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On the optimization of the first wall of the DEMO water-cooled lithium lead outboard breeding blanket equatorial module

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Within the framework of EUROfusion R&D activities a research campaign has been carried out at the University of Palermo in order to investigate the thermo-mechanical performances of the DEMO water-cooled lithium lead (WCLL) breeding blanket first wall (FW). The research campaign has been mainly focused on the optimization of the FW geometric configuration in order to maximize the heat flux it may safely withstand fulfilling all the thermal, hydraulic and mechanical requirements foreseen by safety codes. Attention has been focused on the FW flat concept endowed with square cooling channels and the potential influence of its four main geometrical parameters on its thermo-mechanical performances has been assessed performing a parametric analysis by means of a qualified commercial finite element method code. A set of 5929 different FW geometric configurations has been considered and the thermal performances of each one of them have been numerically assessed in case it undergoes 26 different values of heat flux on its plasma-facing surface. The resulting 154154 thermal analyses have allowed to select those cases fulfilling the adopted thermal-hydraulic requirements, whose thermo-mechanical performances have been numerically assessed under both normal operation and over-pressurization steady state loading scenarios to check whether they met the mechanical requirements prescribed by the pertaining SDC-IC safety rules. Four optimized FW configurations have been found to safely withstand a heat flux up to 2 MW/m^2 fulfilling all the rules prescribed by safety codes. Finally, the thermo-mechanical performances of these FW optimal configurations have been further investigated under both normal operation and over-pressurization steady state loading scenarios setting-up more realistic 3D FEM models. Results obtained are herewith presented and critically discussed.

Keywords: DEMO reactor; WCLL Blanket; First Wall.

1. Introduction

Within the framework of the DEMO R&D activities envisaged by the Breeding Blanket Working Package 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) to investigate the steady state thermo-mechanical performances of the DEMO water-cooled lithium lead (WCLL) breeding blanket first wall (FW) in view of the optimization of its geometric configuration. To this purpose, attention has been focused on to the equatorial module of the DEMO WCLL outboard breeding blanket [2-4], taking into account its FW flat concept, equipped with square cooling channels.

The research campaign has been specifically intended to optimize the FW geometric configuration, maximizing the heat flux it might safely withstand while fulfilling all the thermal-hydraulic and thermo-mechanical requirements prescribed by safety codes. In particular, from the thermal-hydraulic standpoint it has been assumed that the structural material (EUROFER) maximum allowable temperature, amounting to 550°C, cannot be exceeded and that the velocity of FW channels cooling water has to be lower than the limit value of 8 m/s [5]. Moreover, from the thermo-mechanical point of view, it has been assumed that the FW optimized configuration has to safely withstand the loads it undergoes under both steady state normal operation (NO) and over-pressurization (OP) loading scenarios, ensuring the fulfillment of the pertinent SDC-IC safety criteria [6-7]. A set of 5259 different flat FW geometric configurations have been considered and the thermo-mechanical performances of each one of them have been investigated when subjected to 26 different heat flux values, for an overall number of 154154 parametric analyses. To this purpose, a theoretical-numerical approach, based on the finite element method (FEM), has been followed and a qualified commercial FEM code has been adopted. The parametric analysis procedure has been totally automated by means of Python script files, able to set-up the simplified 3D FEM models, run the pertaining calculations together with the relevant stress linearization procedures and check the fulfillment of the prescribed thermal-hydraulic and thermo-mechanical requirements.

The research activity is herewith synthetically reported, describing the adopted methodology and discussing the results obtained.

2. FW configuration optimization procedure

Within the framework of the research campaign, attention has been focused on the FW flat concept endowed with square cooling channels and a 2 mm-thick tungsten armour, which is under consideration for the DEMO WCLL blanket design.

The FW characteristic geometric parameters potentially affecting its thermal-hydraulic and thermo-

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mechanical performances have been identified in the following ones (Fig. 1):

- cooling channels pitch (P) in the range 16÷26 mm;
- cooling channel width (d_c) in the range 6÷12 mm;
- cooling channel thickness (a) in the range 1÷3 mm;
- FW thickness (D) in the range 19÷25 mm.

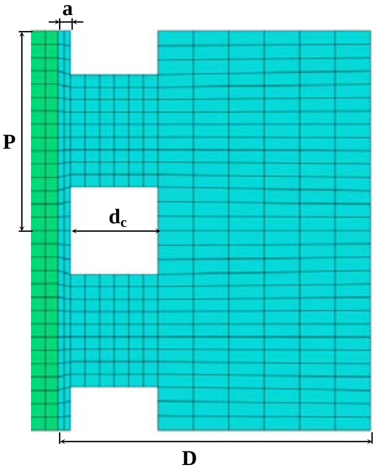

Fig. 1. FW characteristic geometric parameters.

