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On the thermo-mechanical behaviour of DEMO water-cooled lithium lead equatorial outboard blanket module

P.A. Di Maio[a], P. Arena[a], G. Bongiovì[a], P. Chiovaro[a], A. Del Nevo[b], M.L. Richiusa[a]

[a]*Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici, Università di Palermo, Viale delle Scienze, I-90128 Palermo, ITALY*
[b]*ENEA C.R. Brasimone, I-40032 Camugnano (BO), ITALY*

Within the framework of EUROfusion R&D activities an intense research campaign has been carried out at the University of Palermo, in close cooperation with ENEA Brasimone, in order to investigate the thermo-mechanical performances of the DEMO Water-Cooled Lithium Lead breeding blanket (WCLL). In particular, attention has been paid to the most recent geometric configuration of the DEMO WCLL outboard equatorial module, as designed by WCLL project team during 2015, endowed with an attachment system based on the use of radial pins, purposely outlined to connect the module back-plate to its back-supporting structure, that have been properly considered to simulate more realistically the module thermo-mechanical behaviour.

The research campaign has been mainly focused on the investigation of the module thermo-mechanical performances under the Normal Operation (Level A) and Over Pressurization (Level D) steady state loading scenarios envisaged for the DEMO WCLL.

A theoretical-numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified ABAQUS v. 6.14 commercial FEM code has been adopted.

Thermo-mechanical results obtained have been assessed in order to verify their compliance with the design criteria foreseen for the structural material. To this purpose, a stress linearization procedure has been performed along the most critical paths located within the module structure, in order to check the fulfilment of both Level A and Level D rules prescribed by the SDC-IC structural safety code.

Results obtained are herewith presented and critically discussed, highlighting the open issues and suggesting the pertinent modifications to DEMO WCLL outboard equatorial module design aimed to obtain the complete fulfilment of the prescribed safety criteria.

Keywords: DEMO reactor; WCLL Blanket; First Wall.

1. Introduction

Within the framework of the DEMO R&D activities envisaged by the Working Package Breeding Blanket of the EUROfusion action [1], a research campaign has been carried out at the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo (DEIM).

The goal of the research activity has been to investigate the steady state thermo-mechanical performances of the new DEMO water-cooled lithium lead breeding blanket (WCLL) outboard equatorial module geometric configuration, set up in the framework of the 2015 EUROfusion activities [1].

The assumptions and methodology adopted and the results obtained are herewith reported and critically discussed.

2. WCLL breeding blanket

The research campaign has been focussed on the assessment of the thermo-mechanical behaviour of the WCLL outboard equatorial module [2-4] directly welded to the ribs of the Back-Supporting Structure (BSS), purposely lengthened till the back of the module. Moreover, the mechanical effect of the other outboard segment modules has been taken into account by means of the use of "dummy" modules directly tied to the BSS (Fig. 1).

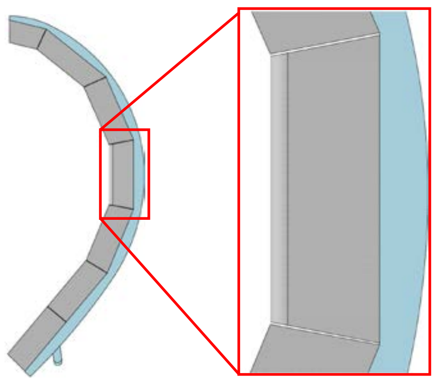

Fig. 1. WCLL outboard segment.

The WCLL outboard equatorial module mainly consists of an external Segment Box (SB), composed by a First Wall (FW) directly exposed to the plasma, two Side Walls (SWs), a Top Cap (TC) and a Bottom Cap (BC) that close the SB in the upper and lower part and a Back Plate (BP) that delimits the module in the radial direction. FW, SWs and caps are cooled by means of square channels in which it flows subcooled water at the pressure of 15.5 MPa (PWR conditions). The SB is reinforced with an internal stiffening grid, which divides the module in 16 toroidal-radial slices along the poloidal direction, and filled with the liquid metal eutectic alloy

author's email: pietroalessandro.dimaio@unipa.it

of Pb-Li acting as breeder and neutron multiplier. The SB internals are cooled by means of bundles of Double-Walled Tubes (DWTs) where it flows water in PWR conditions. Finally, each toroidal-radial slice foresees a further plate, called baffle plate, which acts as a guide for the liquid breeder in its path inside the Breeder Zone (BZ).

The whole of SB, stiffening grid and DWTs are made of the reduced activation ferritic martensitic steel Eurofer. A linear elastic model has been adopted for the Eurofer steel, while regarding the thermo-physical properties of both Pb-Li and Eurofer, they have been assumed depending uniquely on temperature [5].

