Analysis of the thermo-mechanical behaviour of the DEMO Water-Cooled Lithium Lead breeding blanket module under Normal operation steady state conditions

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Within the framework of DEMO R&D activities, a research cooperation has been launched between ENEA-C.R. Brasimone, the University of Palermo and the Commissariat à l'Energie Atomique to investigate the thermo-mechanical behaviour of the outboard equatorial module of the DEMO1 Water-Cooled Lithium Lead (WCLL) blanket under normal operation steady state scenario.

The research campaign has been carried out following a theoretical-computational approach based on the Finite Element Method (FEM) and adopting a qualified commercial FEM code. In particular, two different 3D FEM models (Model 1 and Model 2), reproducing respectively the central and the lateral poloidal-radial slices of the WCLL blanket module, have been set up. A particular attention has been paid to the modelling of water flow domain, within both the segment box channels and the breeder zone tubes, to simulate realistically the coolant-box thermal coupling. A set of uncoupled steady state thermo-mechanical analyses has been carried out with the two models, supposing the module to undergo both 15.5 MPa coolant pressure on its cooling channels walls and thermal deformations due to the flat-top plasma operational state thermal field.

Results obtained have shown that the EUROFER critical temperature of 550 °C is never overcome and that the maximum temperature of 509.7 °C is reached within the Model 1 Breeder Zone. Concerning the mechanical behaviour, the WCLL box experiences moderate Von Mises stress values, that remain under 200 MPa in Model 1 and below 350 MPa in almost the whole segment box of Model 2. Safety verifications, according to SDC-IC codes, are totally satisfied as far as Model 1 is concerned, while they are generally widely satisfied for Model 2, except for that relevant to the potential loss of ductility in the toroidal path located in the second radial cell of poloidal-radial stiffening plates.

Keywords: DEMO reactor; WCLL Blanket; thermo-mechanics.

1. Introduction

The Water-Cooled Lithium Lead (WCLL) blanket concept has been selected, since the European Blanket Concept Selection Exercise organized in 1995, as one of the two most promising European options for the breeding blanket of the DEMOnstration nuclear fusion reactor [1]. It relies on the use of the Pb-Li eutectic alloy as tritium breeder and neutron multiplier, and on EUROFER reduced-activation martensitic steel as structural material. Water at a pressure of 15.5 MPa and at a temperature ranging from 285°C to 325°C is envisaged as the coolant, according to the well-established and mature PWR technology for the power conversion cycle [2].

In view of the DEMO reactor development, EFDA launched and supported R&D activities on the WCLL breeding blanket concept, since it has been considered as a valid alternative to the reference EU helium-cooled breeding blanket concepts for the DEMO1 reactor [3]. Within this framework, a research campaign has been launched in close cooperation with CEA Saclay and ENEA Brasimone by the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo (that has been, long time now, involved in the investigation of liquid metal blankets [4-12]), to theoretically assess the thermo-mechanical performances of the outboard equatorial module of the DEMO1-WCLL blanket. In this context a preliminary work [13] was already carried out to evaluate the thermo-mechanical behaviour of the aforementioned module under both Normal operation and Over-pressurization steady state scenarios.

This paper is focussed on a more realistic assessment of the blanket module thermo-mechanical performances under Normal operation steady state condition. In particular, some changes in the design, with respect to [13], have been taken into account and the forced convective heat transfer between the coolant and the structural material has been properly considered, modelling the water domain. Moreover, as far as the thermal load on the First Wall (FW) is concerned a non-uniform normal heat flux has been applied on its plasma-facing surface. The present paper reports the scope of the research activity, describes its assumptions and methodology and critically discusses results obtained, also in view of the Structural Design Criteria In-vessel Component (SDC-IC) code [14].

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2. WCLL blanket thermo-mechanical study

The research campaign carried out has been focussed on the equatorial module of the WCLL blanket outboard segment, in order to investigate its thermo-mechanical performances under the Normal operation steady state loading scenario. As to [13] the most important changes to the module design regard the Back Plate (BP) and the Caps that in the modified version are actively cooled by means of opportune channels. The Normal operation scenario is mainly characterized by a coolant pressure of 15.5 MPa acting on First Wall-Side Walls (FW-SWs) and Caps cooling channels as well as on breeder tubes inner walls, by a pressure of 0.5 MPa exerted onto breeder wetted surfaces and thermal deformations due to the thermal field distribution relevant to flat-top plasma operational state [15]. The research campaign has been carried out following a theoretical-computational approach based on the Finite Element Method (FEM) and adopting a qualified commercial FEM code. Moreover, stress linearization and SDC-IC verifications have been performed for the most significant and highly stressed paths in order to assess the module aptitude to safely withstand the Normal operation scenario loading conditions.

2.1. WCLL blanket module FEM models

In order to assess the thermo-mechanical behaviour of the WCLL-DEMO blanket concept, two different three-dimensional FEM models (Figs. 1, 2) have been set-up, realistically reproducing the central (Model 1) and the lateral or peripheral (Model 2) poloidal-radial slice of the equatorial module of the DEMO-WCLL breeding blanket outboard segment. Each model includes one breeder cell in the toroidal direction and all the five breeder cells in the radial direction.