Concerning d_c and D parameters, 7 different values have been selected subdividing their range of values in six equal intervals, while, as to a and P parameters, 11 different values have been taken into account subdividing their range of values in 10 equal intervals. Therefore, 5929 different FW geometric configurations have been selected to be numerically investigated and a proper simplified 3D FEM model has been developed for each of them. Moreover, in order to assess the maximum sustainable heat flux arising from plasma (Φ), the thermo-mechanical behavior of each selected FW geometric configuration has been investigated when exposed to 26 different values of Φ, equally spaced in the range 0.5÷3 MW/m^2 [1]. Therefore, for each FW configuration selected, 26 different thermal cases have been simulated for a total of 154154 FEM analyses.

To this purpose, in order to obtain a realistic simulation of the FW thermo-mechanical behavior while saving calculation time, a simplified 3D FEM model has been set-up for each FW configuration considered, reproducing a toroidal-radial slice of the DEMO WCLL outboard breeding blanket equatorial module, extending for two cooling channels pitches (2P) in the poloidal direction, for a breeder cell in the toroidal direction and for the whole module’s depth, up to the back-plate (BP), in the radial direction. In particular, in order to speed-up calculations, Pb-Li breeder, double walled tubes (DWTs) and coolant flow domain have not been modelled and their thermo-mechanical effects have been simulated adopting a proper set of loads, contact models and boundary conditions. Moreover, a mesh composed of linear hexahedral elements has been set-up whose typical lay-out is reported in Figure 2.

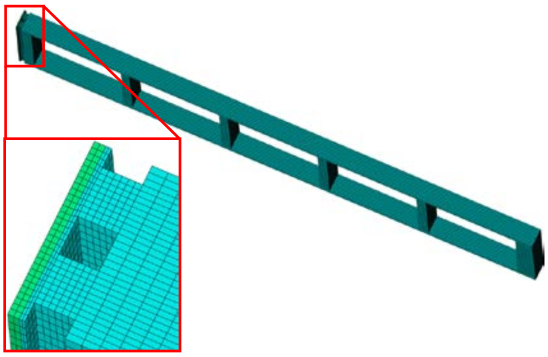

Fig. 2. Typical 3D FEM model.

RAFM EUROFER steel has been assumed as the structural material, except for the 2 mm-thick FW armour that has been supposed made of tungsten (shown in green in Fig. 1). Materials have been considered homogeneous, uniform, isotropic and linearly elastic and their thermo-mechanical properties have been assumed to depend uniquely on temperature as indicated in [7], except for tungsten density that has been assumed to be constant and equal to 19300 kg/m^3 [8,9].

Thermal loads and boundary conditions have been imposed according to the nominal steady state operative conditions envisaged for the DEMO WCLL breeding blanket. In particular, a uniform volumetric density of nuclear deposited heat power has been imposed to the FW domain, whose value has been obtained properly scaling according to NWL that one calculated for the PPCS-A WCLL blanket [1]. Moreover, a uniformly distributed heat flux, Φ, has been imposed on the FW armour plasma facing surface, considering the already mentioned 26 different values equally spaced in the range 0.5÷3 MW/m^2, while a uniformly distributed heat flux amounting to 0.074 MW/m^2 [1] has been imposed on the Pb-Li wetted FW internal surface to simulate heat transfer occurring at the interface between liquid metal breeder and steel. Furthermore, forced convective heat transfer between water coolant and FW cooling channels walls has been simulated adopting a convective boundary condition characterized by proper values of convective heat transfer coefficient and coolant bulk temperature, depending on Φ as a consequence of the system energy balance [1]. Finally, fixed temperature distributions have been imposed to the nodes of the stiffening plates (SPs) and of BP [10].

Mechanical loads and boundary conditions have been applied according to the NO and OP steady state loading scenarios investigated. In particular, in order to model the mechanical action of water flowing through the FW cooling channels, a uniform pressure of 15.5 MPa has been applied to their internal surfaces as to both the loading scenarios considered. Moreover, with regard to the simulation of the breeder mechanical action onto the SB, a uniformly distributed pressure has been imposed to its internal surfaces, whose value has been fixed to 0.5 MPa in case of NO loading scenario and has been increased up to 15.5 MPa as to the OP loading scenario.

