*=65 mm and $R_{B,ext}^*=3 \cdot D_o$, is shown in Fig. 4.

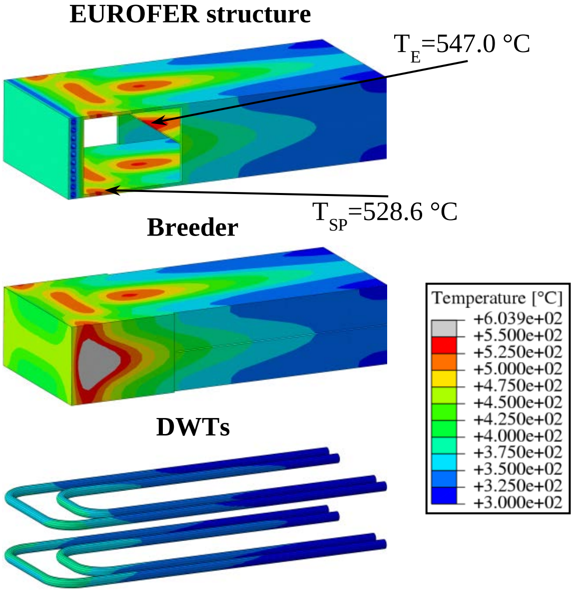

Fig. 4. Temperature distributions in the best DWT layout.

In Fig. 5, the maximum temperatures in the whole EUROFER domain and SPs grid are plotted against the geometrical parameters. Discrepancies between left-hand and right-hand profiles can be justified by the fact that maximum temperature in EUROFER can be obtained also in the BP, even though it is not much relevant since the BP does not play any structural role.

