EUROFUSION WPBB-CP(16) 15521

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Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT
2016)

CFD analysis of WCLL Breeding Blanket module design

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ENEA CR Brasimone has developed during 2015 a design of the equatorial outboard module for DEMO reactor, based on horizontal (i.e. radial-toroidal) water cooling tubes in the Breeding Zone (BZ), and on PbLi flowing in radial-poloidal direction. Therefore, besides the caps zone, the module is composed by 14 segments having the same geometry. The purpose of this work is to describe the CFD model by ANSYS CFX developed to investigate the thermal-hydraulic efficiency of this module; to evaluate the temperature distribution in the structures and the thermal field and flow path in the breeding zone. The geometrical domain includes the breeding zone, the water cooling system in the breeding zone and in the First Wall (FW) and the metallic structures. Periodicity conditions are imposed at the upper and lower horizontal stiffening plates. Sensitivity analyses are performed to optimize the layout of the design, thus improving temperature distribution in the module. Results show a margin of 30°C from the maximum allowed temperature of the EUROFER97.

Keywords: Breeding Blanket, CFD, DEMO, WCLL

1. Introduction

The Breeding Blanket is a key component in a fusion power plant in charge of ensuring tritium breeding, neutron shielding and energy extraction. The Water-Cooled Lithium-Lead Breeding Blanket (WCLL) has been identified as a feasible blanket candidate for DEMO fusion power plant and it is investigated in the EUROfusion Breeding Blanket Project by ENEA, CREATE and the Universities of Palermo, Pisa and Roma.

The WCLL BB system is designed as a modular concept to limit manufacturing issues, thermomechanical and electromagnetic loads on the structural elements, PbLi pressure drop and tritium permeation into the coolant. The blanket structure is segmented in small modules with straight surfaces, attached to a common Back Supporting Structure (along the poloidal direction) housing feeding pipes. The WCLL BB uses reduced activation ferritic-martensitic steel EUROFER97 as structural material filled with Lithium-Lead (PbLi) as breeder, neutron multiplier and tritium carrier, and water at typical Pressurized Water Reactor (PWR) conditions (Tin = 285°C, Tout = 325°C at 15.5 MPa) as coolant. The design might benefit of efficient cooling performances of water as coolant, as well as of a power conversion system, based on conventional and reliable balance of plant [1].

Within the framework of the DEMO R&D activities, a computational thermal and fluid-dynamic model has been developed to investigate the thermal-hydraulic efficiency of the WCLL breeding blanket; to evaluate the temperature distribution in the structures and the thermal field and flow path in the breeding zone. Simulations results highlight where allowable limits are not met and possible criticalities in the PbLi flow paths (i.e. stagnant or low flow zone) giving hints for enhancements of baffle plate geometry and for the layout of the tubes in the breeding zone.

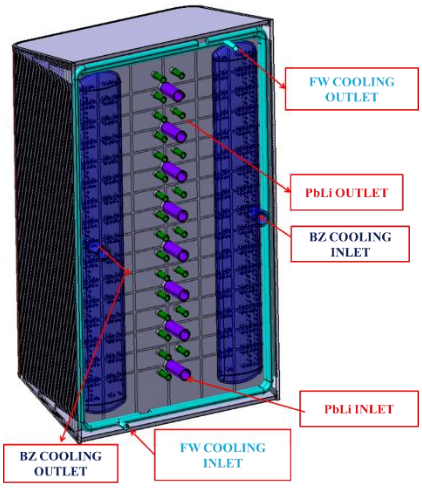

Fig. 1 WCLL BB 2015 equatorial outboard module

2. Models and methods

A three-dimensional finite volume model of the equatorial module of the DEMO-WCLL breeding blanket outboard segment is set-up in order to assess the thermo-hydraulic behavior of the WCLL-DEMO blanket concept (Fig. **1**). The model reproduces a central toroidal-radial slice of the module and includes six breeder cells in the toroidal direction and one breeder cell in poloidal direction. Solid structures (EUROFER97 and tungsten) and fluid domains (PbLi and water coolant) are considered, exploiting the ANSYS CFX (ver. 15.0) solver based on the volume finite method.