A theoretical-numerical approach based on the Finite Element Method (FEM) has been followed and the qualified FEM code Abaqus v.6.14 has been adopted. To this purpose it has been set up a FEM model of the WCLL outboard equatorial module, consisting of a mesh composed of ~13.6M of nodes connected in ~23.2M of both linear tetrahedral and hexahedral.

3. Thermo-mechanical loads and boundary conditions

The loading conditions relevant to the steady state scenarios of Normal Operation (NO) and Over-Pressurization (OP), classified as Level A and Level D, respectively, in the SDC-IC [6] safety code, have been investigated.

From the thermal point of view, two different loading conditions have been taken into account, differing each other in the heat flux value applied on the FW plasma-facing surface. The first, named Case 1, has foreseen a maximum value of 0.5 MW/m² imposed onto the straight surface of the FW, while in the second, named Case 2, a maximum value of 1.4 MW/m² has been imposed onto the same surface. Concerning the bend FW surfaces, a cosine-dependent law has been adopted for them [1]. The non-uniform normal heat flux has been applied to the FW plasma-facing surface by means of a purposely set up FORTRAN routine. A non-uniform spatial distribution of heat power volumetric density has been applied to the model to simulate the deposited nuclear power density taking into account the nuclear heat calculated in [1] and scaled with the DEMO 2015 Neutron Wall Loading.

Forced convective heat transfer between the structure and the coolant has been simulated modelling convective heat transfer within water flow domain with a simplified FEM approach and adopting a proper thermal contact model between the coolant and the structure wetted walls. As to the FEM simulation of convective heat transfer within water, the so-called "frozen" flow field approach has been adopted. This approach is characterized by the assumption that mass flow rate and heat transfer coefficient values within each channel or tube do not change during the analysis. In this particular case they are calculated imposing a water temperature increase of 40 °C (ΔT_{Design}) between the inlet and the outlet manifolds. The inlet coolant temperature has been set equal to 285 °C. Both heat transfer coefficients, calculated adopting the Dittus & Bölter correlation [7], and mass flow rates needed to ensure the ΔT_{Design} have been calculated using a purposely set up iterative procedure [2]. In particular, the DWTs and the cap channels have been divided into different groups on the basis of their radial distance from the FW. A proper mass flow rate and heat transfer coefficient value has been calculated for each of them. Mass flow rate (**G**) and heat transfer coefficient (**HTC**) values, computed adopting the aforementioned iterative procedure, are reported in Table 1.

Table 1. Mass flow rates and heat transfer coefficients.

Case 1		
	G [kg/s]	**HTC [W/m²°C]**
FW channel	0.0676	18801.84
TC channel - Min	0.0071	3083.43
TC channel - Max	0.0262	8793.57
BC channel - Min	0.0079	3375.73
BC channel - Max	0.0251	8509.74
DWT - Min	0.0046	2103.37
DWT - Max	0.0736	19205.32
Case 2		
	G [kg/s]	**HTC [W/m²°C]**
FW channel	0.1464	34877.51
TC channel - Min	0.0081	3436.48
TC channel - Max	0.0213	7475.66
BC channel - Min	0.0092	3803.85
BC channel - Max	0.0213	7475.66
DWT - Min	0.0046	2103.37
DWT - Max	0.0736	19205.32

Concerning the breeder, no buoyancy effects have been taken into account, assuming the Pb-Li as still, while the thermal interaction between breeder and internal SB surfaces, as well as between breeder and DWTs outer surfaces have been considered implementing a thermal contact model characterized by a thermal conductance value of 10^5 W/m²°C.

As far as dummy modules are concerned, a non-uniform thermal field linearly depending on the distance from the FW has been imposed to them. In particular, temperature values ranging from 500 °C on the FW to 300 °C on the BP have been foreseen. This spatial distribution of temperature has been drawn from preliminary analyses performed on the WCLL outboard equatorial module [4].

From the mechanical point of view two different loading conditions have been taken into account for each thermal case, according to the scenario considered. Regarding the NO loading scenario, the mechanical effect of the water coolant flowing into FW, SW and cap channels, as well as DWTs has been reproduced imposing a pressure of 15.5 MPa to all water-wetted surfaces. A pressure of 0.5 MPa has been foreseen for the breeder-wetted surfaces in order to model the mechanical interaction between the breeder and both SB internal surfaces and DWT external ones. As far as the OP loading scenario is concerned, a pressure of 18.6 MPa, equal to the coolant pressure increased by 20% [6], has been imposed onto all wetted surfaces in order to take into account a coolant leak inside the box. Moreover, the thermal deformation field arising within the model as a consequence of its non-uniform temperature distribution and its isotropic thermal expansion tensor has been considered in both the loading scenarios investigated. Finally, the weight force has been applied to the whole model.

