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On the effects of the Double-Walled Tubes lay-out on the DEMO WCLL breeding blanket module thermal behaviour

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The EU-DEMO Water-Cooled Lithium Lead Breeding Blanket (WCLL BB) concept foresees liquid Pb-15.7Li eutectic alloy as breeder and neutron multiplier, whereas pressurized subcooled water as coolant, with operative conditions typical of the PWR fission reactors (temperature in the range of 295-328 °C and pressure of 15.5 MPa). The cooling down of the BB is guaranteed by means of two separated cooling circuits: the one consisted in square channels housed within the complex of Side Walls and First Wall, and the one composed of a set of Double-Walled Tubes (DWTs) submerged in the Breeding Zone (BZ) and deputed to remove heat power therein generated. A parametric thermal study has been carried out in order to optimize the DWTs lay-out within the BZ of the WCLL BB outboard equatorial region ensuring that EUROFER components maximum temperature stays below the allowable value of 550 °C. The analysis has been performed following a theoretical-numerical approach based on the Finite Element Method (FEM) and adopting the ABAQUS qualified commercial code. In the paper, results obtained together with the main assumptions adopted in the parametric analysis are critically discussed and a new, sustainable DWTs configuration is proposed.

Keywords: DEMO, WCLL, Breeding Blanket, DWTs, FEM.

1. Introduction

Within the framework of the EUROfusion project activities concerning the EU-DEMO Breeding Blanket (BB) [1–3], University of Palermo is long-time involved, in close cooperation with ENEA, on the design of the Water-Cooled Lithium Lead (WCLL) BB, which is currently under consideration to be adopted in the EU-DEMO reactor. In particular, it foresees the adoption of the liquid lithium-lead eutectic alloy Pb-15.7Li as breeder and neutron multiplier and the use of pressurized subcooled water as coolant, flowing at the average pressure of 15.5 MPa with an inlet temperature of 295°C and an outlet one of 328°C.

In agreement with the EU-DEMO Baseline 2015 [4], the WCLL BB is foreseen to be segmented into 18 toroidal sectors, each one composed of 3 outboard segments and 2 inboard segments. As to the architecture of each segment, the Single Module System (SMS) approach, characterized by a poloidal-oriented “banana-shaped” structural box housing the breeder, is nowadays the best potential option for the WCLL BB design, showing better performances than the alternative Multi Module System (MMS) configuration, especially in terms of breeder drainage, helium extraction, hot spot temperatures and stress intensity mainly under electro-magnetic loads [4–7]. Both its position and shielding function makes the WCLL BB heavily exposed to intense heat loads due to the high heat flux arising from plasma and to the intense nuclear heat power deposited within its volume. The cooling system plays, hence, a relevant role in the reactor operation and its design results particularly demanding since it has to effectively extract the overall heat power deposited into the module while keeping the structure temperature below its prescribed limit [3].

In the present paper, a research activity focussed on the optimization of the Breeding Zone (BZ) cooling circuit lay-out composed of bundles of Double-Walled Tubes (DWTs) of a typical WCLL BB SMS outboard segment, is reported. In particular, the thermal performances of an alternative poloidal-radial orientation of the DWTs have been investigated in terms of number and disposition. The study has been carried out following a theoretical-numerical approach based on the Finite Element Method (FEM) and performing parametric thermal analyses by means of the ABAQUS v6.14 commercial code.

2. WCLL BB outboard segment

According to the SMS concept, the WCLL BB outboard segment is mainly composed by a EUROFER steel [8] actively-cooled banana-shaped structure named Segment Box (SB) containing the BZ, where neutron multiplication and tritium breeding reactions take place.

In particular, the SB is articulated in a First Wall (FW), two Side Walls (SWs) and a Back Plate (BP) and it is reinforced against over-pressurization accidents and electro-magnetic loads by a system of poloidal-radial (vertical) and toroidal-radial (horizontal) Stiffening Plates (SPs). Conversely, the BZ houses the breeder flowing, under quasi-stagnant conditions, according to a radial-poloidal-radial path. The whole segment may be thought as composed of a poloidal sequence of elementary toroidal-radial cells, each one composed of four Central Units (CUs) and two Lateral Units (LUs), as shown in Fig. 1.