Reynolds Averaged Navier Stokes (RANS) equations are used in the fluid domains and two-equations k-ω

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shear stress transport (SST) model is exploited to simulate the turbulence effects.

Materials properties have been assumed uniquely as a function of temperature (polynomial fitting of data [2]):

$$f_i(T) = A_i T^3 + B_i T^2 + C_i T + D_i$$

2.1 Geometric domains

The water coolant flows in counter-current mode along the SW-FW-SW in eleven square section channels and the BZ cooling loop is based on twenty-one circular section double walled C-shaped tubes flowing in radial-toroidal-radial direction. The 21 tubes have different lengths and are divided into 9 arrays.

The model accounts for solid structures and fluids, as hereafter listed:

- Solid domain (Fig. 2): stiffening plates, baffle plate, double walled tubes, first wall;
- Fluid domain: water coolant (Fig. 3), PbLi Breeder (Fig. 4).

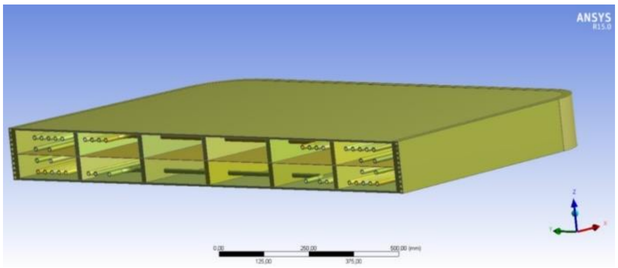

Fig. 2 Solid structures domain

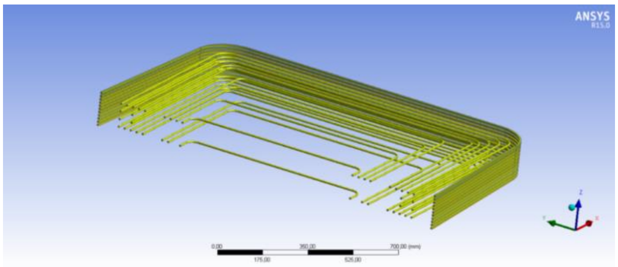

Fig. 3 Water coolant domain

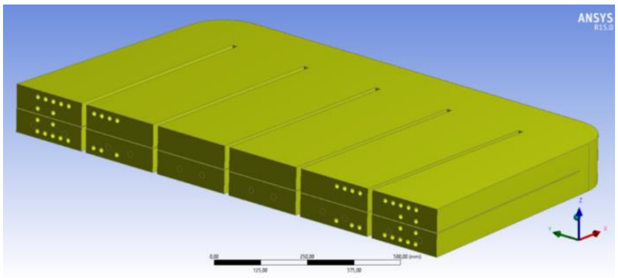

Fig. 4 PbLi breeder domain

2.2 Thermal loads and boundary conditions

The FW surface is subjected to a power deposition due to particles and radiations arising from plasma. This is modelled with a non-uniform heat flux imposed on the external surface. Each element of the FW surface has a normal heat flux calculated by multiplying the nominal heat flux value of 0.5 MW m^{-2} for the cosine of the angle between the radial and the surface normal.

Moreover, a radial distribution of heat power volumetric density is applied to simulate the power deposited by neutrons and photons. To this purpose, the heat power density calculated for PPCS-A WCLL outboard blanket [3] has been scaled with the factor of 1.05/2.56 according to DEMO average Neutron Wall Loadings (NWLs) [4]. Subsequently, it was modified to reflect the different arrangement of the plates between the module of the PCCS-A and the ENEA WCLL2015.OB4 module [1]. The volumetric generation in the coolant is not considered, because it is negligible if compared with the amount of heat exchanged by convection heat transfer.

