EU DEMO WCLL BB breeding zone cooling system design: analysis and discussion

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The Water-Cooled Lithium-Lead (WCLL) Breeding Blanket (BB) is a key component in charge of ensuring Tritium self-sufficiency, shielding the Vacuum Vessel and removing the heat generated in the tokamak plasma. The last function is fulfilled by the First Wall (FW) and Breeding Zone (BZ) independent cooling systems. Several layouts of BZ coolant system have been investigated in the last years in order to identify a configuration that guarantee Eurofer temperature below the limit (823 K) and good thermal-hydraulic performances (i.e. water outlet temperature 601 K). A research activity is conducted to study and compare four configurations, which rely on different arrangement of the stiffening plates (i.e. toroidal-poloidal and radial-poloidal), orientation of the cooling pipes (i.e. horizontal, vertical) and PbLi flow path. The analysis is carried out using a CFD codes, thus a three-dimensional finite volume model of each configuration is developed, adopting the commercial ANSYS CFX code. The objective is to compare the BZ cooling system layouts, identifying and discussing advantages and key issues from the thermal-hydraulic point of view, also considering feedbacks from MHD and neutronics analyses. The research activity aims at laying the groundwork for the finalization of the WCLL blanket design, pointing out relevant thermal-hydraulic aspects.

Keywords: EU DEMO, WCLL, Breeding Blanket, CFD, Thermal-hydraulics

1. Introduction

The WCLL is a candidate breeding blanket for DEMO fusion power plant [10]. It has to ensure an adequate neutron shielding, tritium breeding self-sufficiency, and energy extraction for the electricity production. Lithium Lead (PbLi) is adopted as breeder, neutron multiplier and tritium carrier, Eurofer as structural material, and water at typical Pressurized Water Reactor (PWR) conditions for the FW and BZ cooling systems. The WCLL BB is designed according with the Single Module Segment (SMS) approach [2] [3]. To guarantee adequate mechanical properties, the Eurofer must be cooled at a temperature lower than 823 K during the normal operation [2].

The thermal-hydraulic studies have the responsibility to evaluate and carry out an adequate temperature map of the BB verifying that the maximum temperature of Eurofer structures is kept below the limit, to investigate PbLi flow path in BZ and to evaluate the thermal-hydraulic efficiency of BZ and FW cooling systems. The analyses are focused on the equatorial elementary cell of an OB segment [3]. A detailed three-dimensional finite volume model of the cell is developed, adopting the commercial CFD code ANSYS CFX 18.1. Different geometries are evaluated, concerning the stiffeners orientation and tubes layout in order to compare BZ cooling ability of different tubes layout and mark the advantage and disadvantage of the different layout.

2. DEMO WCLL breeding blanket design

Current WCLL BB design is based on DEMO 2015 specifications [12] and CAD model, characterized by 18 sectors, which each sector covering 20° and including two IB segments and three OB segments. The BB consists of: the FW, an external box of Eurofer water-cooled by 10 counter-current square channels with a Tungsten layer of 2 mm that face the plasma, and the BZ, an internal box filled with liquid PbLi alloy that flows through channels separated by stiffening plates. Both are refrigerated by water that flows in Double Wall Tubes (DWTs). See Fig.1 as sample referred to the design 2016v1.0.

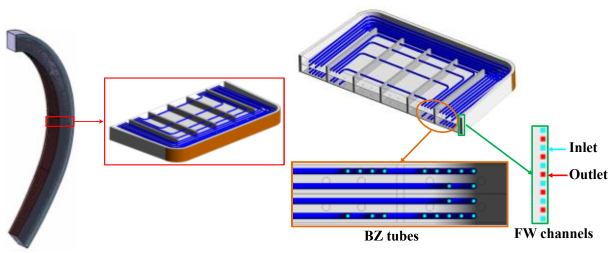

Fig. 1: WCLL BB 2016v1.0 segment with elementary cell: details of FW and BZ tubes.

Two different stiffener arrangements are considered for this comparative analysis, as reported in Fig.2, toroidal-poloidal and radial-poloidal [6]; consequently, this allow different DWTs layouts. Both elementary cells have toroidal length of 1500 mm, radial dimension of 1000 mm and total height of 135 mm. The number and size of the formed channels are different, due to the different stiffeners approach.