All these cells have been properly simulated taking into account their eutectic Lithium-Lead (Pb-Li) breeder, their thirty cooling Double Walled Tubes (DWTs) and the cooling water. Moreover, water flowing through the FW-SWs and the Top and Bottom Caps (TC and BC) has been simulated too.

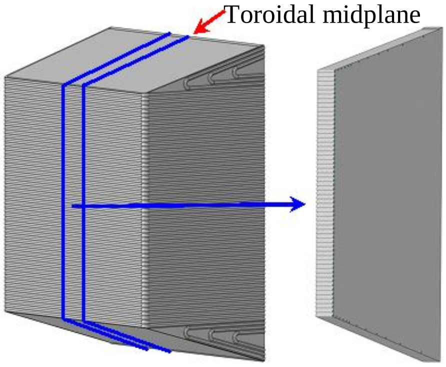

Fig.1. DEMO-WCLL blanket module. Model 1.

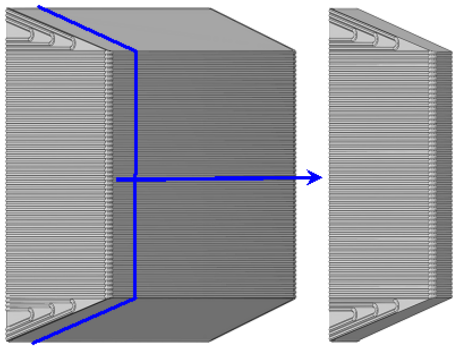

Fig. 2. DEMO-WCLL blanket module FEM model 2.

Due to the geometrical features of the domains to be meshed, in order to optimize nodes number and mesh quality both tetrahedral and hexahedral elements have been adopted and, in particular, as to Model 1, a mesh composed of ~$1.97 \cdot 10^6$ nodes connected in ~$2.04 \cdot 10^6$ elements has been selected, while, concerning Model 2, a mesh composed of ~$2.84 \cdot 10^6$ nodes connected in ~$4.38 \cdot 10^6$ elements has been taken into account.

2.2. Materials

The Reduced Activation Ferritic-Martensitic (RAFM) EUROFER steel has been assumed as the WCLL blanket module structural material, while Lithium-Lead alloy Pb-15.7Li has been taken into account as the breeder material.

Materials have been considered homogeneous, uniform and isotropic and their thermo-mechanical properties have been assumed to depend uniquely on temperature as indicated in [16, 17]. In particular, EUROFER mechanical behaviour has been simulated adopting a linear elastic model.

2.3. Thermo-mechanical loads and boundary conditions - Model 1

The relevant thermo-mechanical loads and boundary conditions are herewith presented and critically discussed as far as FEM Model 1 is concerned.

Thermal loads and boundary conditions

In order to simulate heat power deposition on the FW plasma-facing surface due to particles and radiations arising from plasma, a non-uniform normal heat flux has been applied to the FW plasma-facing surface by means of a purposely set up FORTRAN routine. It imposes to each element face lying on the FW external surface a normal heat flux calculated by multiplying the nominal heat flux value of 500 kW/m^2 [15] for the cosine of the angle α formed by the radial and the surface normal directions. Moreover, a non-uniform spatial distribution of heat power volumetric density has been applied to the model to simulate power deposited by neutrons and

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photons. To this purpose, the radial distribution of nuclear deposited heat power density, calculated for the PPCS-A WCLL outboard blanket and properly scaled according to PPCS-A and DEMO Neutron Wall Loadings, has been adopted [18].

Thermal contact models between breeder and inner Segment Box (SB) surfaces and between breeder and DWTs outer surfaces have been implemented imposing conservatively a thermal conductance value of 100000 W/m^2 °C. Moreover, in the Breeder Zone (BZ), concerning the thermal interaction between inner and outer tubes of each double-walled tube, the copper layer interposed between them has not been modelled and its thermal coupling effect has been simulated by means of a simple thermal contact model, conservatively characterized by a conductance amounting to 100000 W/m^2 °C. All the thirty double-walled tubes have been considered as perfectly tied to the BP from the thermal point of view.

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, assuming fixed mass flow rates and heat transfer coefficients within each channel or tube, calculated imposing a water temperature increase of 40 °C (ΔT_{Design}) between the inlet and the outlet headers of the module. In particular, heat transfer coefficients have been calculated using the Dittus & Bölter correlation, while mass flow rates needed to ensure the ΔT_{Design}, as well as inlet temperatures of FW and Caps channels, have been calculated using an iterative procedure discussed in the following.

Since the coolant flows in countercurrent mode along FW-SWs channels, two different inlet temperatures, named $T_{FW\ even,in}$ and $T_{FW\ odd,in}$, have been imposed to water entering the FW channels. In particular, $T_{FW\ odd,in}$ has been set equal to 308.57 °C while $T_{FW\ even,in}$ has been set equal to 304.70 °C. This difference is due to the fact that water entering from the right side of Model 1 FW has flown through the lateral slice and 4 slices equal to that represented by Model 1, while water entering from the left side of Model 1 FW has flown through the lateral slice and only 3 slices equal to that represented by Model 1. The same approach has been followed to assess the inlet temperatures of water relevant to Model 1 Caps channels, whose values are reported in table 1.