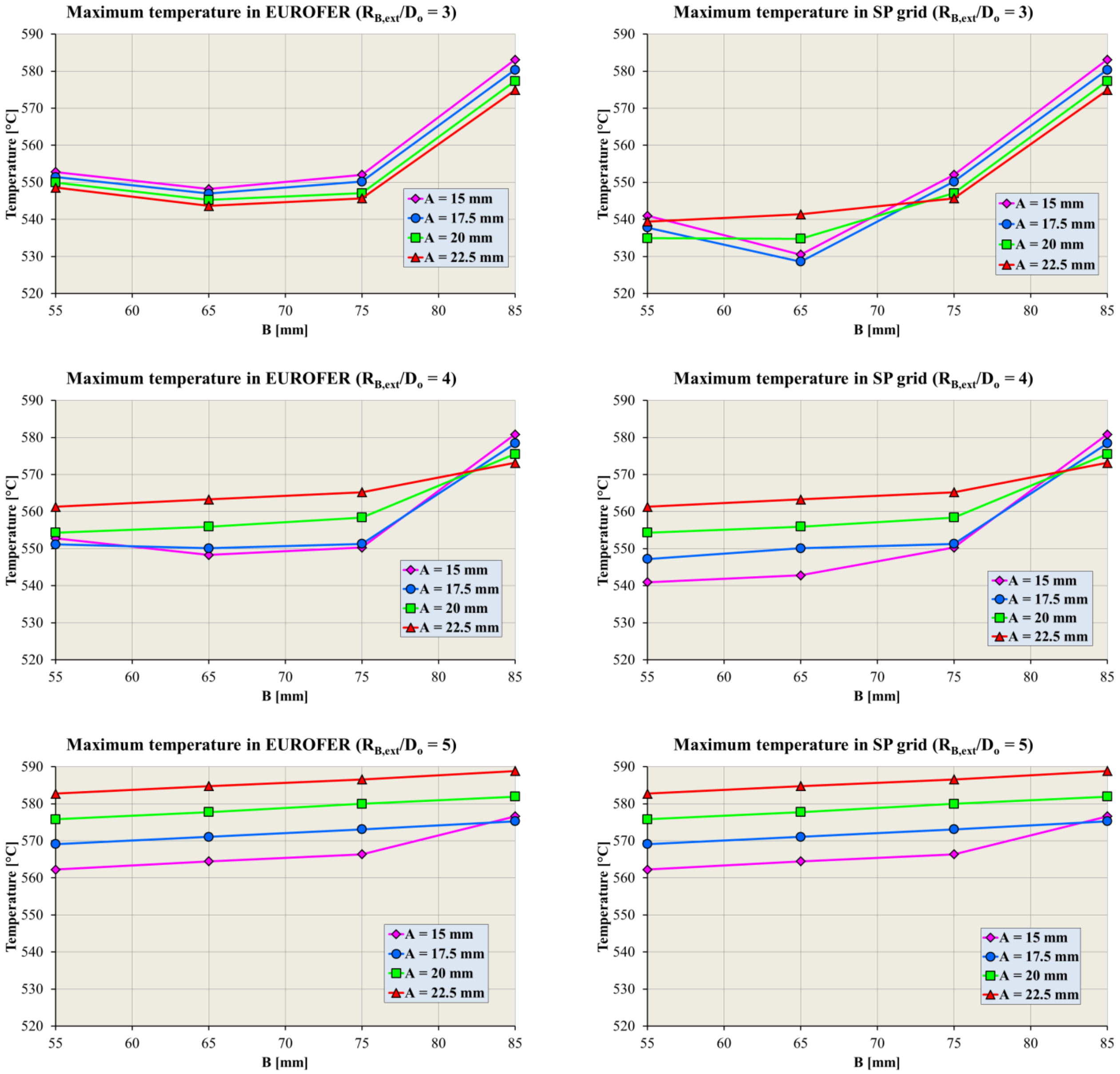

Fig. 5. Results of the parametric thermal analysis.

4. Thermo-mechanical assessment of the optimized equatorial region

A more realistic assessment of the DWTs configuration impact onto the WCLL BB thermo-mechanical performances requires a more detailed model. Assuming the optimized DWTs configuration identified during the first part of the activity, a FE model reproducing two elementary cells located at the equatorial region of the outboard blanket central segment has been set up, composed of ~6M nodes connected in ~10M linear elements (Fig. 6). Since it would have required a dedicated optimization study, the manifold region has not been updated in order to house correctly the new DWTs layout providing the assumed coolant triple-pass flow. However, no significant effects on the thermo-mechanical response of hot regions are expected due to the small modifications required. The same set of loads and boundary conditions adopted for the parametric analysis have been applied to the model in order to determine the thermal field in the structure by means of a steady state thermal analysis.

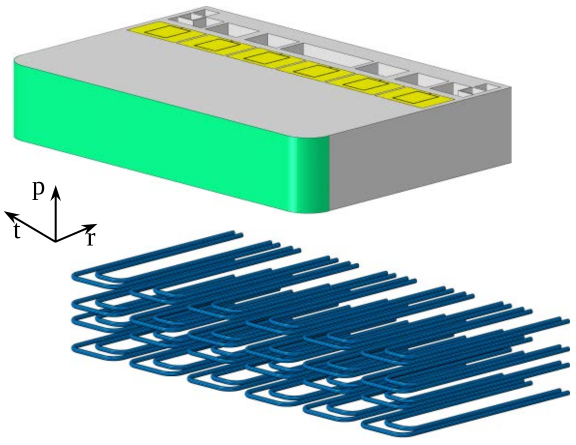

Fig. 6. Detailed FE model of the two equatorial blanket-cells.

Conversely to what previously performed, convective heat transfer coefficients at wall/coolant interfaces have been computed by means of an enthalpy balance-based iterative procedure, able to update the mass flow rates assuming the coolant to undergo the reference inlet-outlet thermal rise of 33 °C. For one elementary cell, a mass flow rate of 0.776 kg/s and 0.961 kg/s has been obtained for the FW-SWs channels and DWTs cooling circuit, respectively. The temperature distribution obtained in the EUROFER domain is shown in Fig. 7.

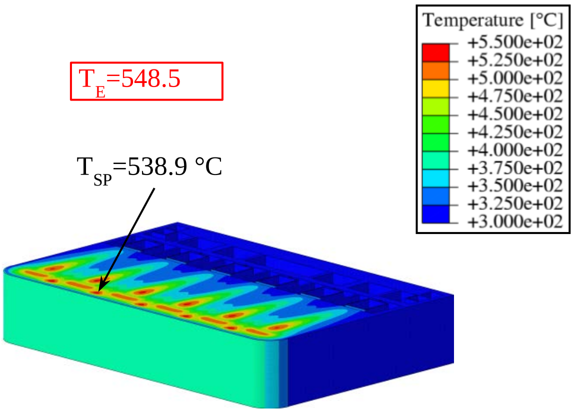

Fig. 7. EUROFER temperature distribution n.