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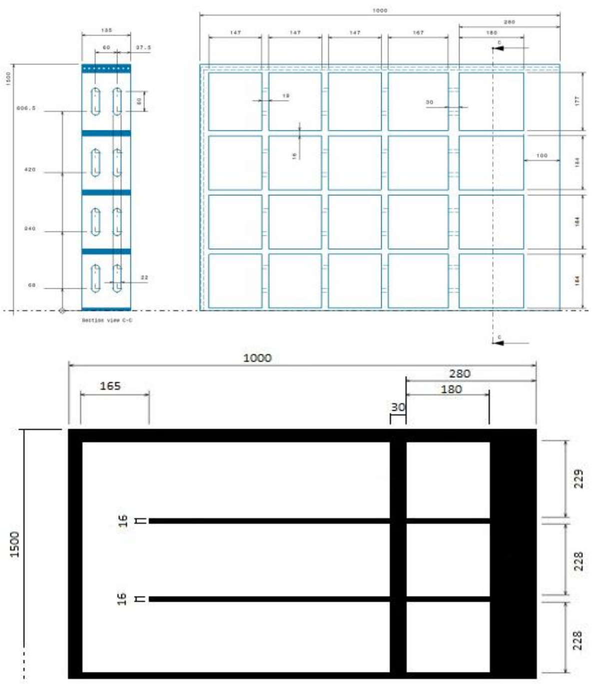

Fig. 2: WCLL 2017 half equatorial elementary cell geometry: a) toroidal-poloidal stiffeners (up), b) radial-poloidal stiffeners (down).

Table 1: BZ Geometrical parameters of WCLL elementary cell

Configuration	Channels [#]		Toroidal [mm]	Radial [mm]
Rad-Pol	Side	2	229	665
	Mid	4	228	665
Tor-Pol	Side	6	177	147
		2	177	167
	Mid	18	164	147
		6	164	167

2.1 Toroidal-poloidal stiffeners

This configuration employs two different tubes layout: vertical (2017.T03) and horizontal (2017.T02) U-shape DWTs.

Vertical layout employs poloidal tubes that pass through the BZ of the whole segment of the WCLL. The tubes path starts from the upper part of the segment where the water flows downwards, passing into the channels formed by the intersection of the stiffeners, to reach the lower part of the segment, and curves in a U-shape to ascend towards the upper part, where the outlet manifold is located.

Horizontal tubes have a radial-toroidal-radial path. The tubes path starts from the manifold placed in the back part of the BZ elementary cell, go straight through predicted holes to the FW crossing the stiffeners (Fig.3) and curves in a U-shape returning to the outlet manifold placed in the back part of the BZ [8].

2.2 Radial-poloidal stiffeners

The elementary cell employs different horizontal tubes layout with U-shape (2017.T01A) or C-shape (2018v0.2) DWTs. Both layouts, as the vertical tubes of the previous configuration, respect the manufacturability requirement to not cross the stiffeners. The tubes path starts from the manifold placed in back part of the elementary cell it goes straight in radial direction reaching the FW, then the tubes bend differently: the U-shape curves within the channel composed by two stiffeners or SW, and the C-shape has a greater length extension in front of the FW going beyond the width of the channel formed by two stiffeners.

3. Problem formulation and numerical model

For this study, to mark up the thermal-hydraulics advantage and disadvantage, different tubes layout with the relative stiffener orientation are analyzed and compared. The Reynolds Averaged Navier Stokes (RANS) equations have been solved for the single-phase fluid domains, using the k-ω Shear Stress Transport (SST) turbulence model. Thermal conduction is enabled allowing the heat transfer between the domains.

The first tubes layout is the configuration 2017.T02 of WCLL [5], analysis and boundary conditions (BCs) are reported in Ref. [8] and only the results will be reported. The geometry is shown in Fig.3.

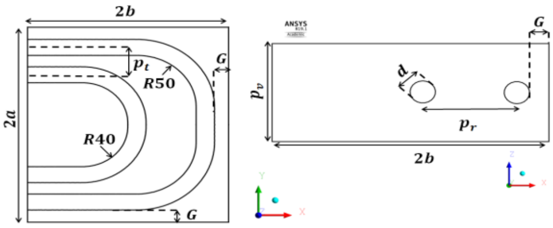

Fig. 3: 2017.T02 Cell geometry: radial-toroidal (left), radial-poloidal (right)

The vertical U-shape WCLL 2017.T03 layout with toroidal-poloidal stiffener orientation, is modelled on the central unit composed of four boxes. Optimization analyses found out that the minimum number of tubes to refrigerate the breeder unit is 14, amounting to a total 112 tubes per OB segment. An overview of the analyzed geometry is reported in Fig. 4.