Regarding the DWTs, they have been divided into two groups. The first includes the 17 tubes that are deputed to cool the first radial breeder cell and a uniform temperature of 285 °C has been imposed to water entering these tubes. The second group contains the remaining 13 DWTs, that are intended to cool the remaining four radial breeder cells. Temperature of water entering this second group of tubes has been set equal to the average value of the water outlet temperatures of the first radial cell tubes.

A summary of the mass flow rates and heat transfer coefficient values is reported in table 2.

Tab. 1. Water inlet temperatures of Model 1 Caps channels.

Channel	TC Inlet [°C]	BC Inlet [°C]
1	306.47	302.89
2	305.19	302.47
3	305.09	302.45
4	304.79	302.31
5	305.78	302.67
6	306.97	303.14
7	306.08	302.80
8	304.60	302.34
9	303.80	302.03
10	303.21	301.83
11	302.52	301.61

Tab. 2. Mass flow rates and heat transfer coefficient values.

Component	G [kg/s]	h [W/m^2 °C]
First-Wall	0.116	27632
Top Cap	0.020	6836
Bottom Cap	0.023	7479
1st radial cell tubes	0.075	19329
2nd - 5th radial cell tubes	0.098	24917

Mechanical loads and boundary conditions

Water coolant mechanical interaction with module channels and tubes walls has been modelled imposing a pressure of 15.5 MPa to all water-wetted surfaces.

Breeder mechanical interaction with module internal walls, belonging to First Wall, to Caps, to Stiffening Plates (SPs) and to the innermost BP, has been taken into account imposing a 0.5 MPa pressure along the internal surfaces of the SB.

The thirty DWTs have been considered as perfectly tied to the BP also from the mechanical point of view.

Finally, the non-uniformly distributed thermal deformation field, arising within the module as a consequence of both its thermal field and its isotropic thermal expansion tensor, has been applied as an imposed deformation field.

Concerning mechanical constraints, toroidal symmetry has been imposed to nodes lying on one of the two poloidal-radial boundary surfaces of Model 1, while nodes lying on the opposite poloidal-radial surface have been assumed to undergo toroidal plane strain. In order to reproduce realistically the mechanical effects of poloidal torque key and of the four flexible radial rods, radial and poloidal displacements of three sets of nodes, belonging to the BP, have been prevented.

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2.4 Thermo-mechanical loads and boundary conditions - Model 2

The relevant thermo-mechanical loads and boundary conditions are herewith presented and critically discussed as far as FEM Model 2 is concerned.

Thermal loads and boundary conditions

In order to simulate heat power deposition on the FW plasma-facing surface due to particles and radiations arising from plasma, a non-uniform normal heat flux has been applied to the model FW plasma-facing surface the same procedure used for the Model 1 has been followed. Moreover, since this model includes the FW corner region, for each single element face belonging to it, the value of normal heat flux, already multiplied for the cosine of the angle α, has been further multiplied, by means of a purposely implemented FORTRAN routine, for the cosine of the angle β formed by radius vector and the radial direction. Heat flux on SW external surfaces has supposed to be zero, in order to take into account the presence of the other blanket modules that have not been modelled.

Furthermore, as in the previous case, a non-uniform spatial distribution of heat power volumetric density has been applied to the model to simulate power deposited by neutrons and photons [6].

Concerning thermal contact models between breeder and the related wetted surfaces, thermal coupling between inner and outer tubes of each DWT due to the copper layer interposed between them and thermal contact between the BP and the thirty DWTs, the same procedure used for the Model 1 has been followed. Also the forced convective heat transfer between the structure and the coolant has been simulated as it has been done in the Model 1, taking into account the SW channels as well (Tab. 2). Using the same approach followed for the Model 1 two different inlet temperatures, named $T_{FW,in}$ and $T_{SW,in}$, have been imposed to water entering the FW-SWs channels. In particular, $T_{FW,in}$ has been set equal to 323.39 °C, since it has flown through the opposite lateral slice and 8 slices equal to that represented by Model 1, while $T_{SW,in}$ has been set equal to 285.0 °C, since it enters directly the module slice represented by Model 2. The same approach has been followed to define the temperatures of water entering Model 1 Caps channels, which values are reported in table 3. Regarding the characterization of the coolant flowing in the DWTs the same approach adopted for Model 1 has been followed.

Tab. 3. Water inlet temperatures of Model 2 Caps channels.

Channel	TC Inlet [°C]	BC Inlet [°C]
1	324.19	285.0
2	318.44	285.0
3	318.34	285.0
4	316.82	285.0
5	321.06	285.0

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Mechanical loads and boundary conditions

The same mechanical loads and boundary conditions imposed in the Model 1 has been adopted except for the mechanical constraints. In particular, toroidal symmetry has been imposed to nodes lying on the internal poloidal-radial boundary surface of Model 2. Moreover, as far as the constraints on the BP are concerned the same procedure followed for Model 1 has been followed.