The maximum temperature obtained in the SPs grid resulted to be ≈10 °C above that computed in the parametric analysis, essentially due to the higher detail in the mass flow rates assessment. The thermal field has been, hence, used to determine the imposed strain induced by thermal expansion in the thermo-structural analysis. In particular, the following loads and boundary conditions, pertinent to both nominal (NO) and over-pressurization (OP) loading scenarios [19] (the latter caused by an in-box LOCA event), have been taken into account for the mechanical simulation:

- pressure load onto water wetted surfaces (15.5 MPa under NO scenario, 18.6 MPa under OP scenario);
- pressure load onto breeder wetted surfaces (0.5 MPa under NO scenario, 18.6 MPa under OP scenario);
- imposed strain due to thermal expansion;

A set of mechanical restraints (Fig. 8) widely adopted in recent studies [8][22] on the thermo-mechanics of WCLL BB modules has been applied to the model.

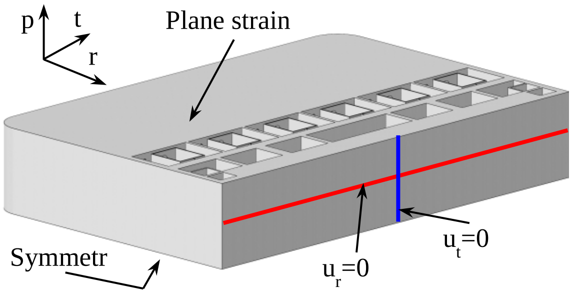

Fig. 8. Mechanical restraints.

The W-armour has not been implemented in the model to avoid the unrealistic compressive effect it exerts on the FW structure due to its lower thermal expansion coefficient. Static linear elastic analyses have been carried out to investigate the mechanical response of the structure under both NO and OP scenarios and the Von Mises stress fields obtained are shown in Fig. 9.

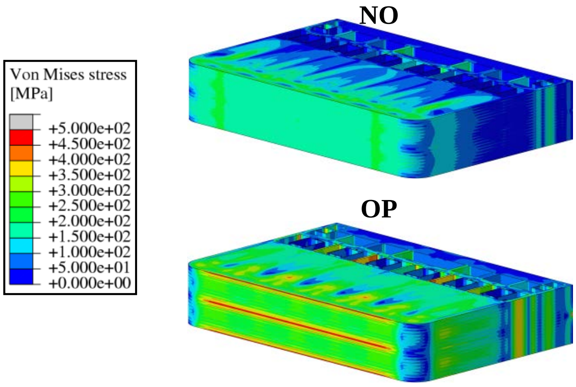

Fig. 9. Von Mises stress fields under NO and OP scenarios.

Structural integrity of the WCLL BB equatorial region has been assessed under both NO and OP scenarios by the verification of the design criteria reported in the RCC-MRx standards [23]. Accordingly, a stress linearization has been carried out along 14 relevant paths located within the structure as in Fig. 10.

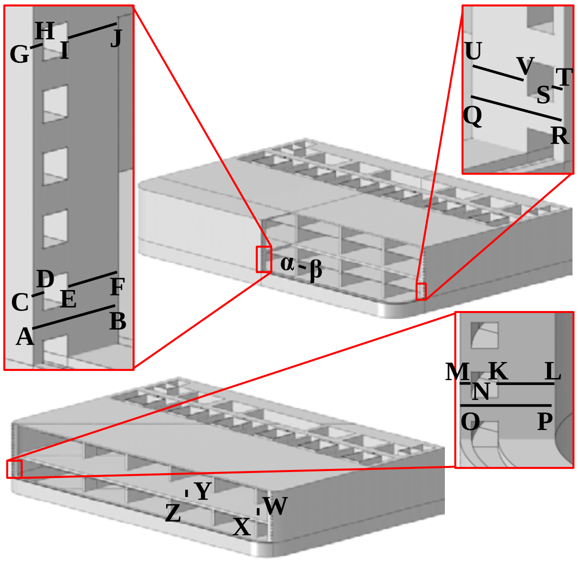

Fig. 10. Stress linearization paths.

The comparison among the several combinations of primary (P), secondary (Q) and peak (F) stresses (both membrane and bending) related to the different failure modes [23], and the respective allowable stresses (S) is reported in Fig. 11. In particular, all the criteria have been fulfilled with wide margin, with the only exception of the immediate plastic flow localization criterion ($P_m+Q_m<S_{em}$), showing lower margin in several regions.

