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Status on DEMO Helium Cooled Lithium Lead Breeding Blanket thermo-mechanical analyses

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The EUROfusion Consortium develops a design of a fusion power demonstrator (DEMO) in the framework of the European "Horizon 2020" innovation and research program. One of the key components in the fusion reactor is the breeding blanket surrounding the plasma, ensuring tritium self-sufficiency, heat removal for conversion into electricity, and neutron shielding. The Helium Cooled Lithium Lead (HCLL) blanket is one of the concepts which is investigated for DEMO. It is made of a Eurofer structure and uses the eutectic liquid lithium-lead as tritium breeder and neutron multiplier, and helium gas as coolant. Within the EUROfusion organization, CEA with the support of Wigner-RCP and IPP-CR, is in charge of the design of the HCLL blanket for DEMO.

This paper presents the status of the thermal and mechanical analyses carried out on the HCLL breeding blanket in order to justify the design. CFD thermal analyses on generic breeding unit including stiffening plates and cooling plates have been performed with ANSYS in order to consolidate results obtained with previous FEM design analyses. Moreover in order to expand the justification of the HCLL Breeding blanket design, the most loaded area of the equatorial outboard module has been analyzed with CAST3M in case of accident, according to RCC-MRx, resulting in relatively good behavior of the box. Additionally analyses have been performed in order to check the good behavior of the tie rods modules' attachments system in normal condition showing promising results.

Keywords: DEMO, Breeding Blanket, HCLL, Design, Cast3M, RCC-MRx

1. Introduction

Within the framework of the EUROfusion consortium, Europe is committed to the development of a near term fusion power plant based on limited technologies and plasma extrapolation from ITER. This so-called DEMOnstration reactor shall prove the feasibility of generating electricity with an integrated fusion plant [1].

In a fusion power plant, the blanket (the first structure surrounding the plasma) is one of the key components since it has to withstand extremely severe operating conditions while insuring tritium self-sufficiency, adequate neutron shielding and coolant temperatures suitable for an efficient power conversion cycle. The Helium Cooled Lithium Lead (HCLL) blanket is one of the candidate blanket concepts selected by the European Union for DEMO and will be tested in ITER as part of the TBM programme. Within the EUROfusion organization, CEA with the support of Wigner-RCP and IPP-CR, is in charge of the design of the HCLL blanket for DEMO. It is based on the use of Eurofer97 [2] as structural material, the eutectic Pb–15.7Li enriched at 90% in ^{6}Li as breeder, neutron multiplier and tritium carrier and He as coolant with inlet/outlet temperatures of 300/500 °C and 8 MPa pressure [3].

Since 2014, a new programme has been defined by the EUROfusion consortium in order to implement the Roadmap to fusion during Horizon2020 [1] leading to the Work Package Breeding Blanket (WPBB) [4],[5] in which the DEMO HCLL breeding blanket is developed.

As a complement of [3], this paper describes the status of new thermal and mechanical analyses carried out on the HCLL breeding blanket in order to justify the design.

1. HCLL design description

The HCLL breeding blanket conceptual design follows the previous Multi Module Segment (MMS) design in order to minimize the stresses from Electro-Magnetic and thermal loads, to facilitate the manufacturing and to be consistent with the maintenance scheme: individual modules are attached with Tie Rods (TR) on a stiff poloidal Back Supporting structure (BSS) in order to form a blanket segment which can be removed from the upper port as a banana-shaped segment (Fig. 1).

The design of the modules has been developed with the aim to capitalize as much as possible on TBM experience by mutualising, when possible, solutions for the design of specific components.

The generic HCLL blanket module consists of an Eurofer steel box formed by an U-shaped plate (First Wall and Side Walls – FW & SW) closed on its sides by cover plates (Side Covers - SCs) and on the back by 4 successive plates (Back Plates – BPs). The box is reinforced by an internal grid of vertical radial-poloidal and horizontal radial-toroidal stiffening plates (vSP and hSP) in order to withstand the Helium pressure (8 MPa) in case of accidental pressurization. The stiffening grid defines an array of internal cells for the breeder units (BUs) where the eutectic PbLi flows around parallel horizontal cooling plates (CPs) connected to a BU back plate ensuring the insert rigidity. Fig. 2 shows the CAD

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design of the outboard central module: a total of 90 BUs (9 in the toroidal direction and 10 in the poloidal direction) are defined by the stiffening grid. All BUs are identical except the external ones (those delimited by the SCs and SWs). An inlet and an outlet chamber on the BU back plate ensure the helium distribution and collection for the CP.

