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

J. Aubert, G. Aiello, R. Boullon, Jc. Jaboulay

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

Julien Aubert[a], Giacomo Aiello[a], Rémi Boullon[a], Francisco A. Hernández[b], Jean-Charles Jaboulay[a]

[a]*DEN-DM2S, CEA, Université Paris-Saclay, F-91191, Gif-Sur-Yvette, France*
[b]*Karlsruhe Institute of Technology, Karlsruhe (KIT), Germany*

In the framework of the European "HORIZON 2020" program, EUROfusion develops a fusion power demonstrator (DEMO). According to a recent study about plasma heat loads, it appeared that the First Wall, which is the first part of the Breeding Blanket in front of the plasma, will face some high heat fluxes on some poloidal locations of the Breeding Blanket.

In order to cope such high heat fluxes, this paper presents the investigation on different Helium cooled First Wall design integrated to the Breeding Blanket 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 performances of the different concepts have 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 - WCLL), 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 3 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.

New HF on the First Wall of DEMO BB have been assessed recently showing high 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 simulations using Cast3M [2] based on a slice of the Helium Cooled Lithium Lead (HCLL) concept. 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.

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 equals to 7 mm. The minimum radial Tungsten thickness equals to 2 mm.

author's email: julien.aubert@cea.fr

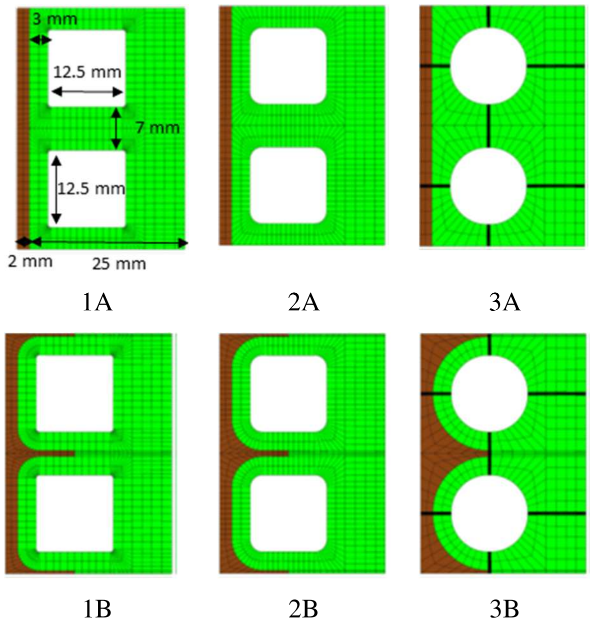


Fig. 1. Cross section of the Eurofer FW (Green - right side) and Tungsten armor (brown – left side) design investigated

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 fields 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 a coupled 1D-advection / 3D-thermal formulation to model the helium flow inside the FW.

For thermal calculations, 4.10^6 linear elements with $1.4.10^6$ nodes are used. For the mechanical calculations only the elements of the Tungsten and of the FW have been transformed into quadratic elements, leading to a total of 3.10^6 nodes.

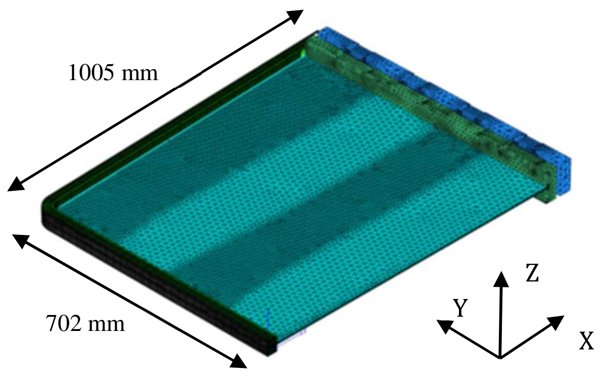


Fig. 2. Mesh of HCLL slice model with 1A FW design

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, since the geometry is relevant of the equatorial outboard module, the Heat Flux load seen by this module equals 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]. The maximum Nuclear Heating value located in the tungsten armor equals to 21.6 W/cm^3 and 8.2 W/cm^3 in the FW.

In normal condition, the pressure load inside the FW channels is equal to 9 MPa taking into account the uncertainty on the cooling loop 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, equals to 9 MPa, and on the back of the FW due to over pressurization of the breeder, equals to 10 MPa. Associated end load on the top surface is applied as well.

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 as function of the Helium bulk temperature but constant in channels cross sections. Value at outlet temperature is equal to 3826 W/m²K. However it has to be highlighted that considering a non-uniform HTC in the cross section could increase the value in front of the plasma for circular channels design. 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 Y min) 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 (X axis). In order to represent the repeatability of slices in the poloidal direction, a relation is set to impose that the displacements in the X and Y directions of all the nodes of both lower and upper surfaces have the same value while a relation is imposed on the displacements of the upper surface in the Z direction in order to make the upper surface move parallel to the lower one.

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 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.