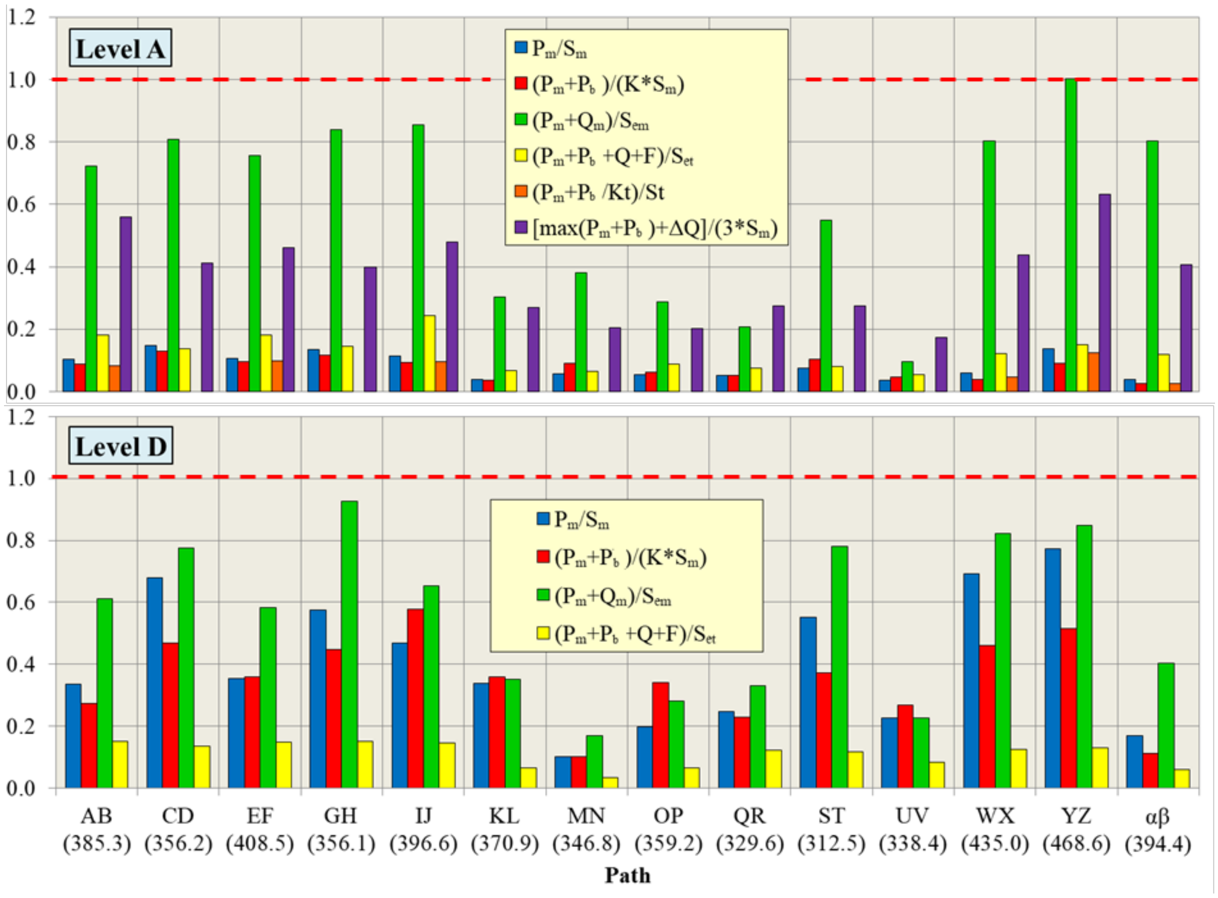

Fig. 11. Results of the verification of the RCC-MRx design criteria (path average temperature [°C] within brackets).

5. Conclusions

Within the framework of the EU-DEMO research activities concerning the WCLL BB, a numerical study aiming at the assessment of the impact of the DWTs layout onto the thermo-mechanical response of the blanket module has been performed. Firstly, a novel concept of DWTs layout has been conceived and optimized by means of a parametric thermal analysis. In a second phase, the thermo-mechanical performances of a two-cells system located at the equatorial region of the segment and equipped with the optimized DWTs layout (24 tubes per cell), has been carried out. The study has shown that the presented DWTs layout is able to guarantee an effective cooling of the BZ, keeping the maximum EUROFER temperature below the allowable limit, and to save its structural integrity, generally complying with the design criteria reported in the RCC-MRx standards.

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References

[1] T. Donnè, European Research Roadmap to the Realisation of Fusion Energy, November 2018, ISBN: 9783000611520.

[2] G. Federici et al., An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, Fusion Engineering and Design, 141 (2019) 30-42, doi: 10.1016/j.fusengdes.2019.01.141.