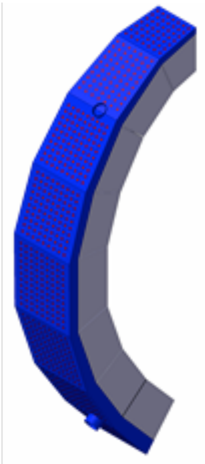

Fig. 1: CAD of the DEMO HCLL outboard segment

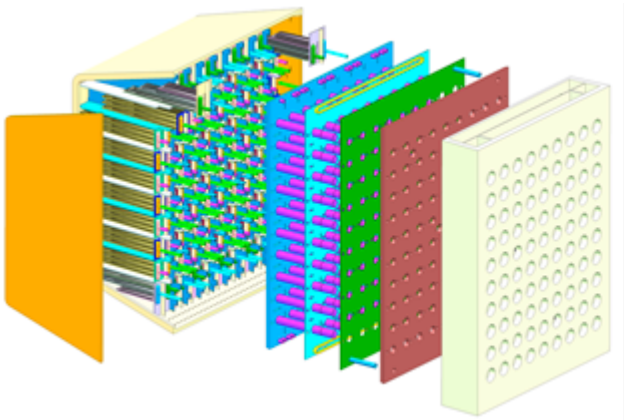

Fig. 2: CAD of the DEMO HCLL equatorial outboard module

2. Thermal CFD analyses of a Breeding Unit

Previous therrmo-hydraulic analyses [3] were performed with the Finite Element Method code Cast3M [6] using a simplified advection model to represent the helium flow in the cooling channels and analytical formulae [7] to calculate the pressure drops. In order to validate these results a detailed CFD analysis of the same generic BU has been performed using ANSYS CFX 14.5.

All the 3 different domains (steel, PbLi, Helium) are meshed with a total of ~10 million hexahedral elements. The loads and boundary conditions for Eurofer, Pb-Li and Helium are based on those used in [3]. The loads are the radial nuclear power density distribution in the Eurofer structures and eutectic Pb-1.57Li and the heat flux deposed on the plasma-facing surface of the FW. Inlet boundary conditions for helium are given in Table 1 . In order to describe the effect of the turbulence, Shear Stress Transport (SST) turbulence model was chosen since it is experienced that this model can give good prediction for flow field in channel flow.

Table 1: Inlet boundary condition for He.

Component	U[m/s]	Tin[°C]
FW	80	340
hSP	37	372
vSP	37	372
Component	Q[kg/s]	Tin[°C]
CP	0.0192	455

The obtained temperature distributions are shown in Fig. 3. Maximum values are slightly higher than the ones obtained in [3], with a maximum Eurofer temperature on the central CP equal to 557°C instead of 545°C, but the location of the maximum values is the same and the temperature distributions show overall a very good agreement considering the different FE modeling. The difference in maximum values could also be explained by a difference in the calculated deposited power.

