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Thermo-mechanical analyses and ways of optimization of the helium cooled DEMO First Wall under RCC-MRx rules

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The EUROfusion Consortium develops a design of a fusion power demonstrator plant (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. Among the 4 candidates for the DEMO Breeding Blanket, 2 of them use helium as coolant, and another one uses helium to cool down the First Wall (FW) only.

Due to uncertainties regarding the plasma Heat Flux load the DEMO Breeding Blanket integrated FW will have to cope with, a set of sensitive thermal and thermo-mechanical analyses have been performed in order to define the possible margin against HF the integrated Helium-Cooled Eurofer FW could have. Based on the Helium Cooled Lithium Lead (HCLL) equatorial outboard module dimensions, thermal and stress FEM analyses have been performed with Cast3M with various FW front wall thicknesses and HF, under normal steady state condition. Stress have been analyzed with RCC-MRx code including high temperature (creep), cyclic (fatigue) and irradiated rules.

This paper shows that the thickness of the plasma-facing wall of the FW should be minimized, within the limits necessary to withstand primary stresses, in order to reduce the temperature on the structure and thus prevent fatigue and creep damage as well as a reduction of the stress limit Sm which is function of temperature to prevent ratcheting.

Moreover, the paper will discuss the importance of having constant HF during the reactor operation. A small variation of HF could increase a lot the risk of damage such as fatigue and creep. At the end, the effect of irradiation shows up to be the limiting criterion and penalizes the capacity of the FW to withstand high HF.

Keywords: DEMO, Breeding Blanket, HCLL, RCC-MRx, Thermo-mechanics, Cast3M, First Wall.

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 breeding 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. Among the 4 candidates for the European DEMO Breeding Blanket, 2 of them use helium as coolant, and another one uses helium to cool down the First Wall (FW) only, which is the first part integrated to the BB that interfaces directly the plasma. The main function of the FW is to contribute to electrical production by removing high Heat Flux (HF) from the plasma with an effective coolant system. All the 4 concepts use Eurofer97 as structural material [2].

The maximum heat load capacity of a DEMO BB integrated FW of reasonable cost may impact the decision of the implementation of limiters or detachable FW in DEMO. An estimate of the engineering limit of the FW heat load capacity is an essential input for this decision. Previous study on water-cooled FW have shown good margin, however, mechanical resistance under cyclic load (fatigue), high temperature (creep) and irradiation is still to be demonstrated [3].

This paper will focus on the possible margin the helium-cooled FW could have regarding radiative Heat Flux. The study is based on the equatorial outboard module of the Helium Cooled Lithium Lead (HCLL) BB concept the CEA with the support of Wigner-RCP and IPP-CR, is in charge of [4]. After a thermo-mechanical analysis on the base of the initial "advanced' geometry design and on thermal results detailed in [5], a set of sensitive FEM thermal and thermo-mechanical calculation have been performed using Cast3M [6] with different FW geometry and Heat Flux, under normal steady state condition. Stress have been analyzed with RCC-MRx code [7] for Level A conditions, including high temperature (creep), cyclic (fatigue) and irradiated rules.

2. Methodology of the FE thermo-mechanical analysis of the Helium cooled FW

2.1 Geometry

The HCLL BB is based on the use of Eurofer97 as structural material, the eutectic Pb–15.7Li enriched at

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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 [4].

A generic ½ slice made of horizontal Stiffening Plates and Cooling Plates (Fig. 1) has been considered in order to take into account the Breeding Zone constraint and thermal displacement on the FW. The slice is composed of 8 FW channels that are in counter current flow one other two channels. The upper horizontal Stiffening Plate (hSP) is in front of the hot FW channel whereas the lower hSP is in front of a cold FW channel. 2mm tungsten layer has been taken into account in the thermal analyses.

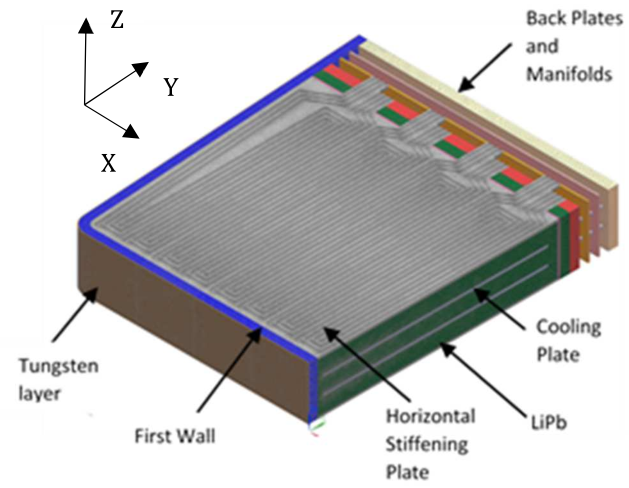

Fig. 1 : Mesh on half slice of the “advanced” HCLL equatorial outboard module.