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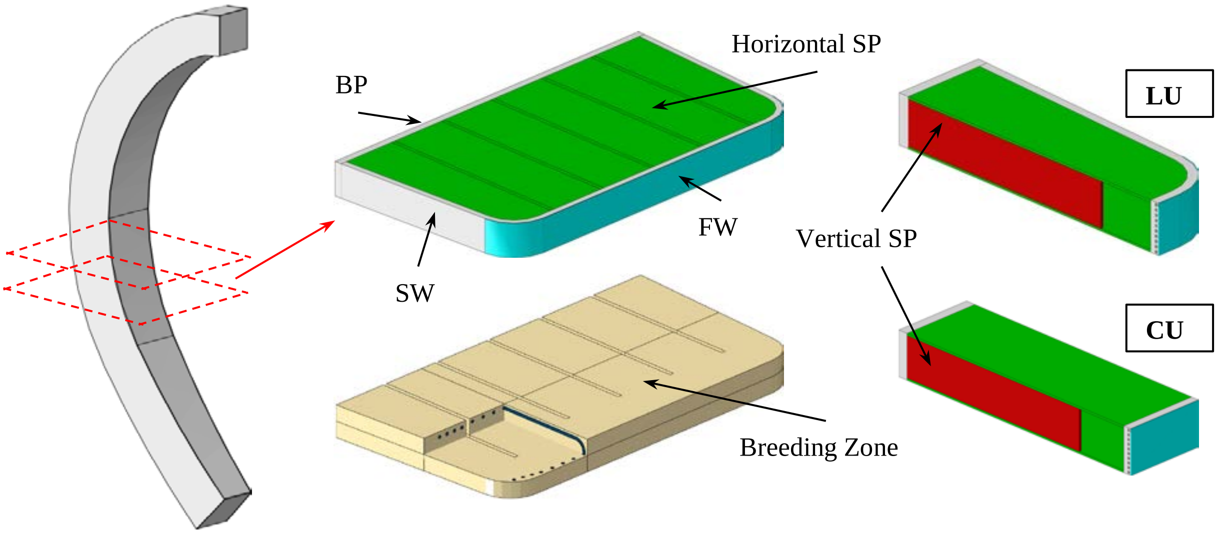

Fig. 1. WCLL BB SMS outboard segment architecure.

In order to safeguard the FW and reduce the undesired "sputtering" effect, a 2 mm thick Tungsten armour is foreseen to be placed onto the whole plasma facing surface.

The WCLL BB outboard segment cooling system is mainly composed of two independent cooling circuits devoted to separately cool the SB and the BZ [9]. The former relies on a set of internal radial-toroidal-radial squared cooling channels (7x7 mm) poloidally arranged with a pitch of 13.5 mm and housed within the complex of SW-FW-SW, where water coolant countercurrent flow occurs with a thermal rise of 33°C from the inlet temperature of 295°C to the outlet one of 328°C. The latter is based on the use of bundles of DWTs submerged within the breeder, where water coolant flows experiencing the same thermal rise as the SB cooling circuit. In particular, DWTs, made of EUROFER and characterized by an internal diameter of 8 mm and a thickness of 5.5 mm, have been widely adopted for the design of the WCLL BB concepts [10,11] with the aim of reducing the probability of undesired liquid metal-water interactions.

3. DWTs lay-out optimization

The design of BZ cooling circuit results particularly demanding and a research campaign has been, hence, launched with the specific aim of assessing an optimized DWTs layout, suitable to effectively meet the design requirements while minimizing the number of tubes to be adopted.