Periodic boundary conditions are imposed on the radial-toroidal plates being the same surface, while the side wall is considered adiabatic in order to take into account the presence of the other blanket modules.

The flow rates flowing in the BZ tubes are estimated analytically using a "manifold approach" (the pressure drops between inlet and outlet of each tube are the same). Only the distributed pressure drops along the fluid path are taken into account, thus the local pressure drops due to inlet, exit and curvature of the fluid inside the tubes are neglected. The Petukhov correlation has been adopted for the Moody friction factor (f) [5]:

$$\Delta P_i = \frac{\rho \cdot {u^2}_i \cdot f_i \cdot L_i}{2 \cdot D} \quad [5]$$

$$f = (0{,}790 \cdot ln(Re) - 1.64)^{-2} \quad 3000 \leq Re \leq 5 \cdot 10^6$$

The inlet conditions are summarized in Table 1 and Table 2.

Table 1. BZ coolant flow rates

Array	Mass Flow [kg/s]
1	0.148
2	0.076
3	0.156
4	0.080
5	0.082
6	0.088
7	0.095
8	0.054
9	0.141

Table 2. Inlet conditions

Parameter	Units	Value
Coolant BZ T_inlet	[°C]	285
Coolant BZ Pressure	[MPa]	15.5
Coolant BZ Mass Flow	[kg/s]	0.92
Coolant FW T_inlet	[°C]	285
Coolant FW P	[MPa]	15.5
Coolant FW Mass Flow	[kg/s]	0.78
PbLi T_inlet	[°C]	325
PbLi Pressure	[MPa]	0.5
PbLi Mass Flow	[kg/s]	0.146

2.3 Mesh details

Hexahedral and tetrahedral elements are adopted taking into account the geometrical features of the domains to be meshed and the required optimization of the node number and mesh quality. Structured hexahedral mesh is adopted in the BZ coolant (Fig. 5) and FW zone coolant domain (Fig. 6); inflation layers at the coolant\solid interface are present and the mesh follows the channel profile in radial-toroidal-radial direction. Structured hexahedral mesh in solid structure are showed in Fig. 7. Structured hexahedral blocks (in the zones around the tubes and walls) and unstructured tetra blocks in PbLi domain with inflation layers at the PbLi\solid material interface are used to allow a better description of the system because those are the zones that require a greater degree of detail due to higher velocity gradients (Fig. 7). Mesh statistics information are summarized in Table 3.