2.2 Mesh

A realistic 3D Finite Element (FE) mesh model has been set up using the Siemens NX 10.0 [8] software in order to perform both thermal and thermo-mechanical analysis. First of all thermal calculations have been performed on each configuration with linear tetrahedron elements (~2 500 000 elements / ~600 000 nodes). One element in the front wall FW thickness is modelled. Then thermo-mechanical calculation have been performed on mechanical meshes made of quadratic tetrahedron elements (~800 000 elements / ~1 500 000 nodes). Thermal fields calculated before are projected on the mechanical mesh and pressure inside the FW channels is applied. Tungsten, Cooling Plates (CP) and LiPb have been suppressed in the stress calculations.

2.3 Loads and boundary conditions

The pressure load inside the FW channels is equal to 8 MPa. The neutron power deposited into the slice is the same as in [5]. The HF is applied on the plasma side of the FW. The mass flow rate is calculated to have Tin/Tout at 300/500°C.

The boundary conditions used for the thermal calculations are those used in [5]. For the mechanical analyses, the Degree Of Freedom (DOF) of the nodes included in the planes of symmetry (bottom surface for poloidal symmetry at Z min and toroidal surface for toroidal symmetry at X max) are fixed according to the normal of the planes and nodes on the back of the Back Plate are fixed according to the radial DOF (Y axis). In order to represent the fact to have just one slice along the poloidal direction and in order to represent the global bending behavior, a very thick shell has been created on top of the slice, on which the temperature field on the top surface of the 3D slice has been projected (lower, middle and upper layer of the shell).

2.4 Design of experiment

The parametric values that have been estimated are the Heat Flux and the Eurofer front wall thickness, between the tungsten layer and the FW channels.

The dimension of Eurofer front wall thickness (e1 on Fig. 2) are at 0.5 mm increments from 1 through to 3 mm. This results in 5 different models on which thermal and stress analyses have been performed. Based on these 5 models, 5 mesh have been created, including CP and LiPb.

The Heat Flux are at 0.1 MW/m^2 increments from 0.5 through to 1.5 MW/m^2. This results in 11 load cases to be applied on each of the 5 models. Thus a total of 55 calculations have been performed. A second set of mechanical calculations have been performed with only these thermal loads in order to extract secondary stresses.

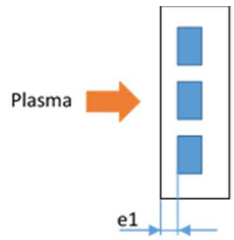

Fig. 2 : Scheme of the FW variable parameter.

2.5 Mechanical analyses

RCC-MRx [7] rules have been used in order to analyze the structure FW according to Class 1 nuclear components criteria. The criteria of Level A are applied. The respect of the criteria must be performed comparing the limits to the linearization of the stresses along some lines through thicknesses of the component. In this study, only the FW has been analyzed.

For this purpose, and in order to cover all the FW area, 14 lines per channels have been studied on the 8 channels (C1 to C8). Lines 1 to 5 analyze the FW surface in front of the plasma, the lines 6 to 9 analyze the wall between two channels and the lines 11 to 14 analyze the thick wall between channels and the LiPb. Thus a total of 112 lines per radial-poloidal plan are analyzed (see Fig. 3). Two areas along the toroidal direction are analyzed, in order to cover the most stressed area: Area A on FW toroidal mid-plane near the plan of symmetry, and area B near the FW bend. So for each of the 55 cases studied RCC-MRx criteria have been checked along 224 lines.

The criteria of the RCC-MRx considered are those to protect the component against the following damage modes:

- immediate plastic collapse and plastic instability
- failure against immediate plastic flow localization and local fracture due to exhaustion of ductility (irradiation of 20 dpa)
- thermal Creep (18000h)
- ratcheting
- fatigue

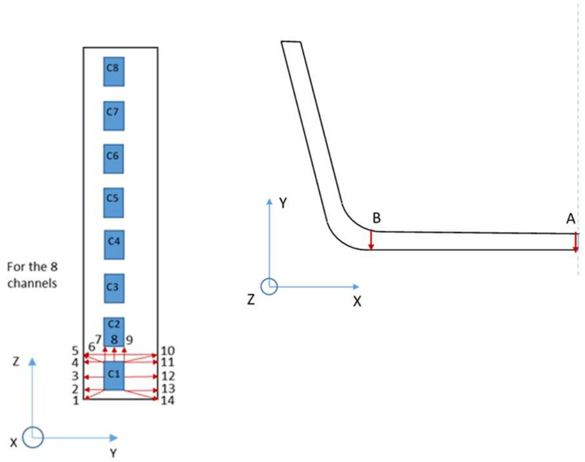

Fig. 3 : Segment on which RCC-MRx stress linearization has been calculated (FW only).