To this purpose, the equatorial cell of the WCLL BB outboard segment equipped with the reference SP grid configuration [6] has been considered, that relies on the use of horizontal SPs extending for the whole radial length of the module while vertical ones stopping themselves 165 mm far from FW, delimiting several toroidal-radial cells articulated in central and lateral units (CUs and LUs), each provided with its own DWTs bundle. The internal Baffle Plates have not been taken into account, since they have no structural role,.

The assessment of the optimized DTWs layout has been carried out independently for either a CU and a LU by running a specific parametric thermal FEM analyses. In particular, the effect of four parameters characterizing the lay-out of the DWTs bundle inside the BZ have been investigated (Fig.2):

- number of tubes (N);
- distance from vertical SPs (A);
- distance from FW (B);
- distance from horizontal SPs (C).

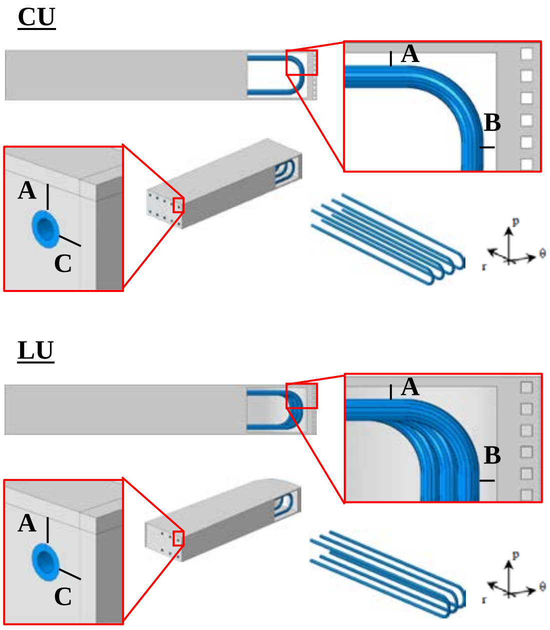

Fig. 2. DWTs lay-out optimization geometrical parameters.

All of the considered configurations are characterized by poloidal-radial DTWs equally spaced along the toroidal direction, so to pursue a more uniform cooling of the SPs. Concerning the LU, it must be highlighted that the distance from the FW (B) is valid only for the DWT closest to the vertical SP whereas the other tubes have been set gradually shorter due to both the presence of the bend region and the SW orientation. Combining different values of the geometrical parameters A, B and C, taken from 5 mm to 14 mm every 3 mm, with an increasing number of tubes from 3 up to 6, a set of 256 cases (Table 1) has been investigated for both the CU and LU.

Table 1. Matrix cases.

N	A [mm]	B [mm]	C [mm]
3	5-14	5-14	5-14
4	5-14	5-14	5-14
5	5-14	5-14	5-14
6	5-14	5-14	5-14

3.1 Central Unit

An appropriate parametric FEM model of the CU including the structure, the breeder and the DWTs has been set-up by means of a Python script. As to the thermal loads, a radial-dependent volumetric density of nuclear-deposited heat power, derived from the nominal steady-state scenario reported in [12], has been applied while a heat flux of 0.5 MW/m^2 has been imposed on the plasma facing surface. Moreover, convective boundary conditions have been implemented at both the FW cooling channels and the DWTs interfaces with coolant. To this purpose, heat transfer coefficients (h) have been computed by means of the Dittus & Bölter correlation [13], taking into account the coolant mass flow rate distribution per channel/tube reported in [12]. The bulk temperature has been uniformly imposed to the average value of 311.5 °C. In Table 2 the resume of the boundary conditions referred to the single tube/channel implemented on the CU model are reported.

Table 2. CU analysis convective boundary conditions.

	N	G [kg/s]	h [W/m^2 °C]
BZ	3	0.0643	17441
	4	0.0483	13855
	5	0.0386	11590
	6	0.0597	16418
FW	10	0.0776	21239

Since the breeder is expected to flow at few mm/s within the BZ, due to the simultaneous action of buoyancy and magneto-hydrodynamic forces, it has been considered as stagnant and a pure diffusive heat transfer has been, hence, assumed within the BZ domain, neglecting convective transport phenomena as widely accepted and already assumed in previous analyses [5,11,14,15]. A thermal contact model has been implemented at all of the breeder-wetted surfaces of the model, characterized by a conservative thermal conductance of 100 kW/(m^2 °C).