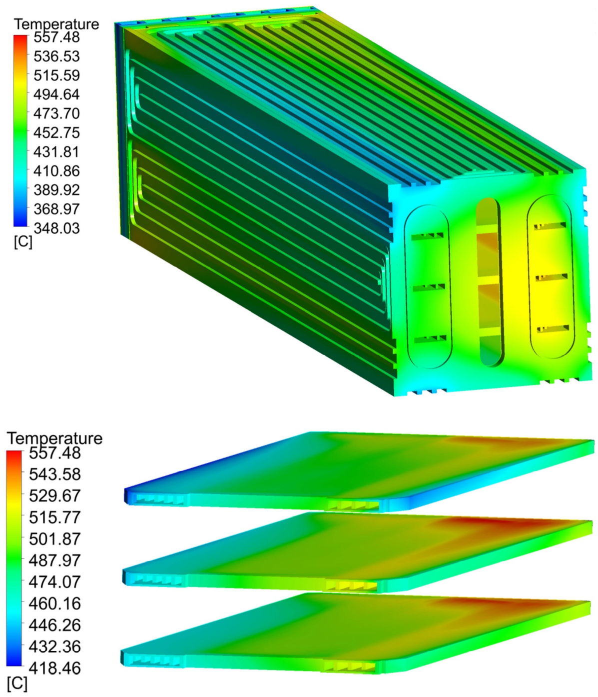

Fig. 3: Temperature distribution calculated by CFD analyses presented in all Eurofer BU components (top) and CPs (bottom)

Large fluctuations in the Heat Transfer Coefficients values occur along the channels' length because of the inversion of the heat fluxes along them: this is due to heat exchanges between adjacent channels at different temperatures. The effect of channel bends on the heat transfer coefficient curves is also observed. The bends disturb the Helium flow; the velocity distribution becomes inhomogeneous (Fig. 4). The swirly flow increase the heat transfer between the fluid and the solid wall, the value of heat transfer coefficient becomes higher in the vicinity of these regions. The average calculated values of the HTC in the SPs and CPs, equal to ~3500 Wm-2K-1 are however in excellent agreement with those reported in [3].

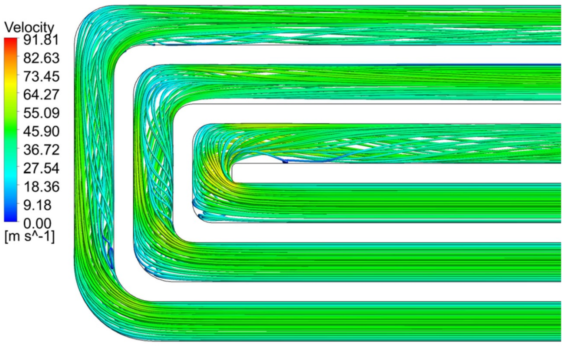

Fig. 4: Streamlines in channel bends

Pressure drops in SPs and CPs have been calculated with ANSYS as well and show some results in the order of 0.05 MPa and 0.07 MPa respectively, values that are very close, and in any case lower, than those calculated by simple analytical formulae in [3]. The analytical approach appears therefore to be conservative.

3. Mechanical FEM analyses in case of accident

The box is analyzed in faulted condition according to the RCC-MRx §RB3251.13 [8]. Irradiation and creep are not considered in this study. The stress limit SmD is taken equal to 274 MPa at 500°C. This temperature is equal to the outlet temperature of the coolant and is conservative for the structure analysis. The CAD model is imported in Siemens NX 8.5 [9] for meshing purpose and FEM elastic calculation is performed with Cast3M [6]. The analysis is performed only on the most loaded BU, the one where the largest Side Wall or First Wall pressure area is, which is the one in the corner. At least one element in each thickness is modeled leading to 490411 elements and 842499 nodes for the model. A pressure of 80 bar inside the box is applied.

The deformed mesh is illustrated in Fig. 5 with amplification x20. Von Mises stresses are shown on the deformed mesh as isovalues. We can see that the FW and the Side Wall have considerable displacements. The maximum stress is localized in the channels outer thicknesses of the hSP on both sides mainly due to pressure on the Side Wall that leads to a toroidal stress. In this corner BU, the area on the Side Wall where the pressure in applied in case of accident is larger than in the others BU where the original hSP thicknesses have been calculated thanks to analytical formulae.

The stress linearization is performed on the most stressed region on the hSP in order to verify design rules defined in the RCC-MRx [8]. The results on the Table 2 show that only the membrane stress is slightly above the stress limit SmD by a factor of 1.09. However the design can comply with the criteria in case of accident by increasing the thicknesses of these hSP channels and taking the SmD limit to a more realistic and lower temperature.