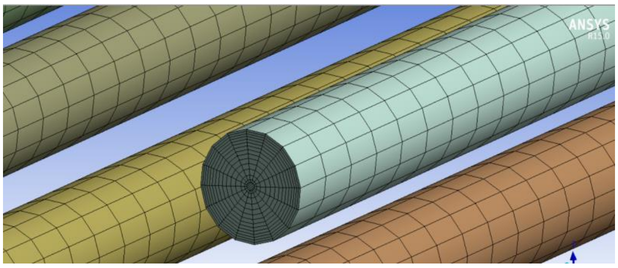

Fig. 5 BZ water coolant mesh detail

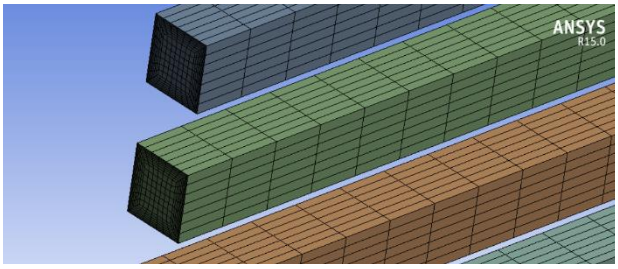

Fig. 6 FW water coolant mesh detail

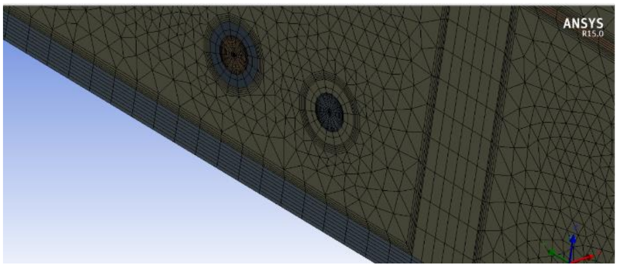

Fig. 7 PbLi mesh detail

Table 3. Mesh statistics

Parameter	Value
Cells	10.3 M
Average Skewness	0.2938
Average Orth. Quality	0.831

3. Results

A significant thermal gradient arises in both radial and toroidal directions within the EUROFER97 domain, due to the external heat flux, heat transfer inside the cooling tubes with PbLi flowing in the BZ and the volumetric density of nuclear power (Fig. 8 and Fig. 9). The current layout of the BZ tubes equipped with a manifold does not refrigerate properly the module: the maximum temperature of the PbLi exceeds tolerable values (Table 4) and the coolant reaches saturation conditions (Table 5). The distribution of the coolant outlet temperature in the BZ is not appropriate. Large differences between the arrays are found and troubling temperature values are reached, in particular in the arrays closer to the FW. Orifices are required to optimize the flow and to improve the temperature field in the module. The PbLi rotates close to the end of the baffle plate (Fig. 10), leaving almost stagnant zones near the FW. Hence, modifications of the baffle plate are suggested for a better fluid flow distribution.

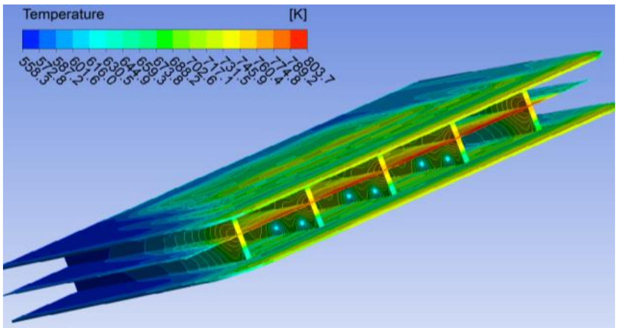

Fig. 8 Stiffening plates temperature distribution

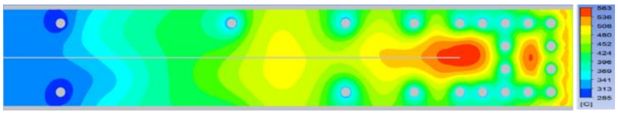

Fig. 9 PbLi temperature distribution in a poloidal-radial plane

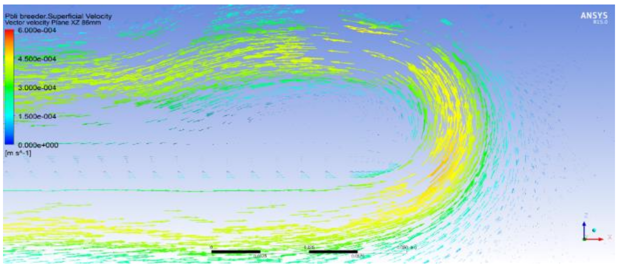

Fig. 10 PbLi velocity vector distribution

Table 4. EUROFER97 and PbLi temperature

Temperature [°C]	PbLi	Stiff. Plate
Max	563.4	540.2
Min	285.4	286.5
Average	382.8	374.7
Outlet_ave	315.6	
Outlet_max	350.7	
Outlet_min	285.4	

Table 5. Coolant outlet temperature

Array	T_out [°C]	P drop [Pa]	V [m/s]
1	satured	3072	1.03
2	339.4	3055	1.06
3	332.0	2994	1.08
4	325.2	2937	1.11
5	326.9	3018	1.14

