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DEMO Breeding Blanket Helium Cooled First Wall design investigation to cope high heat loads

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In the framework of the European "HORIZON 2020" program, EUROfusion develops a fusion power demonstrator (DEMO). The first part of the Breeding Blanket component facing the plasma, the First Wall (FW), has until now been designed for a maximum heat flux extrapolated from ITER TBM, equal to 0.5 MW/m². However, higher heat loads have recently been determined on some poloidal locations.

In order to cope with higher heat fluxes, this paper presents the investigation on different Helium cooled FW design integrated to the BB on the basis of standard square and circular smooth channels and with different options for the Tungsten armor surrounding the channels, taking advantages to the different material properties. The performance of the different concepts has been assessed with thermal and mechanical Finite Element Method numerical simulation based on a slice of the Helium Cooled Lithium Lead concept. Results are compared with the RCC-MRx design rules to prevent failure during normal and accidental condition. The results show that the options with channels surrounded by Tungsten could meet some plasma heat loads requirements from design point of view. However, the concept is still at an early stage of development and open issues are discussed.

Keywords: DEMO, HCLL, Breeding Blanket, First Wall

1. Introduction

Europe is committed to develop 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 DEMO, the Breeding Blanket (BB) is one of the key component surrounding the plasma which has to withstand severe loads while ensuring the following 3 functions: generate tritium for self-sufficiency, shield the magnets against neutrons and heat-up the coolant in a certain range of temperatures suitable for heat extraction in order to supply a turbine for producing electricity [1].

In the framework of the Horizon H2020 program, the European consortium EUROfusion is in charge of the development of 4 Breeding Blanket (BB) concepts for the European DEMO, 1 is using water as coolant (Water Cooled Lithium Lead), 2 of them use helium as coolant (Helium Cooled Pebble beds – HCPB, Helium Cooled Lithium Lead - HCLL), and another one (Dual Coolant Lithium Lead - DCLL) uses helium to cool down the First Wall (FW) only, which is the first component 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, Helium as coolant with inlet/outlet temperatures of 300/500 °C and 8 MPa pressure and a Tungsten layer in front of the plasma.

The FW has until now been designed in order to respect the design criteria and temperature limit of the Eurofer structure for a maximum HF extrapolated from ITER TBM, equal to 0.5 MW/m². New HF on the First Wall of DEMO BB have been assessed recently showing higher values on some poloidal locations of the BB [7].

This paper presents the investigation on the Helium cooled FW design integrated to the BB on the basis of standard smooth channels. Different designs are studied from rectangular to circular channels and with different options for the Tungsten armor surrounding the channels taking advantages to the different material properties. The performance of the different concepts has been assessed with thermal and mechanical Finite Element Method numerical simulation using Cast3M [2] based on a slice of the Helium Cooled Lithium Lead (HCLL) concept, that is one of the four BB concept studied in Europe for DEMO, developed by CEA-Saclay with the support of Wigner-RCP and Centrum výzkumu Řež. The description of the HCLL concept is explained in [3] with optimized features described in [4]. Results will be compared with the RCC-MRx code design rules [5] to prevent failure during normal steady state condition and off normal condition in case of Loss Of Coolant Accident (LOCA) event.

2. Methodology of the FW design investigation

2.1 FW geometry investigated and models

Six FW and Tungsten designs (Fig. 1) have been investigated from 12.5 x 12.5 mm square to 12.5 mm diameter circular smooth channels thanks to an increase of the channels fillet radius from 0.5 mm to 2 mm and 6 mm respectively for designs 1A/B, 2A/B, 3A/B and with different options for the Tungsten armor design, in order to take advantages to the different geometry and material properties. Designs 1A, 2A, 3A having 2 mm flat Tungsten layer while designs 1B, 2B, 3B having a Tungsten surrounding the channels with 1 mm thick inter layer between two channels.

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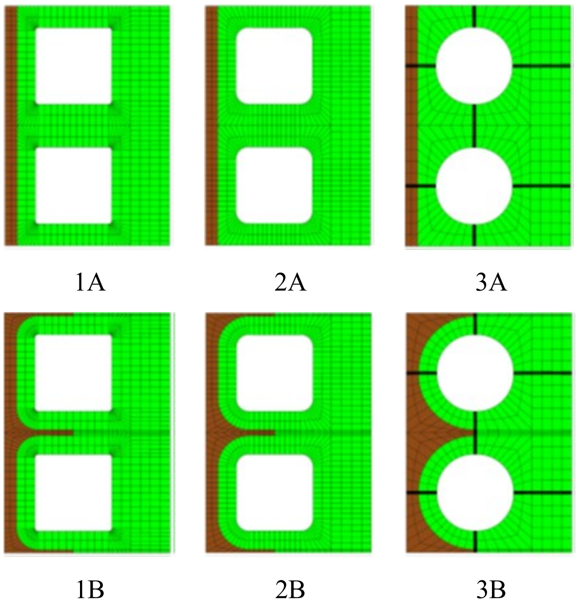
All the designs are considering an overall FW radial thickness of 25 mm, a radial front wall thickness of 3 mm and a rib thickness between two channels equal to 7 mm. The minimum radial Tungsten thickness equals to 2 mm.