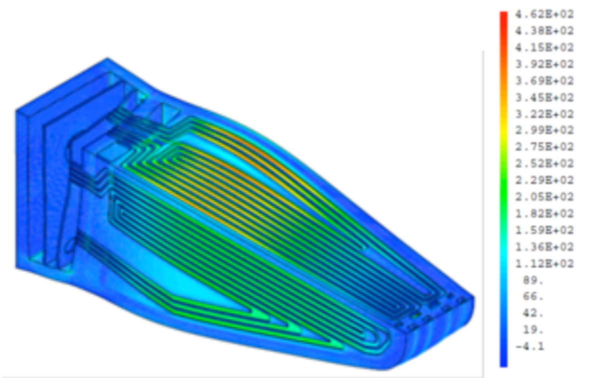

Fig. 5: Deformed mesh in faulted condition (x20) with Von Mises Iso stress field [MPa].

Table 2: Linearization results in the hSP component.

Pm [MPa]	SmD [MPa]	Ratio	Pm+Pb [MPa]	SmD [MPa]	Ratio
298.7	274	1.09	387	429.24	0.90

4. Preliminary thermo-mechanical analyses of the module attachments

The TRs constituting the attachment of the modules to the back supporting structure, they have to withstand all loads acting on the modules: weight, pressure, thermal, electromagnetic, seismic, etc. In the previous paper [3] the number of TRs has been set to 90 (i.e. one per BU) to correspond to the maximum allowed by the space constraints imposed by the crossing of pipes and stiffening grids: the diameters of the TRs could however be (slightly) increased if needed.

A simplified linear FEM model has been used on Cast3M [6], whose "elementary cell" is shown in Fig. 6: an unilateral displacement boundary condition has been used to simulate the contact between the module's backplate (BP4) and the Back Supporting Structure (BSS), which means that detachment of the two surfaces (under load) is allowed. This insures that all loads are actually transmitted to the TRs. Note that while holes for crossing of SP/He pipes are not represented, this has no impact on the assessment TRs structural integrity. The final FE model is shown in Fig. 7.

Applied pressure loads are 8MPa internal pressure on all manifold chambers (module and BSS). The temperature distribution (Fig. 8) in the structure has been calculated by means of a thermal analysis assuming convective heat exchange with helium at the corresponding chamber's temperature [3] and a HTC equal to 1000W/m2K. The module dead weight has been calculated to be approximatly 17 tons considering the weight of Eurofer structures and the PbLi contained in the module. The corresponding force is applied on the module's center of gravity resulting in a torsor applied on the BP1 center of gravity. Electromagnetic loads have been taken from [10] and are reported in Table 3. Values have however been multiplied by a factor 1.6 following a personal communication with the Author in order to take into account more accurate values regarding to the

HCLL concept. All torsor efforts have been translated in elementary forces applied on the BP1 surface (Fig. 7).

Boundary conditions have been defined in order to simulate a blanket attachment system that forbids displacements of the BBS but does not constrain thermal deformation: Radial displacement of all points on the back-plane (outer surface) of the BSS, vertical displacement of all points on the lower back-plane line and lateral displacement of all points on the left back-plane line are forbidden.

The resulting Von Mises stress distribution in the structure is shown in Fig. 8, with details showing that the differential thermal deformation leads to a (limited) detachment of the module from the BSS. This also confirms that all efforts are withstood by the TRs. The corresponding VM stresses in the TRs are shown in Fig. 9. Regarding the RCC-MRx rules [8], the maximum thermo-mechanical stress which is equal to 433 MPa in the TR of the edges is under the allowable 3Sm limit at 500°C (436MPa). Considering the still preliminary character of this analysis, linearization of stresses has not been carried out.