6	319.5	2923	1.22
7	309.8	2900	1.32
8	301.6	2878	1.50
9	289.3	2892	1.96
FW	324.1	10891	2.02

4. Layout improvement

A new layout of the tubes is proposed in the BZ attempting to limit the critical issues highlighted in section 3. Twenty-two tubes are adopted and arranged in a radial-toroidal-radial direction in a configuration symmetrical to the baffle plate and to the poloidal-radial plane at half height of the module (Fig. 11). The baffle plate is lengthened (from 640 to 680 mm) to allow a better fluid distribution near the BZ/FW zone interface. The main advantages are:

- tubes lengths are more homogeneous allowing better flow distribution;
- the solution is more compact allowing to adopt water manifolds with reduced overall toroidal dimension;
- PbLi can leave directly the module through the central and semi-lateral;
- two more tubes close the FW to reduce the maximum PbLi temperature;
- two tubes for cooling the baffle plate and to reduce the maximum steel temperature.

4.1 New layout results

Layout of tubes in BZ is improved compared with the original design. The main highlights are:

- maximum PbLi and steel temperature are significantly reduced (Table 6);
- more homogeneous distribution of flows in BZ tubes;
- maximum coolant temperature is significantly reduced and the outlet coolant temperatures are more homogeneous in the various arrays of tubes (Table 7);
- orifices are still required to improve the temperature field in the module;
- the increased radial length of the baffle plate has reduced PbLi almost stagnant zones close to FW;
- enhanced PbLi output temperature distribution.

Table 6. EUROFER97 and PbLi temperature (new layout)

Temperature [°C]	PbLi	Stiff. Plate
Max	523.1	522.9
Min	285.3	285.9
Average	384.1	380.4
Outlet_ave	318.9	
Outlet_max	343.9	
Outlet_min	285.3	

Table 7. Coolant outlet temperature (new layout)

Array	T_out [°C]	P drop [Pa]	V [m/s]
1	344.9	3021	1.02
2	335.2	2941	1.04
3	333.8	2943	1.07
4	332.0	2924	1.08
5	328.5	2893	1.11
6	322.2	2943	1.17
7	312.6	2845	1.22
8	301.0	2904	1.36
9	290.1	2899	1.64
FW	324.1	10897	2.02

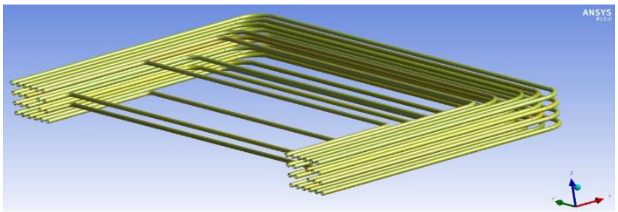

Fig. 11 New tubes arrangement

5. Conclusion

Within the frame of EUROfusion Power Plant Physics & Technology Work Programme this research activity has demonstrated that the first version of the WCLL breeding blanket design, based on DEMO-2015 data [4] and having horizontal tubes layout, has promising thermal-hydraulic features. The analyses have also pointed out areas for improvements; margin exists to enhance the design further, optimizing the layout and the coolant mass flow rate distribution of the tubes, as well as the manifolds. The main outcomes from the analysis are the following:

- the reference layout evidenced temperature of the PbLi above the threshold limit of 550°C and saturated conditions inside the tubes. Proper orifices at inlet of cooling tubes can be used to enhance the temperatures of the coolant at the outlet section.
- An improved layout of the breeding zone cooling tubes is proposed and analysed. Results show a better distribution of the coolant flow rate and the outlet coolant temperatures, as well as a reduction of the maximum coolant velocity with consequent decrease of pressure drops. Moreover, PbLi and structures temperature distribution is improved. The maximum temperature is 523 °C, about 30 °C lower than the limit (550 °C). Nevertheless, differences persist, even though mitigated, between the PbLi temperatures along the toroidal direction. This implies that countermeasures shall be taken to increase the PbLi temperature of the colder part.
- Increasing the baffle plate length, the almost stagnant zones are reduced. These results are conservative and, further analyses are needed activating the buoyancy forces.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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