3. FE thermo-mechanical results on the Helium cooled FW

3.1 Results on initial configuration

In order to have a design of reference for the sensitive analyses, results on the case with 3 mm thick FW front wall (e1 on Fig. 2) and with a Heat Flux of 0.5 MW/m^2 is shown in detail in this chapter.

Analyses have shown that channel 4, which is the hot channel, is also the most stressed one because of the bending stress of the FW occurring in the middle of the slice. Moreover, only results on line 3 will be discussed in detail in this paper because it shows the maximum stresses due to the position in front of the plasma where the thickness is the lowest and temperature is the highest. The analysis shows (Fig. 4) that the effect of irradiation is very high and penalizes the capacity of the FW to withstand high HF. Indeed, the criterion to prevent the risk of failure against immediate plastic flow localization because of the loss of ductility due to irradiation (Pm+Qm<Sem) is the limiting criterion. With such rules and irradiation dose, 0.5 MW/m^2 could not be acceptable for the most thermal stressed area of the FW. Ways to lower the HF, the fluency or design modifications to allow relaxation of the stresses should be investigated. Ratcheting is also a concerning factor, with values of Pm+Pb+ΔQ/3Sm slightly above 1. However the 3Sm criteria is very conservative for Eurofer. In this model, creep (Pm+Pb<St) is not relevant. Excluding effects of irradiation, which have been taken into account for the first time in this analysis, the viability of the reference FW design under a 0.5MW/m^2 HF is confirmed by these results.

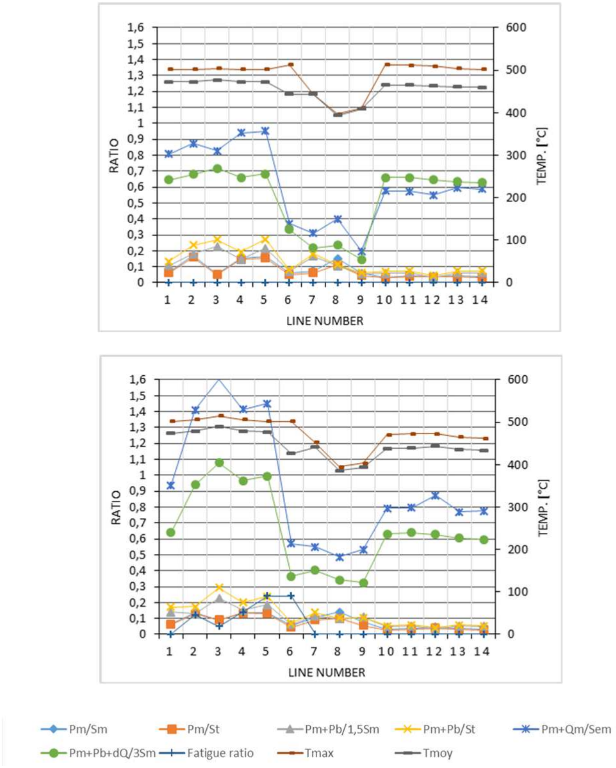

Fig. 4 : Stress criteria / Limit and temperatures plotted against the support line for area A and B on channel 4.

3.1 Results of the sensitive analyses

Results are shown on Fig. 5 for the area B on channel 4 and line 3 (most stressed area). We can see as expected, that when the thickness is reduced, the primary stresses globally increase. But, since the temperature on wall decrease with the thickness, the stress/limit ratio considering creep can be reduced a lot with smallest thicknesses for high HF. Considering only primary stresses, the FW can accommodate up to 1 MW/m^2, whatever the thickness of the front wall is. We can see as well that secondary stresses decrease with thickness while primary stresses increase, both in the same range of values: that makes the sum Pm+Qm and Pm+Pb+ΔQ relatively constant regardless of the thickness. Moreover, Sem is constant with the temperature, while Sm decreases with temperature. Thus the reduction of thickness and the associated reduction in maximum temperature has only slight effect on the criterion on Pm+Qm (irradiation). The stress/limit ratio for Pm+Pb+ΔQ (racheting) instead decreases with thickness proportionally to the increase of Sm. Moreover, the increase of the stress/limit ratio with the heat flux is much steeper at high values of thickness. The fatigue ratio has been analyzed on line 5 and show again that a small increase of temperature (by the increase of thickness or HF) has a dramatic effect on the fatigue ratio. With respect to these results, the design of the FW is never verified with respect to immediate plastic flow localization damage. No accurate quantitative information can be inferred from the 3Sm rule, since, as stated before, it is overly conservative for Eurofer. However, the fact to reduce the thickness of the FW front wall can allow the FW to cope with higher HF (up to 0.6 – 0.7 MW/m^2 with 1.5 or 2 mm).