Table 3: Electromagnetic loads for the whole blanket segments and for the most loaded module as calculated in [10]

	Inboard segment	Outboard segment	**Most loaded module**
F_vert	±3.0 MN	±1.4 MN	**(0.053 MN)**
F_rad	-0,0708 MN	0.24 MN	**0.080 MN**
F_tor	-0.0373 MN	-0.19 MN	**-0.041 MN**
M_rad	9.1 MN m	-15 MN m	**-1.7 MN m**
M_tor	-1 MN m	2.6 MN m	**0.120 MN m**
M_vert	0.25 MN m	0.28 MN m	**1 MN m**

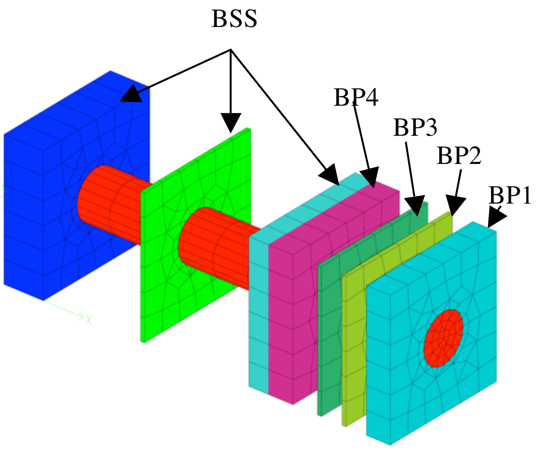

Fig. 6: FE model of the “elementary cell” used to construct the global FE model of the modules’ attachment system.

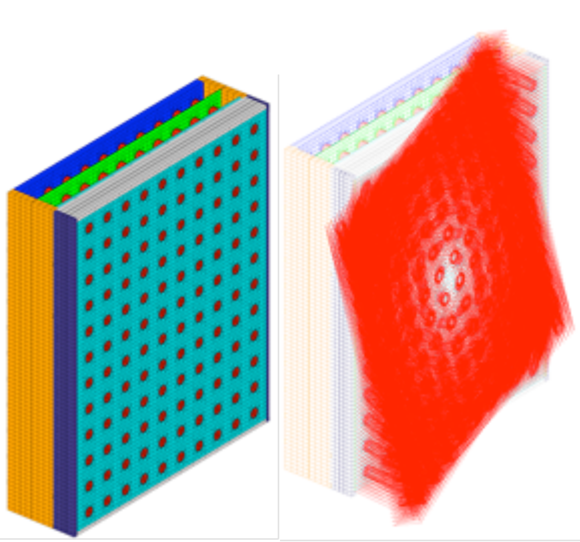

Fig. 7: Global FE model of the modules’ attachment system and force fields resulting from the application of torque on the BP1 surface.

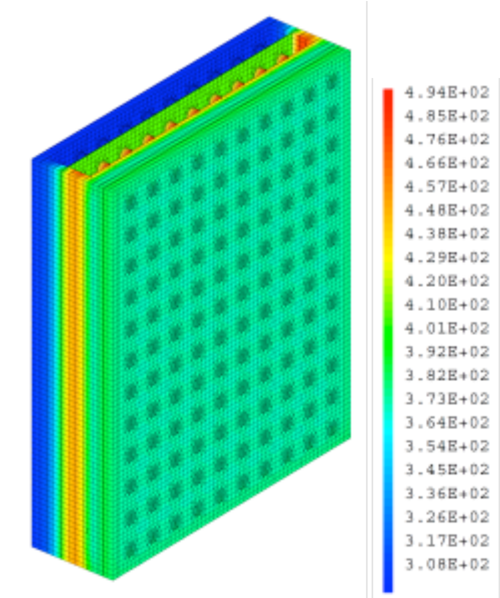

Fig. 8: Temperature distribution in the manifold and BSS [°C].

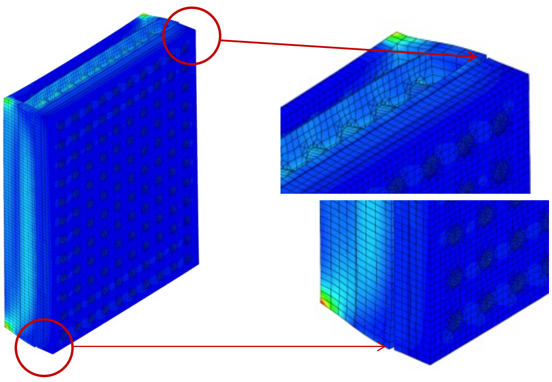

Fig. 9: Von Mises stress distribution on the BSS+module assembly.