Furthermore, the non-uniformly distributed thermal deformation field arising within each model as a consequence of its thermal field and its isotropic thermal expansion tensor has been implemented. Finally, in order to reproduce the mechanical action of the module attachment system as well as to simulate the geometric continuity of the DEMO WCLL blanket module, the radial displacements of a set of nodes lying on the BP external surface have been prevented (red nodes in Fig. 3) and symmetry and plain strain conditions reported in figure 3 have been imposed.

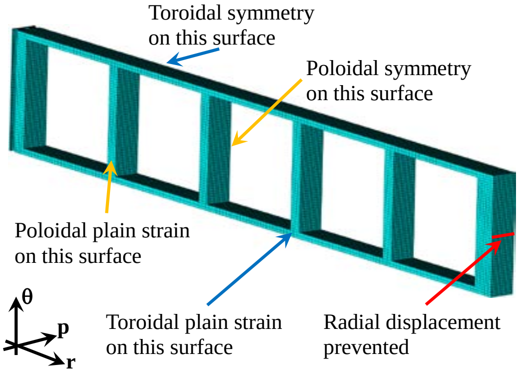

Fig. 3. Mechanical boundary conditions.

In order to assess the potential influence of the selected FW flat concept geometric parameters on its thermal-hydraulic and thermo-mechanical performances so to optimize its geometric configuration maximizing the heat flux it might safely withstand, a two steps operative procedure has been followed.

In a first step, the previously mentioned 154154 steady state thermal FEM analyses have been run, assessing the spatial distribution of the thermal field arising within each investigated FW configuration for each considered thermal case. Results have been processed in order to check the fulfillment of the prescribed FW thermal-hydraulic requirements and exclude all those thermal cases and configurations in which these requirements would have not been fulfilled. In particular, for each FW configuration, all those thermal cases in which the maximum allowable EUROFER steel temperature, fixed to 550 °C according to [5], has been exceeded have been considered as unacceptable and excluded from any further investigation of their thermo-mechanical performances. Moreover, a further filter has been applied to the remaining thermal cases, checking that the average velocity, u, of FW channels cooling water would result lower than the prescribed limit of 8 m/s, according to [5]. At the end of the first step, a reduced set of thermal cases have been found to fulfill the prescribed thermal-hydraulic requirements for each selected FW geometric configuration and exclusively their thermo-mechanical performances have been investigated in the second step by means of dedicated mechanical FEM analyses under both NO and OP steady state loading scenarios.

During the second step, the previously selected steady state mechanical FEM analyses have been run, mainly assessing the spatial distribution of the stress tensor field arising within each investigated FW configuration for each considered thermal case. Results have been processed performing stress linearization procedures in some critical paths of the FW (Fig. 4) to verify whether its thermo-mechanical stress state would comply with the requirements prescribed by SDC-IC safety rules according to NO loading scenario (Level A criteria) and OP loading scenario (Level D criteria).

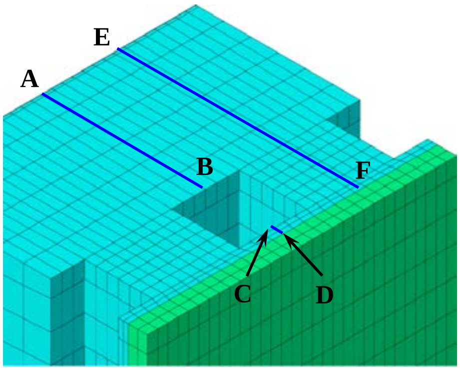

Fig. 4. Stress linearization paths.

3. FW configuration optimization results

The application of the optimization procedure has allowed to select, at the end of the first step, 66443 combinations of FW configurations and thermal cases suitable to fulfill the prescribed FW thermal-hydraulic requirements whose mechanical behavior under both NO and OP loading scenarios has been numerically simulated within the second step of the procedure.

The results of the mechanical analyses of the abovementioned 66443 combinations of FW geometric configurations and thermal cases have been processed during the second step of the procedure, allowing the selection of 4 FW optimized configurations, reported in Table 1, that are able to fulfill the adopted SDC-IC safety criteria up to a maximum Φ value of 2 MW/m^2. It has to be underlined that, as it might be expected, the only difference among these optimized configurations relies on the D parameter.

Table 1. FW optimized configurations.