2.5 The iterative procedure

According to what mentioned in the previous sections, an iterative procedure (Fig. 3) has been set up with the aim of calculating mass flow rates and heat transfer coefficients of water flowing into FW-SWs and Caps channels and into BZ DWTs. The same procedure has been adopted also to assess the inlet temperatures of water flowing through FW and Caps channels. Mass flow rate and heat transfer coefficient values have been indicated as $G_j^{(i)}$ and $h_j^{(i)}$. Inlet temperatures of water entering Model 1 and Model 2 channels have been reported as $T_{C-j,in}^{(i)}$ and $T_{L-j,in}^{(i)}$ respectively, where the subscript j indicates the component (FW, SW, TC, BC), and the superscript i indicates the iteration considered. An initial evaluation of the total heat power deposited within FW-SWs, Caps and their relevant cooling water has been made in order to calculate the values of the mass flow rates $G_j^{(0)}$ and the heat transfer coefficients $h_j^{(0)}$. Inlet temperatures $T_{C-j,in}^{(0)}$ of coolant water flowing through Model 1 FW and Caps have been assumed to be equal to 305 °C, calculated as the water inlet temperature of 285 °C increased by the half of the total thermal rise (40 °C). A preliminary thermal analysis, named “Analysis zero”, has been launched in order to assess the temperatures $T_{C-j,out}^{(0)}$ of water exiting FW and Caps channels of Model 1. By means of so assessed $T_{C-j,out}^{(0)}$ values, the temperatures $T_{C-j,in}^{(1)}$ of water entering Model 1 FW and Caps channels have been calculated and adopted to perform another thermal analysis (Analysis 1), with the aim of evaluating the water outlet temperatures $T_{C-j,out}^{(1)}$ of Model 1 FW and Caps channels and the related thermal rise $\Delta T_{C-j}^{(1)}$.

$T_{C-j,out}^{(1)}$ and $\Delta T_{C-j}^{(1)}$ have been used to calculate the temperatures $T_{L-j,in}^{(1)}$ of water entering Model 2 FW and TC channels, as follows:

$$T_{L-j,in}^{(1)} = T_{C-j,in}^{(1)} + 4 \cdot \Delta T_{C-j}^{(1)} \qquad (1)$$

Because of the countercurrent coolant flow mode, $T_{L-SW,in}^{(1)}$ has been imposed equal to 285 °C, as well as the temperatures of water entering the BC channels, $T_{L-BC,in}^{(1)}$.

Assuming the values of $T_{L-j,in}^{(1)}$ calculated by means of equation (1), a thermal analysis has been launched with reference to Model 2, obtaining the pertaining thermal rises. These temperature variations are different for water entering the SW and water entering the FW, as well as for water entering TC and BC channels. Therefore, a mean value $\Delta T^{(1)}_{L-j}$ has been calculated. The total water coolant thermal rise $\Delta T^{(1)}_{TOT-j}$ has been finally estimated as follows:

$$\Delta T^{(1)}_{TOT-j} = 2 \cdot \Delta T^{(1)}_{L-j} + 8 \cdot \Delta T^{(1)}_{C-j}$$

This thermal rise is compared with the reference value ΔT_{Design} amounting to 40 °C. Since $\Delta T^{(1)}_{TOT-j}$ is not equal to ΔT_{Design}, mass flow rates, heat transfer coefficients and $T^{(1)}_{C-j,in}$ values initially assumed have to be re-calculated by a further iteration. To this purpose they have to be revised by adopting apposite corrective factors. The aforementioned procedure is then repeated until convergence is obtained and a self-consisting set of mass flow rates, heat transfer coefficients and inlet temperatures is assessed for both the two FEM models. Convergence has been reached in five iterations for water flowing into FW and Caps channels, while only two iterations have been needed for water flowing into BZ DWTs.

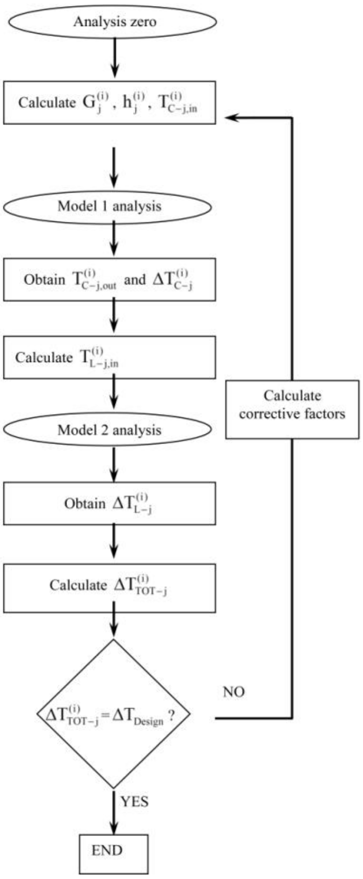

Fig. 3. The iterative procedure.

3. DEMO-WCLL blanket module steady state analysis

Uncoupled thermo-mechanical steady state analyses have been carried out to investigate the DEMO-WCLL blanket module thermo-mechanical behaviour under Normal operation scenario loading conditions, in order to assess the potential aptitude of this blanket concept to safely withstand the loads it undergoes under flat-top plasma operational state without incurring in significant deformations or yielding-induced structural crisis.

As to Model 1, in a first phase, a steady state thermal analysis has been carried out by means of a qualified commercial FEM code, running in parallel on an Intel® Core™ i7-3820 3.60 GHz workstation, equipped with 64 GB RAM, in about 6 hours.