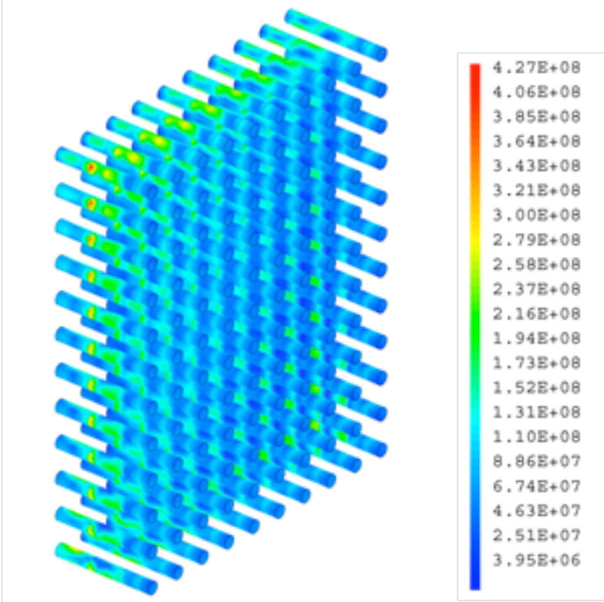

Fig. 10: Von Mises stress distribution [MPa]

5. Discussion and conclusion

This paper presents the status of the outboard segment and equatorial module design of the DEMO HCLL breeding blanket for which, in the framework of the EUROfusion consortium and especially in the Work Package Breeding Blanket, the CEA with the support of Wigner-RCP and IPP-CR is in charge of. The DEMO HCLL breeding blanket design capitalizes on the experience acquired on the HCLL Test Blanket Module designed for ITER. Design improvements have been implemented to adapt the design to DEMO specifications and performance objectives.

3D CFD thermal analyses on generic HCLL Breeder Unit including stiffening plates and cooling plates as well as estimation of pressure losses in HSP/VSP and CP cooling channels have been performed in order to consolidate results obtained with previous FEM design analyses. Even if the calculated maximum temperature in two CPs is higher than the design limit (557.7 °C), the location of the maximum values is the same and the temperature distributions show overall a very good agreement considering the different FE modeling. Moreover even if some large fluctuations in the Heat Transfer Coefficients values occur along the channels' length the average calculated values of the HTC in the SPs and CPs, equal to ~3500 $Wm^{-2}K^{-1}$ are however in excellent agreement with those obtained with the previous FE model. Pressure drops in SPs and CPs have been calculated as well and show results in the order of 0.05 MPa and 0.07 MPa respectively, values that are very close, and in any case lower, than those calculated by simple analytical formulae. The analytical approach appears therefore to be conservative.

Moreover in order to expand the justification of the HCLL Breeding blanket design, the most loaded area of the equatorial outboard module has been analyzed with CAST3M in case of accident, according to RCC-MRx, resulting in relatively good behavior of the box. Results show that the Von Mises stress on most of the components are below the stress limit criteria or should fulfil the criteria when linearizing the stresses, except the horizontal Stiffening Plate where the membrane stress on the most loaded line (thickness of a channel) is above the SmD limit by 10 %. This is mainly due to the fact that the pressure on the BU's corner is applied on a larger surface due to the oblique FW and SC. The calculations are conservative and there are still some margins with respect to the assumed temperature used to calculate stress limits, but the thickness of the SG in the corner could be increased to fulfil the RCC-MRx design criteria if needed.

Additionally analyses have been performed in order to check the good behavior of the tie rods modules' attachments system in normal condition taking into account also electromagnetic, thermal and dead weight loads showing attractive results. Although the results seem to indicate that this solution is viable, the analysis should be repeated using more detailed FE models and (possibly) improved boundary conditions. Dimensioning of the rods/bolts needs to be done according to selected C&S (RCC-MRx). This includes calculation of clamping forces on bolts.

Acknowledgments

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