1A 2A 3A

1B 2B 3B

Fig. 1. Cross section of the Eurofer FW (Green - right side) and Tungsten armor (brown – left side) design investigated

A generic ½ slice of the HCLL equatorial outboard module [3] made of one horizontal Stiffening Plates (hSP) and pieces of Back Plates have been considered in order to take into account the Breeding Zone constraint and thermal displacement on the FW. The slice is composed of 2 FW channels that are in counter current flow one other two channels. The full mesh of the slice is presented in Fig. 2. In order to simplify the calculation process, the mesh of the hSPs and BPs as well as the associated thermal field corresponding to the equatorial outboard module of the HCLL BB have been imported from [4]. Thus the breeder has not been meshed and only the FW has been accurately simulated with helium convection model thanks to Gnielinski equation [6].

For thermal calculations, 398690 linear elements with 142659 nodes are used. For the mechanical calculation only the elements of the Tungsten and of the FW have been transformed into quadratic elements, leading to a total of 297371 nodes.

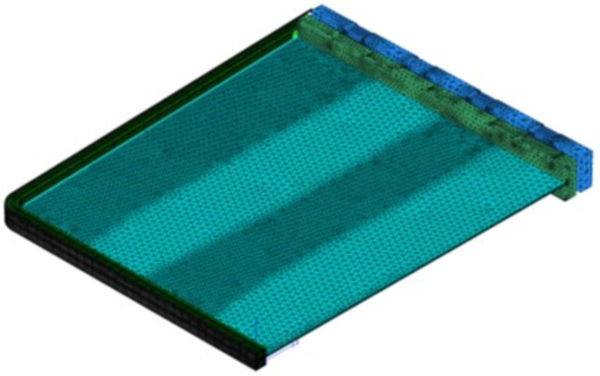


Fig. 2. Mesh of HCLL slice model with 1A FW design

2.2 Loads and boundary conditions

Two operating conditions are analyzed: normal steady state condition and off normal condition in case of Loss Of Coolant Accident (LOCA) event.

For normal condition, for the first phase of the design investigation, the Heat Flux load seen by the equatorial outboard module equal to 0.308 MW/m2 [7] is applied on the plasma side of the Tungsten. The neutron power deposited into the Tungsten and FW is detailed in [8].

In normal condition, the pressure load inside the FW channels is equal to 9 MPa and pressure on the back of the FW due to PbLi breeder hydrostatic pressure is equal to 0.5 MPa. End load on the top surface of the Tungsten and FW has been applied as well in order to reproduce the pressure of the breeder on the caps.

For accidental condition, only pressure is applied inside the FW channels, equal to 9 MPa, on the back of the FW due to over pressurization of the breeder, equal to 10 MPa, and associated end load on the top surface.

As boundary conditions for the thermal calculations, the inlet helium temperature in the FW channels is set at 300°C. The mass flow rate is calculated to have Tin/Tout at 300/500°C considering the total power deposited in the equatorial outboard module available in [7] thus the mass flow rate per FW channel is equal to 0.0458 kg/s. The Heat Transfer Coefficient (HTC) calculated with Gnielinski equation [6] is applied all around the channels and value at outlet temperature is equal to 3826 W/m²K. A node to node relation is imposed in order to get equal thermal field between lower and upper FW surfaces to reproduce the repeatability of the FW geometry.

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 to represent the global bending behavior, a relation is set on the upper surface in order to impose that the displacement in the X, Y and respectively Z direction of all the nodes of this surface has the same value.

2.3 Code and Standards analyses

RCC-MRx rules [5] have been used in order to analyze the FW according to Class 1 nuclear components criteria. The criteria of Level A and Level D are applied. The respect of the criteria are 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 on the lower channel have been studied on two areas along the toroidal direction, in order to cover the most stressed area: Area A on FW toroidal mid-plane near

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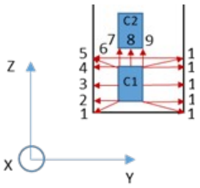
the plan of symmetry, and Area B near the FW bend (Fig. 3).

The criteria of the RCC-MRx considered for Level A 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.

For Level D, only immediate plastic collapse and plastic instability are analyzed, considering a stress limit SmD at 550°C.