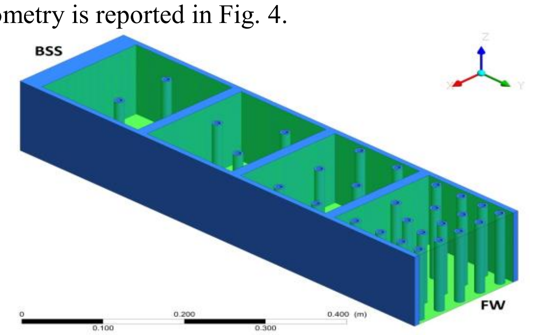

Fig. 4: WCLL 2017.T03 tubes layout for breeder unit geometry of toroidal-radial configuration

The modelled domains are: Eurofer for structures and tubes and solid PbLi for breeder. The water-side heat transfer is modeled by the Heat Transfer Coefficient (HTC) BC, and the pipes thermal resistance is calculated by the code. This method reduces calculation time. The passive cooling of the BZ from the FW is simulated by a negative heat flux, $q'' = -130\ kW/m^2$ at the surface in touch with the FW [8]. Periodic BC are imposed on the upper and lower surfaces of toroidal-poloidal stiffeners and tubes. The HTC is $h_{int} = 38793\, W/m^2\, K$, calculated from the Dittus-Boelter correlation assuming an average water velocity $u_{water} = 5\,m/s$ and considering a water bulk temperature of 584 K [8]. To perform the analysis, a radial power density curve in W/m^3 depending on the radial direction is created into the PbLi and Eurofer structures, based on the results in Ref. [6] [7].

The third configuration analyzed is the WCLL V2017.T01A with three rows of U-shape horizontal tubes [7] with radial-poloidal stiffeners orientation. This layout is carried out after optimization of Ref. [6], [7]. The analyzed geometry is the equatorial elementary cell of the OB segment based on the DEMO Baseline 2015. Dimension and geometry are reported in Ref. [6]. In this analysis, the PbLi is set as solid domain to consider the MHD influence on the suppression of the buoyancy forces, as a conservative assumption. The BCs are reported in Ref. [6].

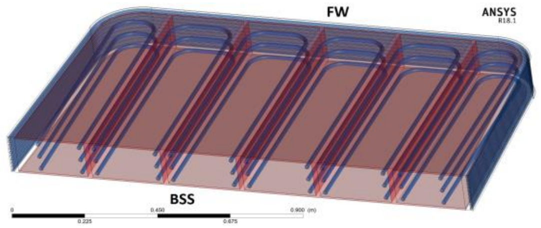

Fig. 5: WCLL 2017.T01A OB equatorial elementary cell geometry

The last configuration is the WCLL 2018v0.2 of the equatorial OB segment. The geometry of this configuration is reproduced considering the thermo-mechanical analysis provided in Ref. [9] and the dimensional analysis made by Ref. [5]. The breeding unit has a toroidal distance of 1500 mm, the radial dimension is 540 mm and the total height is 135 mm. The BZ coolant system consists of 20 C-shape DWTs, due to the optimal cooling performance obtained in Ref. [3]. The number of tubes to refrigerate the configuration is evaluated on the previous analyses carried out on Ref. [3], [6] and [7]. The elementary cell includes 10 square channels in the FW of 7×7 mm into the model. Volumetric power deposition curve in radial direction is modelled, according Ref. [6] [7]. Water mass flow rate for BZ and FW is calculated with the enthalpy balance for the DEMO 2017 baseline. An overview of the numerical model is reported in Fig.6

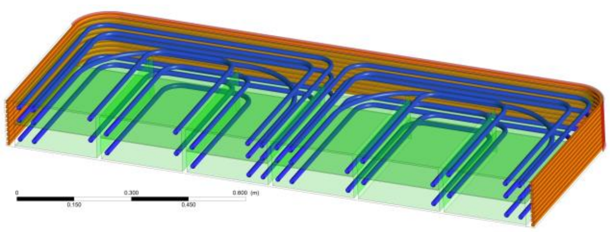

Fig. 6: WCLL 2018v0.2 OB equatorial elementary cell geometry

4. Results and discussion

Regarding the WCLL 2017.T02, without the magnetic field, the channel is strongly dominated by buoyancy forces with high cooling performance due to the high velocity (around $v{\sim}15\ {}^{cm}/_{s}$) of the PbLi, that passes from a laminar flow to a turbulent flow. PbLi velocities are two order of magnitude higher than the forced convection. The highest temperature reached is $T = 715\ K$ (Fig. 7) [8].