	FW 1	**FW 2**	**FW 3**	**FW 4**
d_c [mm]	7	7	7	7
P [mm]	16	16	16	16
a [mm]	1.0	1.0	1.0	1.0
D [mm]	22	23	24	25
Channels	93	93	93	93
u [m/s]	6.43	6.43	6.43	6.43
T_{Max} [°C]	496.8	497.0	496.9	497.0

As it can be deduced from results reported in Table 1, the maximum FW temperature reached in the 4 selected configurations is well below the EUROFER allowable value (550 °C) as well as the maximum coolant velocity, which is quite lower than the prescribed limit of 8 m/s.

4. Analysis of the FW optimized configurations

In order to verify the outcomes of the parametric analysis, the thermo-mechanical performances of the 4 optimized configurations selected have been investigated by running more detailed and accurate FEM analyses. To this purpose, 4 different 3D FEM models have been set-up, realistically reproducing the central poloidal-radial slice of the DEMO-WCLL outboard breeding blanket equatorial module. Each model includes one breeder cell in the toroidal direction and all the five breeder cells in the radial direction (Fig. 5). Moreover, Pb-Li breeder, DWTs and water flow domain have been modelled too.

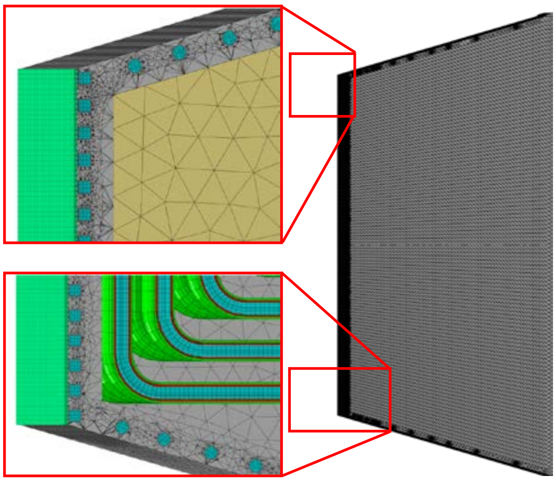

Fig. 5. Detailed 3D FEM model.

As to materials, proper libraries describing Pb-Li and water thermo-physical properties have been adopted [1].

As to thermal loads and boundary conditions, the same modelling assumptions adopted for the parametric analysis have been made, integrated by a non-uniform spatial distribution of heat power volumetric density [1] and by thermal contact models at the interface between breeder and both segment box inner surfaces and DWTs outer surfaces, intended to simulate a “perfect” thermal coupling (thermal conductance of 10^5 W/m^2°C) between Pb-Li and steel. Moreover, forced convective heat transfer between the structure and the coolant has been modelled by a simplified FEM simulation of coolant flow and by adopting the well-known Dittus and Boelter correlation for the calculation of the heat transfer coefficient as a function of coolant flow velocity [1].

Concerning mechanical loads and boundary conditions the same modelling assumptions adopted for the parametric analysis have been made, except for the constraints that aim at reproducing the mechanical effects of the back supporting structure on the module.

4.1 Results

Uncoupled thermo-mechanical steady state analyses have been carried out in order to assess the potential aptitude of the 4 FW optimized configurations to safely withstand the loads they undergo under NO and OP loading scenarios according to SDC-IC safety code.

With respect to the thermal behaviour predicted under NO loading scenario at the maximum heat flux on the FW armour of 2 MW/m^2, results obtained (Fig. 6) suggest that, for all the configurations investigated, the structure and breeder thermal field is sufficiently uniform along the poloidal direction, at least far from the cap regions, being characterized by a pronounced radial thermal gradient, clearly due to thermal loads and coolant flow distributions. In particular, the maximum temperature predicted in the EUROFER steel is well below 550 °C for all the configurations investigated with a highest value of 504 °C. Moreover, the highest temperature is predicted into the tungsten armor (~525 °C), while the peak breeder temperature amounts to ~509 °C. Finally, it has to be underlined that, as previously assumed for the parametric analysis, the thermal behaviour under the OP loading scenario has been considered equal to that relevant to the NO scenario since thermal loads and boundary conditions are the same and the transient due to the loss of coolant accident development is neglected.

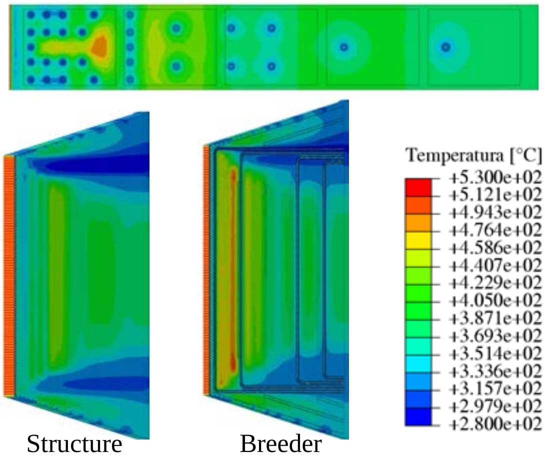

Fig. 6. Thermal field distribution - 4th FW configuration.