Both the WCLL outboard equatorial module and the 6 dummy modules have been considered directly welded to the BSS ribs. In order to reproduce the mechanical effect of the outboard segment attachment system to the Vacuum Vessel, the displacements of some sets of nodes have been prevented in both NO and OP loading scenarios. In particular, the displacement along the radial direction has been forbidden to nodes highlighted in blue in Fig. 2, the toroidal ones to nodes highlighted in red, while radial and poloidal displacements have been prevented to nodes highlighted in yellow.

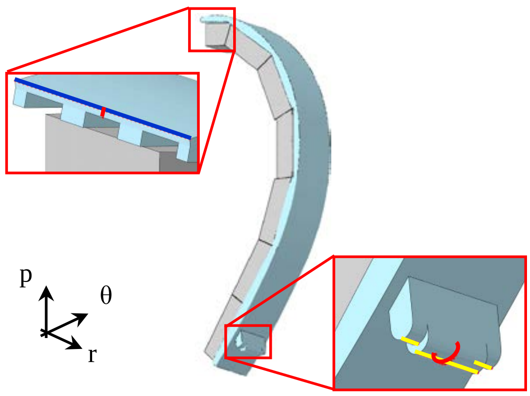

Fig. 2. Mechanical constraints.

4. Results

Un-coupled steady state analysis have been run in order to assess the thermo-mechanical behaviour of the WCLL outboard equatorial module, as well as verify that the limit design value foreseen for the structural material and the safety criteria of the SDC-IC are successfully fulfilled.

From the thermal point of view, results have shown that temperature values remain below the Eurofer maximum allowable value of 550 °C except in Case 2, where the temperature reaches the maximum value of 582 °C in very restricted areas located near the Cap corners (Fig. 3). Concerning the SB, the hottest parts are located at the interface between baffle plate extremities and breeder, probably due to the fact the breeder circulation has not been modelled. The thermal field calculated for the coolant has shown that, regarding water flowing into SW-FW and cap channels, the maximum temperatures are reached in correspondence of the bend regions of the channels, as a consequence of the counter-current flow. The minimum coolant margin against saturation is predicted in Case 2 and it amounts to 5.6 °C. Regarding the BZ tubes, water flowing into the bundles of DWTs located in the boundary slices experiences temperature values higher respect to that reached in the coolant of the DWTs situated in the inner slices.

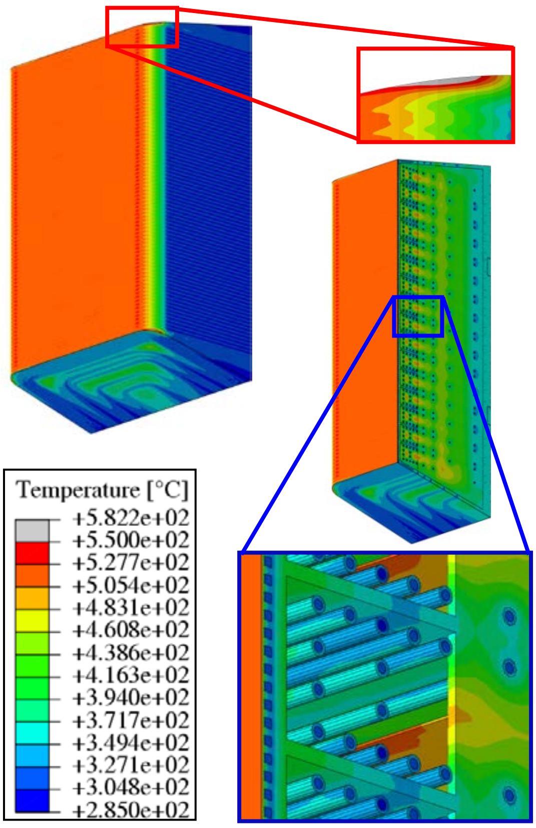

Fig. 3. Case 2 thermal results.

As far as mechanical results are concerned, a stress linearization procedure has been carried out along some significant paths of the SB in order to verify whether the Level A and Level D safety criteria are fulfilled. In particular, paths lying on the toroidal mid-plane have taken into account for FW and BP (Fig. 4), while paths lying on different poloidal and radial planes have been considered for the SPs (Fig. 5).