Subsequently, breeder and water coolant nodes have been eliminated from the computational domain and, on the basis of the thermal field distribution obtained, a steady state mechanical analysis has been performed, running on the same workstation in about 1 hour, to assess the spatial distribution of total stresses. Furthermore, a further steady state mechanical analysis has been carried out, considering only thermal loads, to directly assess secondary stress distribution. Finally, primary stress spatial distribution has been derived as the difference between those already obtained with regard to total and secondary stresses.

Concerning Model 2, the same procedure followed for Model 1 has been adopted. Steady state thermal analysis of this model has been carried out in about 11.5 hours, while steady state mechanical analysis has been performed in about 1 hour.

In order to study the DEMO WCLL blanket module thermal behaviour, attention has been focussed on the assessment of the spatial distribution of its thermal field as well as of its pertaining thermal gradients. On the other hand, in order to investigate the DEMO WCLL blanket module mechanical behaviour, attention has been mainly focussed on the assessment of the spatial distribution of the Von Mises equivalent stress field σ_{VM} and on displacements field values. In particular, the analysis of the σ_{VM} distribution has aimed to evaluate if the module SB would be able to safely withstand those thermo-mechanical loads it undergoes under the loading scenario investigated. Since the design of DEMO breeding blanket has to be based on a consistent set of rules taking into account, at the same time, regulation requirements for nuclear components, the peculiarities of EUROFER mechanical behaviour and the specific operating conditions foreseen for DEMO reactor environment, a stress linearization procedure has been carried out, with the specific aim to evaluate general or local primary membrane stress tensor (P_m or P_L), primary bending stress tensor (P_b), general or local secondary membrane stress tensor (Q_m or Q_L), secondary bending stress tensor (Q_b) and peak stress (F) in some peculiar and particularly significant paths of the module.

Stress values calculated have been adopted to verify if the module thermo-mechanical stress state complies with requirements prescribed by SDC-IC rules, that are both the most conservative and comprehensive of all possible damage modes for level A criteria [14, 18].

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3.1. Normal operation scenario results –Model 1

With respect to the thermal behaviour predicted under the Normal operation scenario for the central slice of the outboard equatorial module of the DEMO-WCLL breeding blanket concept, results obtained (Fig. 4) indicate that a significant thermal gradient arises in both radial and poloidal directions within the model, due to the external heat flux it undergoes, to convective heat transfer with water coolant flow and to the volumetric density of nuclear deposited heat power.

In particular the maximum temperature of 509.7 °C is predicted to be reached into the breeder, while the maximum temperature predicted in EUROFER components amounts to 443.6 °C, achieved in the second radial cell of the poloidal-toroidal and poloidal-radial stiffening plates ($SP_{p\theta}$ and SP_{pr}). This temperature is well below the critical EUROFER temperature set to 550 °C. Results suggest that the FW thermal field is quite uniform along the poloidal direction, while a pronounced thermal gradient arises within this component, probably due to the internal and external heat fluxes it undergoes and to convective heat transfer with water coolant flow.

Concerning Pb-Li breeder, results obtained show a significant radial thermal gradient, as it may be expected according to the cooling channels arrangement and to the spatial distribution of the volumetric density of nuclear deposited heat power imposed to the model.

Concerning the DEMO-WCLL blanket module mechanical behaviour assessed under the Normal operation scenario, results obtained (Fig. 5) are not affected by mechanical constraints assumed for nodes lying on BP external surface and on the two poloidal-radial boundary surfaces of the model.

They indicate that the most heavily stressed region of the model, except for an extremely narrow BC region where a geometrical discontinuity induce an "hot spot", is located within the $SP_{p\theta}$ near to the area in which maximum EUROFER temperature is achieved. However values of Von Mises equivalent stress field are predicted to remain below 200 MPa in the whole module.

Finally, with respect to the displacement field, attention has been paid to radial, toroidal and poloidal displacements (respectively u_r, u_θ and u_p) within the model, in order to check that no excessive displacements take place during flat-top operation plasma state.

Results obtained indicate that displacements predicted within SPs, FW and Caps are physically meaningful and acceptable from a qualitative point of view. In particular, the highest displacement value in both radial and poloidal directions for these components amounts to 3.6 and 3.7 mm respectively.

Moreover, significant values of toroidal displacements (~1.7 mm) have been calculated for the Pb-Li tubes, suggesting that a constraint along this direction should be considered and properly investigated. A summary of the most significant results obtained is reported in tables 4 and 5.

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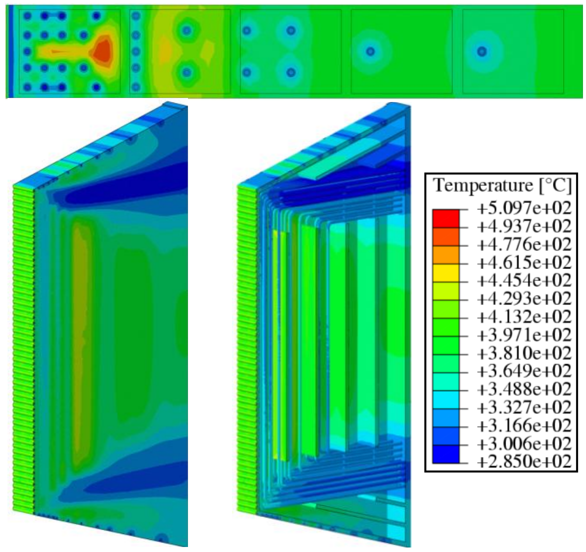

Fig. 4. Thermal field: poloidal mid-plane section and 3D views.