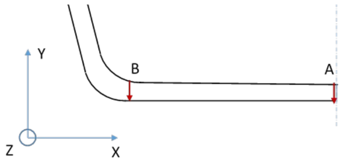


Fig. 3. Segment on which RCC-MRx stress linearization has been calculated (FW only)

3. Results

3.1 Thermal and stress results in normal condition

The thermal field on the whole HCLL slice model with 1A FW design is presented in Fig. 4. Maximum temperature on the FW and temperature field are in a good agreement with the results of [4] considering the same HF, however, stresses due to thermal field are over estimated here (not shown in this paper). It has been shown in [9] that boundary conditions imposed on the slice are too conservative but enough to compare the designs. In order to compare the different FW designs, Fig. 5 and Fig. 6 show respectively the thermal field and the primary + secondary stresses on the middle cross section of the Eurofer part for all the 6 designs investigated.

It can be seen that going from square to circular channels with flat Tungsten (1A, 2A, 3A) increases the maximum temperature on the Eurofer FW structure and thus thermal stresses. The same trend occurs regarding temperature when channels are surrounded by Tungsten (1B, 2B, 3B), but temperature are far lower.

Moreover, due to the more homogeneous thermal field and less stiffness due to radial Tungsten interlayer, Fig. 6 shows that secondary stresses induced by thermal field are getting lower with surrounding tungsten layer. RCC-MRx stress linearization ratio are plotted on Fig. 7 for the line 3 that is the most stressed line highlighted in [9] and it confirms the ability of designs with surrounded tungsten layer to reduce the secondary stresses. However, it shows also that going to circular channels increases the stresses ratio, which could be explained by the increase of temperature and thus the decrease of stress limit.

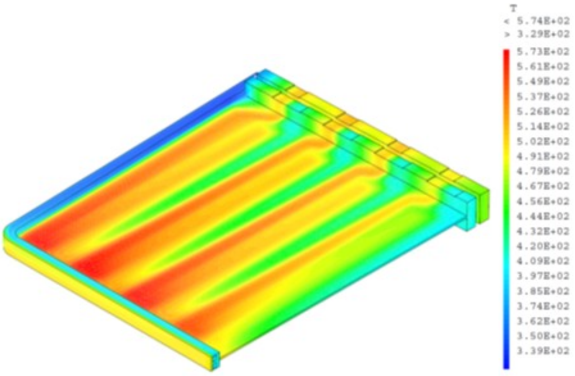


Fig. 4. Thermal field on the HCLL slice model with 1A FW design [°C]

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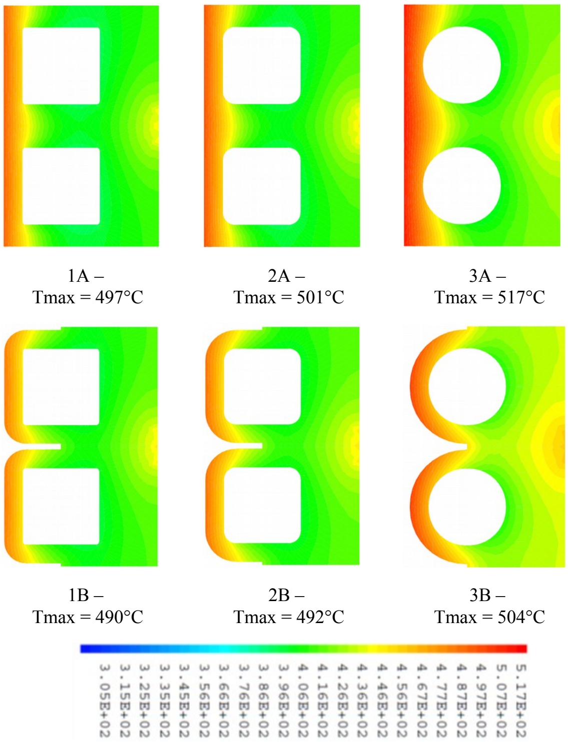
1A – Tmax = 497°C
2A – Tmax = 501°C
3A – Tmax = 517°C
1B – Tmax = 490°C
2B – Tmax = 492°C
3B – Tmax = 504°C

Fig. 5. Thermal field in the mid plane cross section on the Eurofer FW for the design investigated [°C]