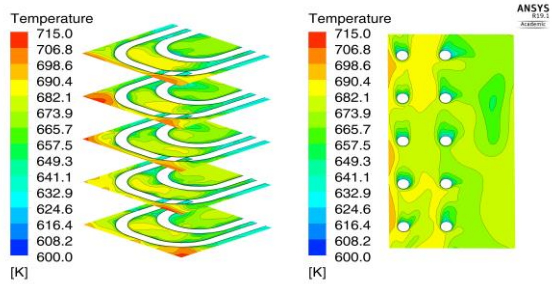

Fig. 7: OHD 5-cell stack temperature distribution on the horizontal planes passing through the pipe center (left) and the vertical central plane (right)

The MHD analysis returns a solution with: buoyancy forces almost suppressed and laminar flow. The temperatures are above the limit of 823 K (Fig. 8). Introducing the passive cooling of FW to the BZ with imposed heat flux of $q'' = -100\ kW/m^2$ and reducing the distance between cooling elements to $p_v = 40\ mm$ the temperature limit is met, but there are still hot spot in the corner due to the radius of the tubes. (Fig. 8) [8].

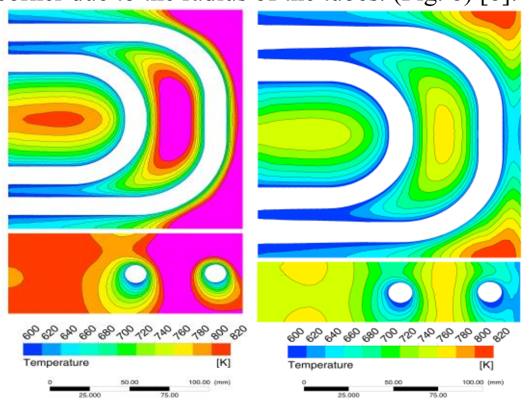

Fig. 8: Temperature distribution with MHD effect: flow without FW passive cooling (left), flow with FW passive cooling and reduced vertical tube pitch (right).

The results of WCLL V2017.T03 show a temperature field below the limit of 823 K for the Eurofer. As reported in Fig. 9, no hot spot is present inside the BZ and the temperature field symmetric.

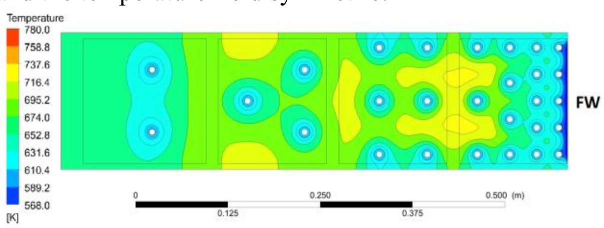

Fig. 9: Temperature distribution in the WCLL 2017.T03

Evaluating the water thermodynamic cycle of DEMO, it results that the number of tubes is not sufficient to meet the imposed water limit velocity of 7 m/s. The number of tubes must be increased to more than 500 tubes per segment to reach velocity of 7 m/s inside the pipes (Fig. 10), thus increasing the amount of water and steel and reducing the for the amount of PbLi in the BZ.

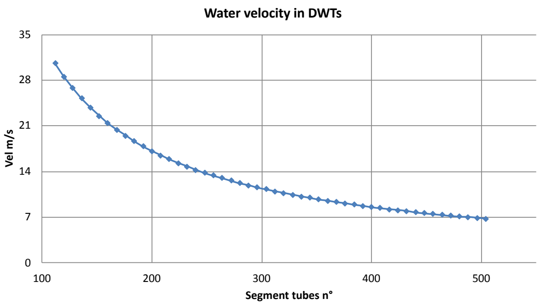

Fig. 10: Water velocity trend with increasing number of tubes

The third analysis, made on 2017.T01A, provides a symmetric temperature field into the BZ but, as it could be deduced from Ref. [6], three rows of tubes are not enough to satisfy the Eurofer temperature limit. As shown in Fig. 11, there are hot spot into the channels reaching temperature around 1200 K. The hot spots are connected with the minimum curvature radius of the DWT (i.e. 50 mm) and the presence of the vertical stiffener plates. Indeed, they are placed about in the center of the DWT curvature and between two adjacent tubes, always close or in front of the FW. The mitigation of the high temperature zones would require a larger number of tubes in the elementary cell. No further analysis is conducted to find a solution for the hot spot suppression, being available the analyses on the same layout are reported in Refs. [6] [7].