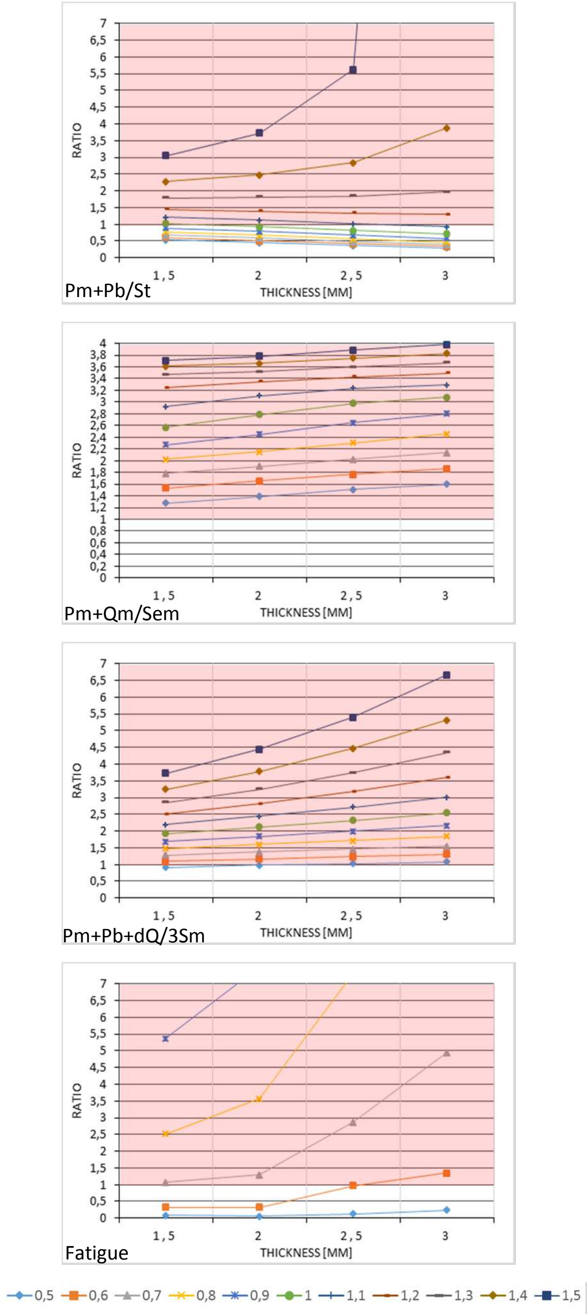

Fig. 5 : Stress criteria / Limit and temperatures plotted against the front wall thickness for area B and for each HF value (on channel 4, Line 3).

4. Discussion and conclusion

The conclusion of this study leads to design the FW front wall with a smaller thickness than the 3 mm initially designed because it allows to reduce the temperature on the structure, preventing fatigue and creep damage, and also allows to reduce the stress limit Sm which is function of temperature to prevent ratcheting during high HF. It seems that 1.5 mm is a good compromise between the resistance against primary and secondary loads. However, this conclusion still has to be confirmed when considering the pressurization of the box in case of accident that may lead to the need to increase this front wall thickness because of the FW bending. Moreover, analyses should be investigated on more accurate meshes that could lead to increase stresses especially for mechanical calculation and more relevant model.

It should be noted that this study has been performed without changing the channel geometry (dimensions and aspect ratio). However, in any cases, the channels geometry should be optimized, in order to decrease the steel temperature and thus reducing the stress/limit ratio, aiming to allow highest HF. But care should be taken, since this channel optimization is HF dependent, and could compromise the pressure drops if the HF is lower than the value for which the channels have been optimized.

Moreover, it is important to note the importance to have constant HF during the reactor operation. A small variation of HF could increase a lot the risk of damage such as fatigue, ratcheting and creep.

At the end, the effect of irradiation is very high and penalizes the capacity of the FW to withstand high HF. Indeed, the criterion to prevent the risk of failure against immediate plastic flow localization because of the loss of ductility due to irradiation is the limiting criterion. With such rules and irradiation dose, 0.5 MW/m^2 could not be acceptable for the most thermal stressed area of the FW. Ways to lower the HF, the fluency or design modifications to allow relaxation of the stresses should be investigated.

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