[3] F.A. Hernández et al., Advancements in the Helium-Cooled Pebble Bed Breeding Blanket for the EU DEMO: Holistic Design Approach and Lessons Learned, Fusion Science and Technology, 75 (5) (2019) 352-364, doi: 10.1080/15361055.2019.1607695.

[4] A. Del Nevo et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fusion Engineering and Design, (2019) In press, doi: 10.1016/j.fusengdes.2019.03.040.

[5] F. Moro et al., Neutronic analyses in support of the WCLL DEMO design development, Fusion Engineering and Design, 136 (2018) 1260-1264, doi: 10.1016/j.fusengdes.2018.04.113.

[6] P. Chiovaro et al., Parametric study of the influence of First Wall cooling water on the Water Cooled Lithium Lead Breeding Blanket nuclear response, Fusion Engineering and Design, In press, doi: 10.1016/j.fusengdes.2019.03.105.

[7] P.A. Di Maio et al., Numerical assessment of the thermomechanical behaviour of the DEMO Water-Cooled Lithium Lead inboard blanket equatorial module, Fusion Engineering and Design, 136 (2018) 1178-1185, doi: 10.1016/j.fusengdes.2018.04.098.

[8] P.A. Di Maio et al., On the effect of stiffening plates

configuration on the DEMO Water Cooled Lithium Lead Breeding Blanket module thermo-mechanical behaviour, Fusion Engineering and Design, (2019) In press, doi: 10.1016/j.fusengdes.2019.03.163.

[9] R. Forte et al., On the effects of the Double-Walled Tubes lay-out on the DEMO WCLL breeding blanket module thermal behavior, Fusion Engineering and Design, (2019) In press, doi: 10.1016/j.fusengdes.2019.01.105.

[10] P. Arena et al., Parametric thermal analysis for the optimization of Double Walled Tubes layout in the Water Cooled Lithium Lead inboard blanket of DEMO fusion reactor, Journal of Physics: Conference Series, 1224 (1) (2019), doi: 10.1088/1742-6596/1224/1/012031.

[11] F. Edemetti et al., DEMO WCLL breeding zone cooling system design: Analysis and discussion, Fusion Engineering and Design, (2019) In press, doi: 10.1016/j.fusengdes.2019.04.063.

[12] Abaqus Analysis User's Guide: Online Documentation. Version 6.14-2, Simulia, Dassault System.

[13] G. Bongiovì et al., Multi-Module vs. Single-Module concept: Comparison of thermomechanical performances for the DEMO Water-Cooled Lithium Lead breeding blanket, Fusion Engineering and Design, 136 (2018) 1472-1478, doi: 10.1016/j.fusengdes.2018.05.037.

[14] A. Tassone et al., Recent Progress in the WCLL Breeding Blanket Design for the DEMO Fusion Reactor, IEEE Transactions on Plasma Science, 46 (5) (2018) 1446-1457, doi: 10.1109/TPS.2017.2786046.

[15] B. Van der Schaaf et al., The development of EUROFER reduced activation steel, Fusion Engineering and Design, 69 (1-4) (2003) 197-203, doi: 10.1016/S0920-3796(03)00337-5.

[16] F. Gillemot et al., Material Property Handbook pilot project on EUROFER97 (MTA EK, KIT), (2016), EFDA IDM Ref.: EFDA_D_2MRP77.

[17] D. Martelli et al., Literature review of lead-lithium thermophysical properties, Fusion Engineering and Design, 138 (2019) 183-195, doi: 10.1016/j.fusengdes.2018.11.028.

[18] Goodfellow, Metals, Alloys, Compounds, Ceramics, Polymers, Composites. Catalogue 1993/94

[19] A. Del Nevo et al., WCLL Design Report 2018, (2018), EFDA IDM Ref.: EFDA_D_2NUPDT.

[20] P. Chiovaro et al., “Neutronics: Design & Analyses”, Presentation at WCLL BB Design Review Meeting 01.2019, ENEA Brasimone, 8- 10 July 2019.

[21] F.P. Incropera, Fundamentals of Heat and Mass Transfer, John Wiley & Sons Inc., 2011, ISBN: 9780470501979.

[22] G. Zhou et al., Progress on the helium cooled Molten Lead Ceramic Breeder concept, as a near-term alternative blanket for EU DEMO, Fusion Engineering and Design, 146 (2019) 1029-1034, doi: 10.1016/j.fusengdes.2019.01.151.

[23] RCC-MRx, Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN, 2013.