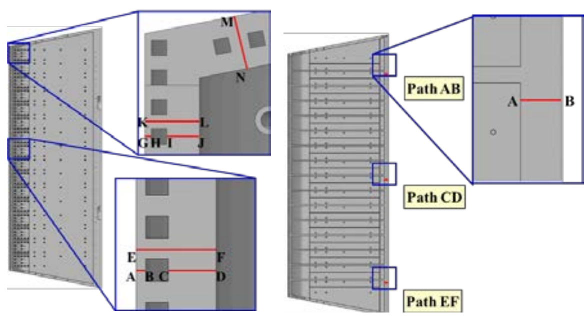

Fig. 4. FW and BP paths at toroidal mid-plane.

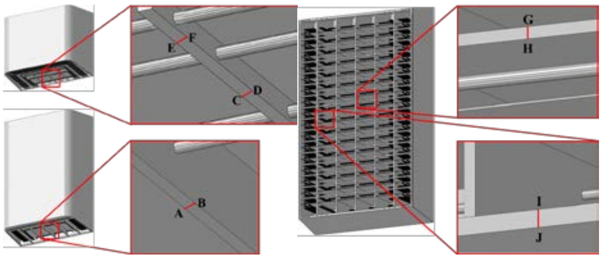

Fig. 5. Paths located within SPs.

Mechanical results relevant to NO scenario have shown, for both Case 1 and Case 2, that the most critical areas are those related to paths located within the SPs and near the Cap, where the criterion against plastic flow localization is not fulfilled. This is probably due to the resistance exerted by vertical SPs against the thermal expansion of horizontal SPs and vice versa, as well as to the compression exerted by BP and Caps, due to their lower poloidal thermal expansion with respect to FW, for paths located near the Cap (Tab. 2).

Table 2. SDC-IC safety criteria in most critical paths.

Case 1	**Stress linearization path**			
	FW_{GH}	**FW_{IJ}**	**SP_{AB}**	**SP_{CD}**
$T_{Max\text{-}Path}$ [°C]	407.7	404.2	411.7	456.3
Level A criteria				
P_m/S_m	0.074	0.094	0.052	0.046
$(P_m+P_b)/K_{eff}\ S_m$	0.070	0.077	0.035	0.034
$(P_m+Q_m)/S_e$	**2.030**	0.521	**1.490**	**1.680**
Level D criteria				
P_m/σ_{lim}	0.676	**1.200**	0.714	0.858
$(P_m+P_b)/K_{eff}\ \sigma_{lim}$	0.616	**1.350**	0.477	0.574
$(P_m+Q_m)/2\ S_e$	**1.690**	**1.370**	**1.020**	0.269
$W_t[1.35\ (P_m+P_b/K)]$	-	-	-	**36.10**
Case 2	**Stress linearization path**			
	FW_{GH}	**FW_{IJ}**	**SP_{AB}**	**SP_{CD}**
$T_{Max\text{-}Path}$ [°C]	520.6	397.3	410.4	456.3
Level A criteria				
P_m/S_m	0.090	0.093	0.052	0.046
$(P_m+P_b)/K_{eff}\ S_m$	0.084	0.077	0.035	0.031
$(P_m+Q_m)/S_e$	**3.640**	0.526	**1.456**	**1.656**
Level D criteria				
P_m/σ_{lim}	0.832	**1.190**	0.713	0.859
$(P_m+P_b)/K_{eff}\ \sigma_{lim}$	0.784	**1.340**	0.476	0.574
$(P_m+Q_m)/2\ S_e$	**2.680**	**1.350**	**1.010**	0.275
$W_t[1.35\ (P_m+P_b/K)]$	**2.470**	-	-	**36.30**

Concerning the OP loading scenario, paths located near the Cap continue to do not satisfy all safety criteria, especially in Case 2 where the high temperatures reached on the FW cause the failure also for creep damage. On the other hand, less SP paths fail to fulfil the criteria, probably due to the effect of the higher pressure imposed on the internal SB surfaces.

All paths located within the BP successfully fulfil all safety criteria in all loading scenarios investigated.

5. Conclusions

A research campaign has been carried out at DEIM in order to investigate the thermo-mechanical performances of the DEMO WCLL outboard equatorial module whether connected to the BSS under both NO and OP steady state loading scenarios. Two load cases have been investigated differing as far as the heat flux on the FW-SW plasma facing surface is concerned. From the thermal point of view, results obtained in case of Φ = 0.5 MW/m² show that an acceptable temperature distribution is reached within structure, breeder and coolant domains, while in case of Φ = 1.4 MW/m² hotspots are predicted in a poorly cooled restricted area located in the bottom and top corners of FW. From the mechanical point of view, results obtained in both cases show that a revision of the SPs has to be performed in order to limit their secondary stresses, by possibly changing their thickness and number, as well as to enforce the FW top and bottom corner regions to avoid their failure due to immediate plastic flow localisation.

Acknowledgments

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