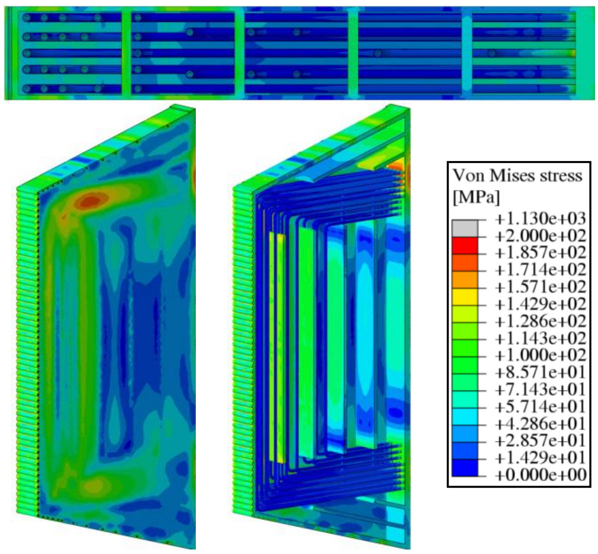

Fig. 5. Von Mises stress field: poloidal mid-plane section and 3D views.

Tab. 4. Model 1, summary of the thermal results.

Model 1 - Thermal results		
	T_{Max} [°C]	T_{Min} [°C]
FW	442.7	316.6
$SP_{p\theta}$	443.6	304.7
SP_{pr}	443.5	285.5
Caps	393.2	306.2
Pb-Li	509.7	285.2
Pb-Li tubes	379.1	285.0

Tab. 5. Model 1, summary of the mechanical results.

Model 1 - Mechanical results						
	Maximum Von Mises Stress [MPa]					
FW	188.4					
$SP_{p\theta}$	171.1					
SP_{pr}	180.3					
Caps	182.0					
Pb-Li tubes	184.7					
	Displacement [mm]					
	$u_{r\ Max}$	$u_{r\ Min}$	$u_{\theta\ Max}$	$u_{\theta\ Min}$	$u_{p\ Max}$	$u_{p\ Min}$
FW	-3.146	-3.631	0	-0.562	3.232	-3.072
$SP_{p\theta}$	0.016	-2.922	0	-0.562	3.393	-3.400
SP_{pr}	0.158	-3.546	0	-0.562	3.621	-3.645
Caps	0.022	-3.341	0	-0.562	3.694	-3.724
Pb-Li tubes	0.557	-3.067	1.095	-1.673	3.285	-2.942

Stress linearization

Proper linearization paths have been identified in correspondence to the most heavily stressed areas of FW, SPs, Pb-Li tubes and BP, taking into account also areas where, in spite of not particularly high Von Mises equivalent stress values, high temperatures have been predicted that result in the calculation of lower values of maximum allowable stress intensities. Within the FW, three stress linearization paths have been identified, lying on two different sections. The first is a toroidal-radial section located at the FW poloidal mid-plane in correspondence to the cooling channel toroidal axis, the second is another toroidal-radial section located nearby the former at the throat between two subsequent cooling channels. Figure 6 reports, as an example, the stress linearization paths concerning the SPs.

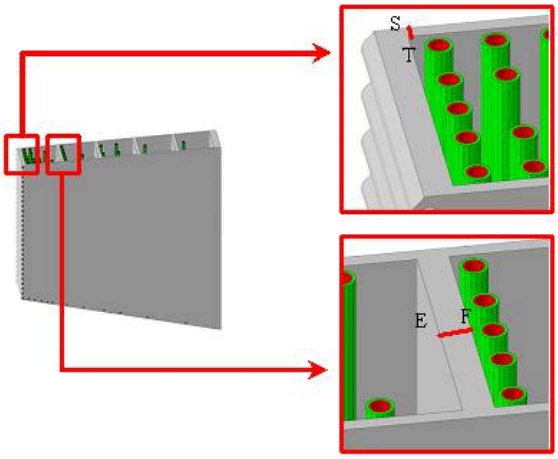

Fig. 6. SP_{pr} and $SP_{p\theta}$ stress linearization paths.

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In case of Normal operation scenario, rules prescribed by SDC-IC code for level A criteria have been taken into account, adopting low temperature rules and, if path mean temperature overcomes the value of 450 °C, also high temperature ones. To this purpose, the following assumptions have been made:

- K_{eff} has been assumed equal to 1.5 [14], which implies that K_t amounts to 1.25 [14, 19];
- the allowable stress limit S_m has been assumed to depend uniquely on thickness averaged temperature T_m, neglecting its possible dependence on neutron fluence Φt_m as suggested in [14] with reference to irradiation-hardening materials, and tabular data reported in [17] have been properly interpolated to calculate its values;
- the allowable stress limit S_t has been calculated from tabular data reported in [17], assuming 5200 heat cycles for the life of the starter blanket, each one characterized by a hold time of 2 h, for an overall operation time amounting to 10400 h;
- the allowable stress limit S_e has been calculated from graphical data reported in [19], conservatively assuming it to uniquely depend on thickness averaged temperature T_m and neglecting its possible dependence on neutron fluence Φt_m.

