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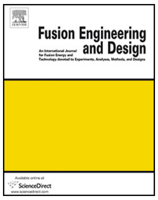

Thermo-mechanical analyses and ways of optimization of the helium cooled DEMO First Wall under RCC-MRx rules

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ABSTRACT

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 (BB) surrounding the plasma, ensuring tritium self-sufficiency, heat removal for conversion into electricity, and neutron shielding. Among the 4 candidates for the DEMO BB, 2 of them use helium as coolant (HCPB, HCLL), and another one (DCLL) uses helium to cool down the First Wall (FW) only.

Due to uncertainties regarding the plasma Heat Flux (HF) load the DEMO BB integrated FW will have to cope with, a set of sensitive thermal and stress 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 Finite Element Method 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 limits Sm, 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.

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 DEMO reactor shall prove the feasibility of generating electricity with an integrated fusion plant [1].

In a fusion power plant, the Breeding Blanket (BB), (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 BB, 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 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),

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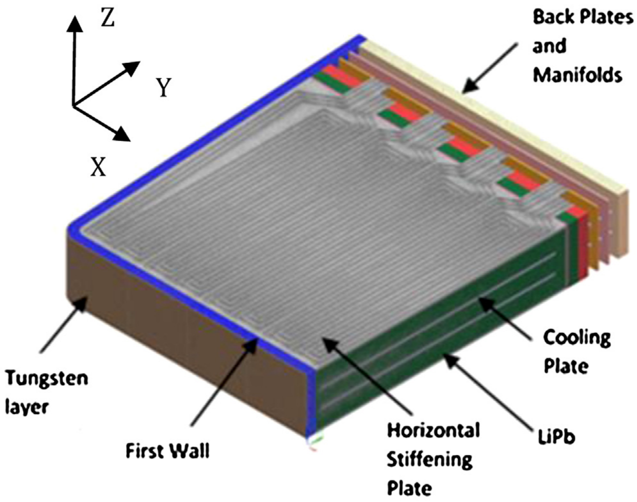

Fig. 1. Half slice of the “advanced” HCLL equatorial outboard module.

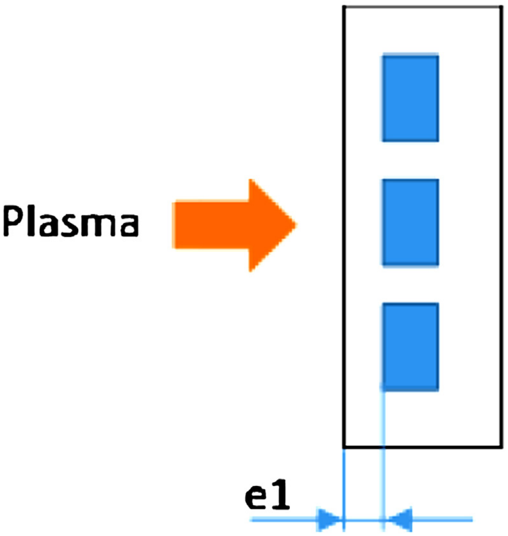

Fig. 2. Scheme of the FW variable parameter.

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 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 Finite Element Method (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–15.7 Li 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 [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 full geometry is presented in [5]. 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. 2 mm tungsten layer has been taken into account in the thermal analyses.

2.2. Mesh

A mesh has been set up on the geometry presented in Fig. 1, using the Siemens NX 10.0 [8] software in order to perform both thermal and thermo-mechanical FEM 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 calculations 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 detailed in [9]. 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 detailed 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 HF 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.

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

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