A steady-state thermal analysis has been performed for each configuration under investigation and its thermal response has been numerically assessed. Among the 256 configurations analyzed, only 48 cases have been able to maintain the EUROFER maximum temperature below the prescribed limit of 550 °C [6], fixing the minimum number of DWTs to five. The results concerning the eligible DWTs lay-outs have been reported in Fig. 3, where the suitable configurations (for five and six tubes) are plotted as a function of the three geometrical parameters as well as the temperature margin (ΔT) with respect of the limit value of 550 °C, represented by the bubble diameters. With the aim of minimizing the number of tubes (i.e. the steel amount) inside the BZ, as well as keeping sufficient distances between tubes and walls in order to facilitate their installation, the case 147 (A=8 mm, B=5 mm, C=11 mm) equipped with five tubes has been selected as a promising lay-out, showing a maximum temperature of 541.8 °C in correspondence of the horizontal SP (Fig. 4).

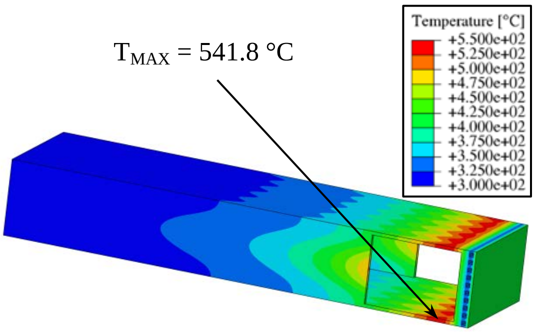

Fig. 4. CU Case 147 SB temperature distribution.

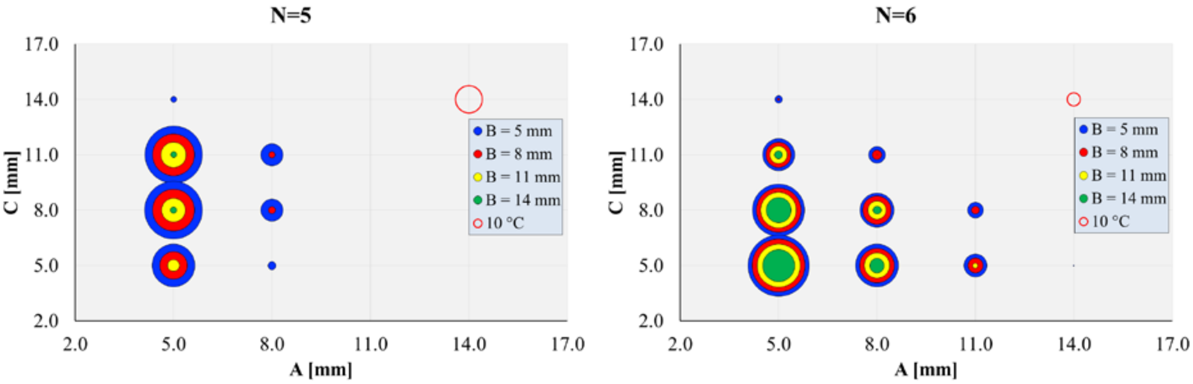

Fig. 3. CU eligible configurations for N=5 and N=6 (bubble diameters represent the ΔT margin with respect of the limit value of 550 °C). The circle in red on the top right shows the bubble dimension referred to a ΔT=10 °C.