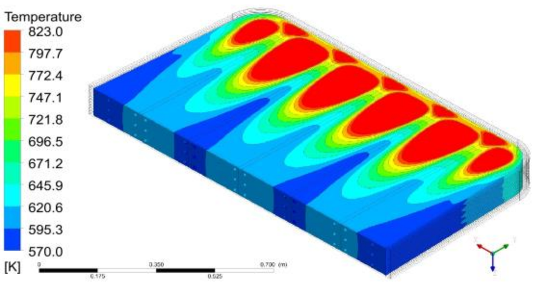

Fig. 11: WCLL 2017.T01A breeder temperature with hot spot

The WCLL 2018v0.2 is investigated to overcome the issues of version 2017.T01A. The analysis returns a solution with temperature symmetry in the toroidal direction, the Eurofer domain is slightly below the limit of 823 K (Fig. 12), the PbLi forced convection in the radial flow does not consider the recirculation due to the buoyancy effect.

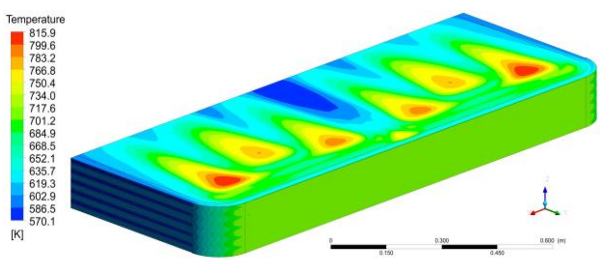

Fig. 12: WCLL 2018v0.2 Eurofer and Tungsten domain temperature

Although in the poloidal direction the buoyancy forces are almost suppressed, as seen in Ref. [8], no hot spot in that part of BZ occurs. High cooling performance are reached due to BZ and FW water outlet temperature, that is around 601 K (FW T～608 K and BZ T～600 K). It also results that there is a difference between the power deposited and the power extracted in the FW, phenomena investigated in Ref. [3].

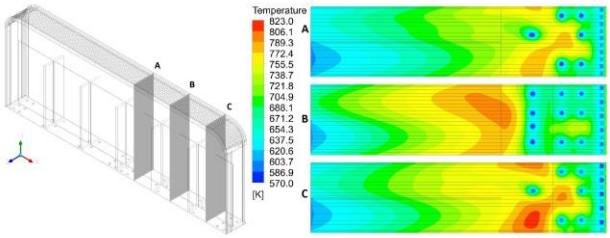

Fig. 13: WCLL 2018v0.2 temperature field radial poloidal view, A) plane at 121.5 mm from the center; B) plane at 364.5 mm from the center; C) plane at 607.5 mm from the center.

5. Conclusions

Temperature symmetry in toroidal direction is achieved for all configurations, but the cooling performance is satisfied only for three of them, not exceeding the Eurofer limit of $T_{max} \leq 823\,K$. As reported in the analyzed cases, the layout results simplified using horizontal tubes, as it allows a simplified manifold and feeding pipes distribution considering the available space between the back plate and the BSS and constraints of DEMO 2017 specifications. Regarding the stiffener approach the radial-poloidal is selected as the reference layout, due to the lower percentage of Eurofer structures. Also, the PbLi flow path not having a long poloidal path, reduces the MHD HTC suppression.

The WCLL 2017.T02 and 2017.T03 configurations reported promising temperature results but: in the first layout the amount of pipes required to cool down the hotspot is too high, thus creating a very large number of slots for the passage of the tubes not guaranteeing however the suppression of those at the corners, and in the second layout more than 500 tubes are needed, reducing the PbLi inventory inside the segment, thus penalizing the TBR performances. The WCLL 2017.T01A configuration, considering the previous analysis, presents a hot spot of T～1200K, which requires a larger number of tubes to mitigate.

The WCLL 2018v0.2 configuration presents a symmetric temperature field and below the required limit. BZ and FW have high cooling performance with a reduced number of tubes, without crossing stiffeners. This configuration is the selected design for the further analysis concerning the MHD effect and an optimized mass flow rate to enhance the cooling performance.

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