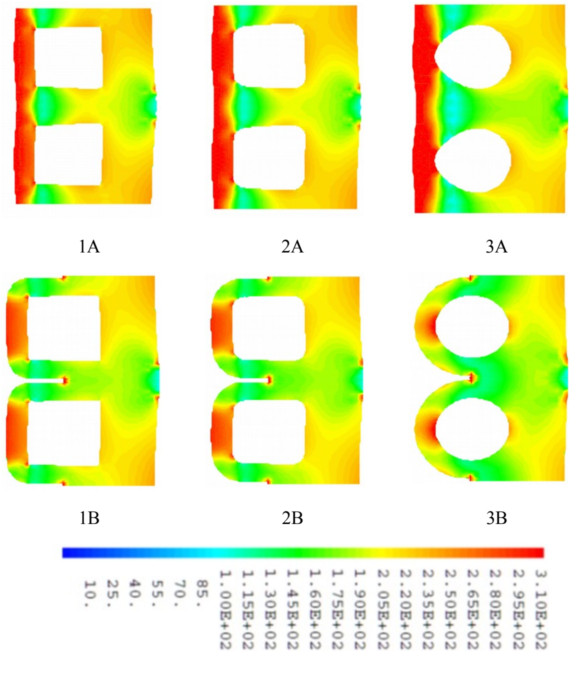

Fig. 6. Von Mises primary + secondary stress field in the mid plane cross section on the deformed (x200) Eurofer FW for the design investigated – normal condition [MPa]

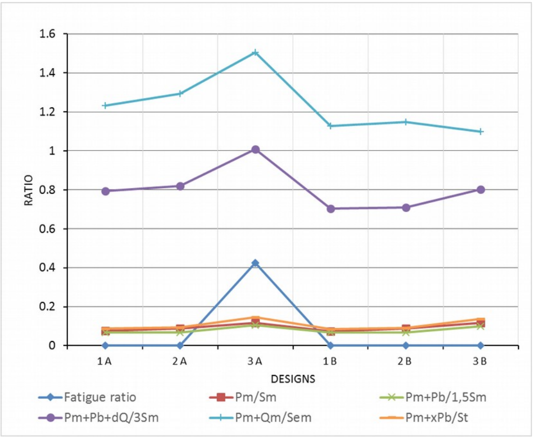

Fig. 7. RCC-MRx criteria ratio against FW designs in normal condition in toroidal area A on line 3

3.3 Mechanical results in accidental condition

Primary stress field in case of LOCA in shown in Fig 8. for designs 2A and 2B and RCC-MRx stress linearization ratio in Level D are plotted on Fig. 9 for the line 3. It shows that in faulted condition, geometry with surrounded Tungsten are less stressed on the front wall of the FW as well. It could be explained because the front wall of the FW are detached to each other, thus the end load applied and the PbLi pressure on the back of the FW are creating less bending stresses on this area.

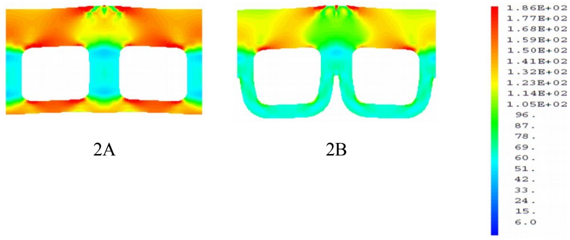

Fig. 8. Von Mises stress field in the mid plane cross section on the deformed (x200) Eurofer FW for 2A and 2B design [MPa]

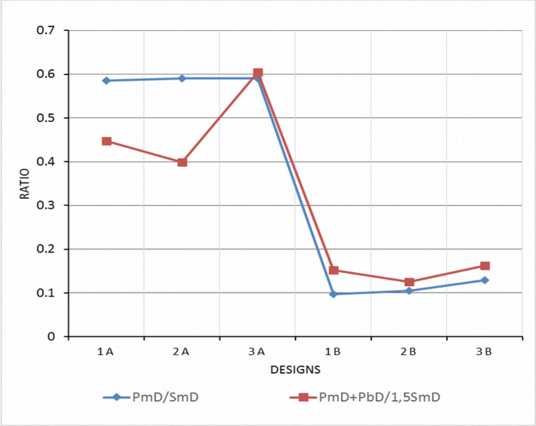

Fig. 9. RCC-MRx criteria ratio against FW designs in accidental condition in toroidal area A on line 3

4. Conclusion

The analyses on the 6 DEMO Helium cooled FW designs shows that having a tungsten layer surrounding the channels has a clear benefit for the integrity of the structure both for normal and accidental conditions

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regarding. These kind of design could lead to cope with higher HF from the Plasma. Especially it comes out that square channels with large filet (design 2B) in this configuration is the best option. However, this design has to be tested on a more accurate BB model in order to avoid margin due to boundary conditions. Moreover, additional studies should be launched such as fast fracture analysis because of the notch created by the interlayer between channels and manufacturing process of such complex tungsten layer. Other options are investigated in [10] with complex channel geometries analysed with CFD calculation in order to cope higher HF.

Acknowledgments

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