Since no information has been found on the allowable stress limit S_d for the EUROFER material, the related verifications have not been carried out. As an example of the results obtained on Model 1 for stress linearization and verifications, table 6 reports the outcomes related to the path ST on the SP_{pr}.

Tab. 6. Model 1, first radial cell SP_{pr} - Path ST.

Calculated and allowable stress intensities				
T_m [°C]	S_m [MPa]	$K_{eff} S_m$ [MPa]	S_t [MPa]	S_e [MPa]
370	159	239	-	187
	$\overline{P_m}$	$\overline{P_m + P_b}$	$\overline{P_m + P_b/K_t}$	$\overline{P_m + Q_m}$
	2.11	2.72	-	79.05

Rule verification		
$\overline{P_m}/S_m$	0.01	YES
$\left(\overline{P_m + P_b}\right)/K_{eff} S_m$	0.01	YES
$\overline{P_m}/S_t$	NOT PERFORMED	
$\left(\overline{P_m + P_b/K_t}\right)/S_t$	NOT PERFORMED	
$\left(\overline{P_m + Q_m}\right)/S_e$	0.42	YES

3.2. Normal operation scenario results –Model 2

Concerning the lateral slice of the outboard equatorial module of the DEMO-WCLL breeding blanket concept thermo-mechanical behaviour assessed under the Normal operation scenario, results obtained (Figs. 7 – 8) are quite similar to those obtained for Model 1. Thermal results show that the maximum temperature of 508.7 °C is reached within the breeder, while the maximum temperature that EUROFER steel components experience is 455.1 °C, well below the EUROFER maximum allowable temperature of 550 °C. Also in this case significant radial and poloidal thermal gradients arise within the SB and the breeder, according to loads and boundary conditions adopted to perform calculations. From the mechanical point of view, results show that the Von Mises equivalent stress is below the value of 350 MPa in a wide region of the model, except for a restricted area in the external surface of the SW where stress concentrations due to a geometrical discontinuity have been observed. However, most stressed regions are placed in the corner region of FW-SW external surface and in the SP_{pr}. Results obtained seem to be not affected by mechanical constraints assumed for nodes lying on the BP external surface and on the external surface of SP_{pr}. Finally, with respect to the displacement field, attention has been paid again to radial, toroidal and poloidal displacements (respectively u_r, u_θ and u_p) within the model, in order to check that no excessive displacements take place during Normal operation scenario. Results obtained indicate that displacements predicted within SPs, FW, SWs, Caps and Pb-Li tubes are physically meaningful and acceptable from a qualitative point of view. In particular, the highest displacement value in radial direction for these components is about 3.6 mm, while maximum displacement in poloidal direction is about 3.3 mm. Also in this case a significant toroidal displacement (~ 2.18 mm) has been calculated in the Pb-Li tubes. A summary of the most significant results obtained is reported in tables 7 and 8.

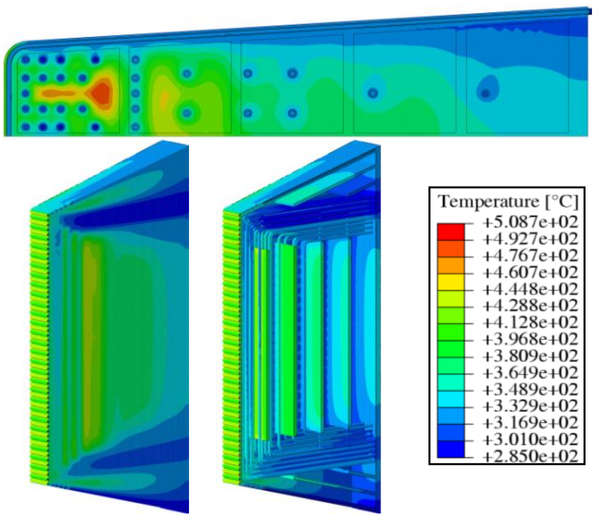

Fig. 7. Thermal field: poloidal side-plane section and 3D views.

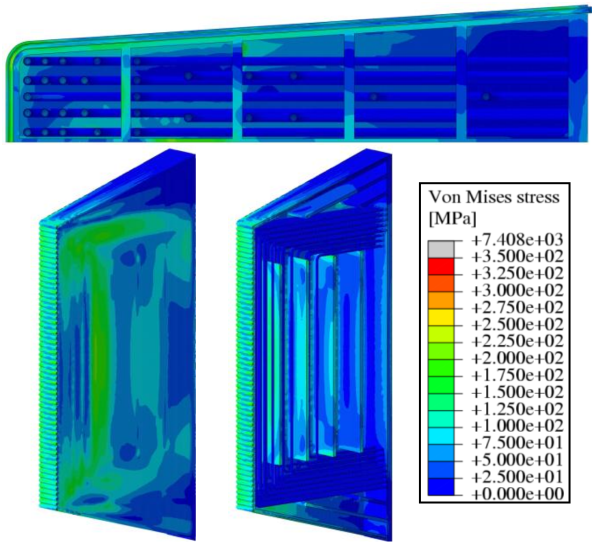

Fig. 8. Von Mises stress field: poloidal side-plane section and 3D views.

Tab. 7. Model 2, summary of the thermal results.