As to the mechanical behaviour predicted under both NO and OP loading scenarios, results have been processed performing stress linearization procedures in some critical paths of the FW to verify whether its thermo-mechanical stress state would comply with the requirements prescribed by the pertaining SDC-IC safety rules. In particular, there have been considered the paths lying on the toroidal midplane reported in Fig. 7 as well as their corresponding ones (OP, MN, QR, EF, CD, AB) located nearby the joint between the FW and the SP, that have not been reported for the sake of brevity. To this purpose, it has to be noticed that path OP corresponds to UV as well as path CD corresponds to IJ.

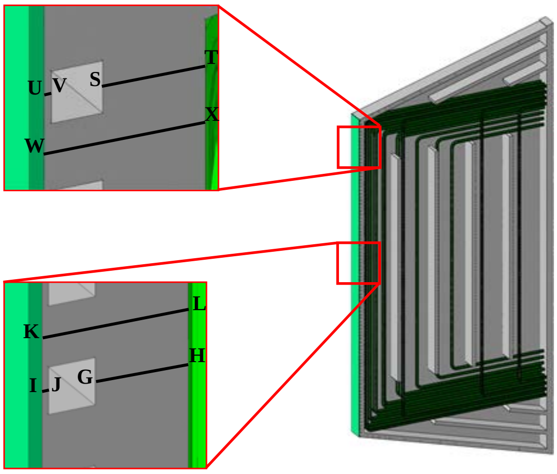

Fig. 7. Stress linearization paths at toroidal midplane.

Results show that for all the 4 FW configurations investigated the most critical paths are those located in the plasma-facing region both at poloidal midplane and nearby the cap, independently from their toroidal position. Along these paths all safety rules but one are generally fulfilled, the rule related to the potential loss of ductility resulting not verified both in the NO and in the OP loading scenarios. In particular, Table 2 reports a summary of the results obtained in the critical paths as to the 4th FW configuration investigated that turns out to be the most promising to be considered for a further study.

Table 2. Stress linearization results.

	Stress linearization path			
	CD	**IJ**	**OP**	**UV**
$T_{Max\text{-}Path}$ [°C]	447.9	449.34	423.2	425.0
Level A criteria				
P_m/S_m	0.066	0.087	0.093	0.098
$(P_m+P_b)/K_{eff}\ S_m$	0.052	0.064	0.063	0.066
$(P_m+Q_m)/S_e$	**1.036**	**1.059**	**2.028**	**2.140**
P_m/S_t	0.048	0.063	0.062	0.066
$(P_m+P_b/K)/S_t$	0.055	0.069	0.063	0.066
Level D criteria				
P_m/σ_{lim}	0.207	0.501	0.250	0.277
$(P_m+P_b)/K_{eff}\ \sigma_{lim}$	0.143	0.337	0.169	0.186
$(P_m+Q_m)/2\ S_e$	0.361	0.194	**1.102**	**1.158**
$W_t[1.35\ (P_m+P_b/K)]$	$2\cdot10^{-8}$	$4.3\cdot10^{-4}$	$4\cdot10^{-9}$	$1.4\cdot10^{-8}$

5. Conclusions

Within the framework of the DEMO R&D activities a research campaign has been carried out at the DEIM to investigate the steady state thermo-mechanical performances of the FW of the DEMO WCLL outboard breeding blanket equatorial module with the specific aim to optimize its geometric configuration, maximizing the heat flux it might safely withstand while fulfilling all the thermal-hydraulic and thermo-mechanical requirements prescribed by safety codes. Attention has been paid to the FW flat concept, equipped with square cooling channels, and a campaign of 154154 parametric analyses has been carried out whose results have shown that only 4 FW configurations are able to withstand a heat flux up to 2 MW/m^2 on the armour plasma facing surface. Later on, more detailed FEM thermo-mechanical analyses have been run out for each optimized configuration under both NO and OP steady state loading scenarios. The results obtained have shown more realistically that the selected configurations fail to verify only the rule related to the potential loss of ductility, as to both the scenarios considered, especially in the region between the FW and the Cap. Anyway they indicate that the 4th FW configuration is promising and results worth of a further development.

Acknowledgments

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