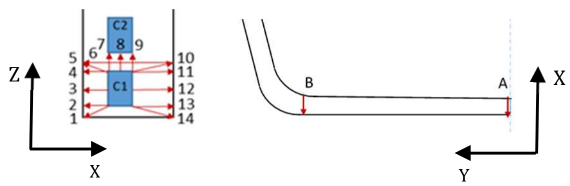


Fig. 3. Segment on which RCC-MRx stress linearization has been calculated (FW only)

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.

Moreover, due to the more homogeneous thermal field and lower thermal expansion of the Tungsten interlayer, and since primary stresses are equals between A and B designs (For design 2A and 2B, Pm=14Mpa and Pm+Pb = 16Mpa on line 3), Fig. 6 shows that secondary stresses induced by thermal field are getting lower with surrounding tungsten layer. RCC-MRx stress linearization ratios 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. Note that the 3Sm and Sem rules are very conservative for Eurofer [7]. Margin could be reduced in the future.

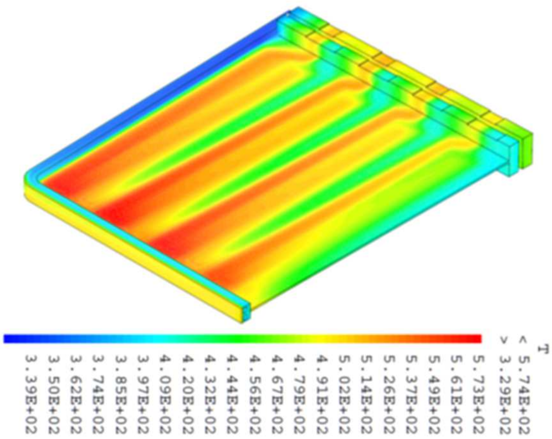


Fig. 4. Thermal field on the HCLL slice model with 1A FW design [°C]

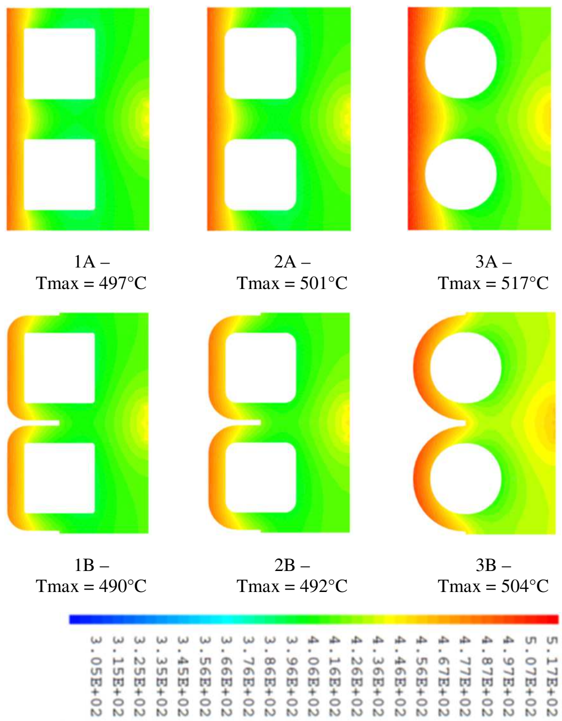
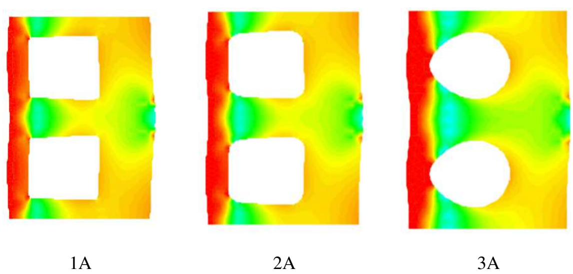


Fig. 5. Thermal field in the mid plane cross section on the Eurofer FW for the design investigated [°C]



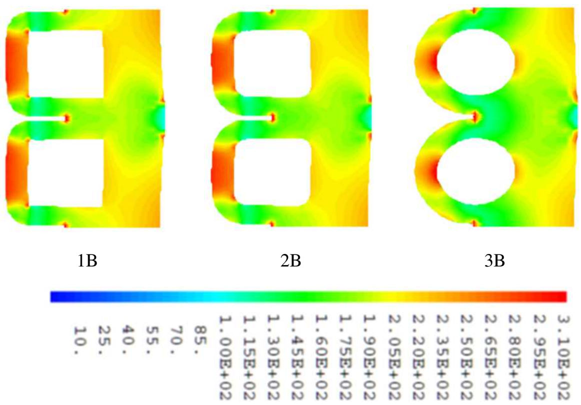


Fig. 6. Von Mises primary + secondary stress field in the mid plane cross section on the deformed (x200) Eurofer FW for the design investigated – normal condition [MPa]