Model 2 – Thermal results		
	T_{Max} [°C]	T_{Min} [°C]
FW	455.1	304.6
$SP_{p\theta}$	445.1	289.5
$SW\text{-}SP_{pr}$	443.0	285.5
Caps	398.6	285.5
Pb-Li	508.7	285.3
Pb-Li tubes	394.6	285.0

Tab. 8. Model 2, summary of the mechanical results.

Model 1 – Mechanical results						
	Maximum Von Mises Stress [MPa]					
FW	302.1					
$SP_{p\theta}$	219.0					
$SW\text{-}SP_{pr}$	350.0					
Caps	210.2					
Li-Pb tubes	308.6					
	Displacement [mm]					
	$u_{r\ Max}$	$u_{r\ Min}$	$u_{\theta\ Max}$	$u_{\theta\ Min}$	$u_{p\ Max}$	$u_{p\ Min}$
FW	-3.023	-3.633	0.638	0	2.942	-3.013
$SP_{p\theta}$	0.024	-2.920	0.743	0	3.034	-3.053
$SW\text{-}SP_{pr}$	0.167	-3.542	0.885	0	3.301	-3.315
Caps	0.071	-3.216	0.734	0	3.343	-3.347
Li-Pb tubes	0.194	-3.619	1.825	-2.181	3.285	-3.349

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Stress linearization

Linearization paths corresponding to those already identified in Model 1 have continued to be taken into account in FEM Model 2. Furthermore, it has to be underlined that other three paths, lying on the corner region of FW-SWs, have been considered and another path placed in the FW maximum temperature area. The path named ST (Fig. 6) in Model 1 and placed in the 1st radial cell of SP_{pr}, is now placed in the 2nd radial cell of SP_{pr}.

Rules prescribed by SDC-IC code for level A criteria have been taken into account, adopting low temperature rules and, if appropriate, also high temperature ones according to the component local thermal state. To this purpose, the same assumptions made for Model 1 have been taken into account. As an example of the results obtained on Model 2 for stress linearization and verifications, table 9 reports the outcomes of the most critical path taken into account where the rule related to the potential loss of ductility is not verified.

Tab. 9. Model – 2, second radial cell SP_{pr} - Path ST.

<table>
<tr><th colspan="5">Calculated and allowable stress intensities</th></tr>
<tr><td>T_m [°C]</td><td>S_m [MPa]</td><td>$K_{eff} S_m$ [MPa]</td><td>S_t [MPa]</td><td>S_e [MPa]</td></tr>
<tr><td rowspan="3">441</td><td>147</td><td>220</td><td>-</td><td>152</td></tr>
<tr><td>$\overline{P_m}$ [MPa]</td><td>$\overline{P_m + P_b}$ [MPa]</td><td>$\overline{P_m + P_b / K}$ [MPa]</td><td>$\overline{P_m + Q_m}$ [MPa]</td></tr>
<tr><td>5.88</td><td>5.88</td><td>-</td><td>201.95</td></tr>
<tr><th colspan="5">Rule verification</th></tr>
<tr><td colspan="2">$\overline{P_m} / S_m$</td><td>0.04</td><td colspan="2">YES</td></tr>
<tr><td colspan="2">$\left(\overline{P_m + P_b}\right) / K_{eff} S_m$</td><td>0.03</td><td colspan="2">YES</td></tr>
<tr><td colspan="2">$\overline{P_m} / S_t$</td><td colspan="3">NOT PERFORMED</td></tr>
<tr><td colspan="2">$\left(\overline{P_m + P_b / K_t}\right) / S_t$</td><td colspan="3">NOT PERFORMED</td></tr>
<tr><td colspan="2">$\left(\overline{P_m + Q_m}\right) / S_e$</td><td>1.33</td><td colspan="2">NO</td></tr>
</table>

4. Conclusions

Within the framework of DEMO R&D activities, a research cooperation has been launched between ENEA Brasimone, CEA Saclay and the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo to theoretically investigate the thermo-mechanical behaviour of the outboard equatorial module of WCLL-DEMO breeding blanket concept under Normal operation steady state scenario.

Two FEM models, named Model 1 and Model 2, reproducing respectively the central and the lateral poloidal-radial slices of the WCLL blanket module have been set up and optimized in order to save time calculations.

Results obtained for both configurations have shown that the EUROFER critical temperature of 550 °C is never overcome and that the maximum temperature of 509.7 °C is reached within the Model 1 BZ.

Concerning the mechanical behaviour of the WCLL blanket module, the structure experiences moderate Von Mises stress values. In fact, results have shown that they remain under 200 MPa in Model 1, resulting higher in Model 2, where, nevertheless, they remain under 350 MPa in almost the whole SB, except for some narrow regions, very likely due to geometrical discontinuities or numerical singularities. Moreover, significant toroidal displacements (~ 2 mm) has been calculated in the Pb-Li tubes which suggest that a constrain along this direction should be considered.

Safety verifications, according to SDC-IC codes, are totally satisfied as far as Model 1 is concerned, while they are generally widely satisfied except for that relevant to the potential loss of ductility in the toroidal path located in the 2nd radial cell of SP_{pr}. High temperature rules have been performed only for one Model 2 path, since in all other paths investigated temperature values did not overcome the temperature of 450 °C.

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