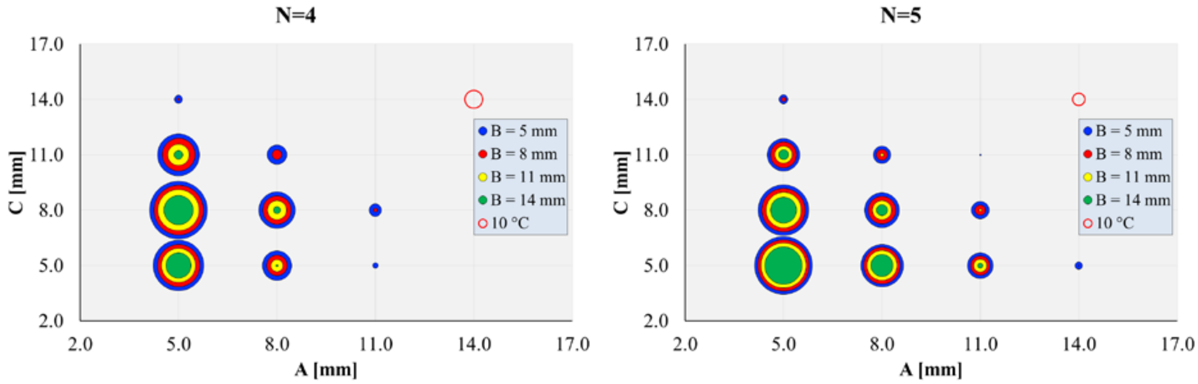

Fig. 5. LU eligible configurations for N=4 and N=5 (bubble diameters represent the ΔT margin with respect of the limit value of 550 °C). The circle in red on the top right shows the bubble dimension referred to a ΔT=10 °C.

3.2 Lateral Unit

As far as the LU DWTs lay-out optimization is concerned, the same procedure adopted for the CU has been followed, implementing the same radial-dependent volumetric density of nuclear-deposited heat power as well as applying an heat flux of 0.5 MW/m^2 onto the plasma facing surface, where a decreasing value representing the normal component according to cosine law, has been assumed for the bend region. Different heat transfer coefficients (Table 3) have been implemented onto the internal DWTs surfaces due to the lower mass flow rate foreseen for the LU BZ cooling system [12].

Table 3. LU analysis convective boundary conditions.

	N	G [kg/s]	h [W/m^2 °C]
BZ	3	0.0397	11869
	4	0.0298	9429
	5	0.0238	7888
	6	0.0198	6817
SW-FW	10	0.0776	21239

A set of 98 cases have been resulted as eligible for the LU, where a minimum of four DWTs are needed for its cooling. The results obtained are shown in Fig. 5 adopting the same format as the CU neglecting the extreme cases equipped with six tubes. In particular, obeying the same decisional criteria of the CU analysis, the case 110 (A=8 mm, B=5 mm, C=11 mm), foreseeing the use of four DWTs, has been selected as a suitable lay-out, showing a maximum temperature of 538.9 °C in correspondence of the horizontal SP (Fig. 6).

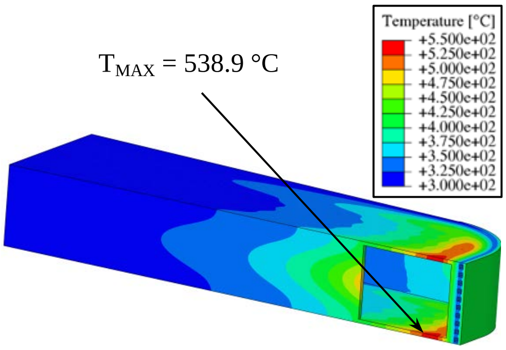

Fig. 6. LU Case 110 SB temperature distribution.

4. Conclusions

Within the framework of the EU-DEMO WCLL BB design activities, a research campaign aimed at the optimization of the DWTs lay-out inside the BZ has been launched by ENEA and University of Palermo. Parametric thermal analyses have been carried out and the steady-state thermal performances of an alternative poloidal-radial orientation of the DWTs have been investigated in terms of number and disposition. An optimized DWTs lay-out is then proposed, which foresees the placement of five and four tubes inside the CU and LU, respectively. Further work consisting in CFD analysis of the proposed lay-out may be pursued, aiming at the assessment of a more realistic thermal response of the WCLL BB SMS outboard equatorial cell.

Acknowledgment

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