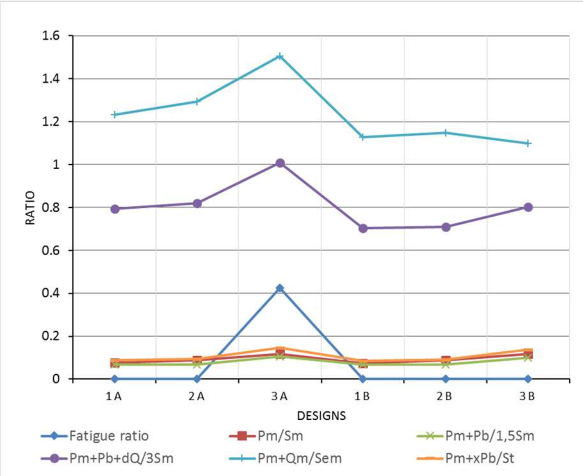


Fig. 7. RCC-MRx criteria ratio against FW designs in normal condition in toroidal area A on line 3

3.3 Mechanical results in accidental condition

Primary stress field in case of LOCA is shown in Fig 8. for designs 2A and 2B and RCC-MRx stress linearization ratios in Level D are plotted on Fig. 9 for all the lines. It shows that in faulted condition, geometry with surrounded Tungsten (2B) is less stressed on the front wall of the FW as well. It could be explained because the front walls 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.

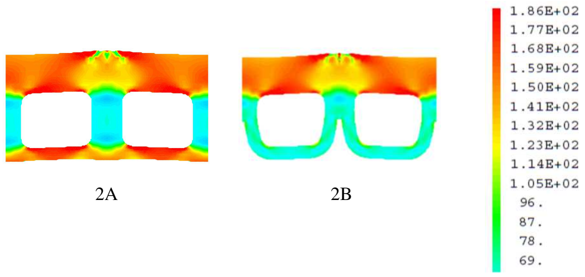


Fig. 8. Von Mises stress field in the mid plane cross section on the deformed (x200) Eurofer FW for 2A and 2B design [MPa]

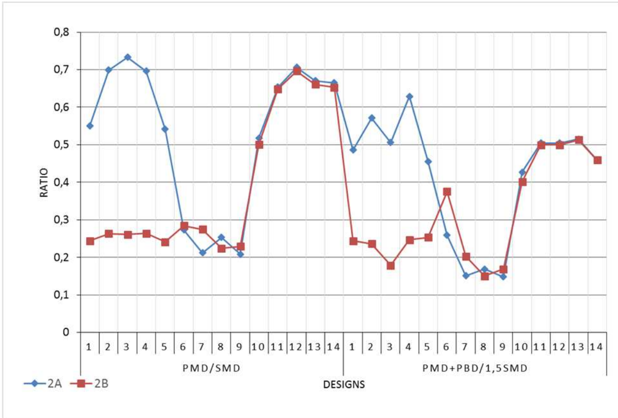


Fig. 9. RCC-MRx criteria ratio lines for designs 2A and 2B in accidental condition in toroidal area A

4. Conclusion

The analyses on the 6 DEMO Helium cooled FW designs show that having a tungsten layer surrounding the channels has a clear benefit for the integrity of the structure both for normal and accidental conditions. These kind of designs could lead to cope with higher HF from the Plasma. Especially it comes out that square channels with large fillet (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 too much conservatism due to boundary conditions and by using advanced design rules for ratcheting and in case of irradiated materials. Moreover, additional studies should be launched such as fast fracture analyses because of the notch created by the interlayer between channels and manufacturing process of such complex tungsten layer has to be investigated. Other options are investigated in [10] with complex channel geometries analysed with CFD calculation in order to cope with higher HF.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Fusion Electricity – A roadmap to the realization of fusion energy, F. Romanelli et al. EFDA, 2012

[2] Cast3M 2017 http://www-cast3m.cea.fr/

[3] J. Aubert et al., Status of the EU DEMO HCLL breeding blanket design development Fusion Engineering and Design In press (2018).

[4] R. Boullon et al., The DEMO Helium Cooled Lithium Lead “Advanced-Plus” Breeding Blanket: design improvement and FEM studies, this conference

[5] RCC-MRx, Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN, 2018

[6] V. Gnielinski, New equations for heat and mass transfer in turbulent pipe and channel flow, International Chemical Engineering, Vol. 16, No.2, pp. 359-368 (1976)

[7] J. Aubert et al., Report on Deliverable DDD 2017 for HCLL, WPBB-DEL-BB-2.1.2-T006-D001
[8] J-C. Jaboulay et al., Nuclear Analysis of the HCLL “Advanced-plus” Breeding Blanket, Fusion Engineering and Design , In press (2018)
[9] J. Aubert et al., Thermo-mechanical analyses and ways of optimization of the helium cooled DEMO First Wall under RCC-MRx rules, Fusion Engineering and Design, Volume 124, November 2017, Pages 473-477
[10] T. Melichar et al., Application of RANS CFD models for helium cooled first wall with fins for heat transfer enhancement, this conference