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Development of HCLL DEMO First Wall design for SYCOMORE System Code

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The conceptual design of the DEMOnstration reactors is already started and several reactor configurations have to be tested by exploring different design parameters. To justify the final design, it is necessary to simulate the physical behavior of the components with accuracy. Within the European framework, SYCOMORE (SYstem COde for MOdelling tokamak REactor) has been developed by the Commissariat à l'Energie Atomique et aux Energies Alternatives. SYCOMORE includes several specific modules linked together, one of which is aimed to define a suitable design of the Helium Cooled Lithium Lead Breeding Blanket. The research activity has been devoted to improve the method to define automatically the First Wall design starting from thermal-hydraulic and thermo-mechanical considerations, using analytical design formulae and, also, taking into account the design criteria coming from Codes&Standards. Thanks to these considerations, it has been possible to derive the first dimensions of the First Wall channels from which all the other characteristics are deducted. Afterwards, it has been assessed the thermal and mechanical field using a theoretical approach coded in a dedicated Python script. Therefore, in order to compare and validate the results, a 3D geometric model has been created and FEM analyses have been carried out.

Keywords: DEMO, system code, SYCOMORE, breeding blanket, FW HCLL.

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1. Introduction

For the development of a Fusion reactor, the first step is to define one or several possible reactor configurations by exploring some design parameters. Indeed, the goal of the exploration phase is to understand the influences of the different parameters on some important selected criteria (e.g. global efficiency). Within the European framework, SYCOMORE (SYstem COde for MOdelling tokamak REactor) has been developed by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) [4] in order to investigate several DEMO design. SYCOMORE includes several specific modules (i.e. plasma physics, divertor, etc.). Among the different modules, the research activity has been focused on the development of the Breeding Blanket (BB) module because it is one of the most sensible components in relation to the associated functions [1]. The paper focuses on the improvement of the Helium Cooled Lithium Lead (HCLL) BB module of SYCOMORE and, in particular, on the First Wall (FW) geometrical design starting from thermal-hydraulic and thermo-mechanical considerations and using analytical formulae for taking into account the criteria coming from Codes&Standards (C&S). The goal has been to provide to the engineers a configuration of the FW that complies with the criteria analyzing its behavior from a holistic point of view thanks to the capabilities of SYCOMORE. The research activities have been conducted in collaboration with KIT (Karlsruhe Institute of Technology, Karlsruhe) and CEA.

2. FW geometry and heat loads

The HCLL FW is made by U-shape steel plate where He circulates. The structural material of the HCLL module is the Reduced Activation Ferritic/Martensitic steel Eurofer [2]. The flow scheme of the cooling channels is reported in Fig. 1 (left-side). In Fig. 1 (right-side), the 2D draw of the FW in the poloidal-radial direction [3] has been selected as the representative geometry for the following discussion.

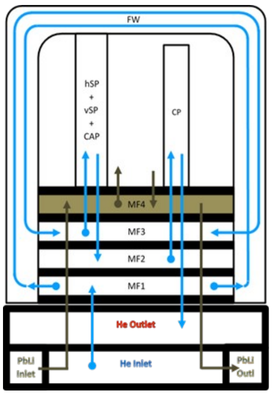

Fig. 1. Distribution scheme (left) [2], FW geometry (right).

The geometry of FW (Fig. 1, right-side) is characterized by: the radial Tungsten thickness (s), the overall FW thickness (t), the plasma facing wall thickness (e_1), the Breeding Zone (BZ) facing wall thickness (e_2), the poloidal channel dimension (d_1), the radial channel dimension (d_2), the distance between two channels (2r, the rib) and the pitch between two channels (P). The additional notations used in the paper are given in Table 1.

The heat loads identified for the FW design [2] are: a) heat flux (HF) coming from plasma, b) nuclear power directly deposited into FW structure and c) HF on the FW backside at boundary with the BZ. The total power deposited in the FW (P_{FW}) is the sum of the three contributions. Concerning the contribution a), the current equatorial blanket module is based on the assumption of a constant HF equal to 0.5 MW/m^2 [2]. The b) and c) contributions cannot be exactly determined without knowing the geometry as well as the interaction between the FW and BZ. When running in SYCOMORE, these quantities are calculated iteratively starting from the total power deposited in the module [4]. For the first iteration, it is assumed that the 20% of the overall nuclear power is released in the FW [3]. Knowing the power deposited in the module and considering the operational temperatures of HCLL (300°C and 500°C [2], inlet/outlet), it is easy to calculate the mass flow rate ($\dot{m}_{tot}$) for each BB module. Then, knowing the fraction of the total power deposited in the FW (P_{FW}), the bulk temperature ($T^{FW}_{out_b}$) to the outlet of FW can be obtained [3].

Table 1. Symbols used.

f_r	Ratio between 2r and d1. Dimensionless parameter.
f_d	Ratio between d2 and d1. Dimensionless parameter.
f_e	Ration between e1 and d1. Dimensionless parameter.
f_p	Fraction of the thermal power used for the pumping power. Dimensionless parameter.
u_c	Channel coolant velocity
K	Concentrated pressure loss coefficient
f	Darcy-Weisbach friction factor
L	Channel lenght
ρ	Helium density
n_c	Number of FW parallel channels
S_c	Cross section of FW channel
c_p	Helium specific heat
P_{FW}	Power deposited in the FW.
T^{F}_{ou}	FW outlet bulk temperature
T_{in}	FW inlet temperature
T^{P}_{w}	Plasma facing wall channel temperature
T^{P}_{p}	Plasma facing temperature
T^{P}_{A}	Plasma facing armor temperature
T^{E}_{w}	BZ facing wall channel temperature
T^{E}_{p}	BZ facing temperature
T^{P}_{w}	Middle rib temperature
T^{A}_{w}	Channel 1 wall temperature on the ribs
T^{A}_{w}	Channel 2 wall temperature on the ribs
q''_{F}	plasma heat flux
q''_{B}	BZ thermal flux
λ_{E}	Thermal conductivity of EUROFER
λ_{A}	Thermal conductivity of Tungsten
h	Convective heat transfer coefficient
P_d	Design pressure

P_{des}		
P_m	Membrane primary stress
P_b	Bending primary stress
S_m	Allowable membrane stress
Q_m	Membrane secondary stress
Q_b	Bending secondary stress
$\varepsilon_x - \varepsilon_y$	Strain in x and y direction
ν	Poisson's ratio
α	Thermal expansion coefficient
X	FW toroidal dimension
Y	FW poloidal dimension
Z	FW radial dimension
H	Distance between two horizontal Stiffening Plates

3. Determination of FW geometrical parameters

In order to determine the FW channel dimensions, design limits on primary stresses are considered.

The innovative approach, which is proposed in the following, is based on the introduction of criteria coming from C&S [5]. They can be calculated using dimensionless parameters for the FW geometric characteristics [3].

The first dimensionless parameter introduced is f_r that can be estimated starting from the P_{des} acting on d1. The resulting membrane stress P_m acting on the thickness 2r must verify the rule $\overline{P_m} < S_m$ in RCC-MRx [5]. This gives:

$$\frac{2\cdot r}{d_1} = \frac{P_{des}}{S_m} = f_r$$

The second dimensionless parameter introduced is f_d, corresponding to the “aspect ratio” of the channels in the FW. It cannot be determined only by considerations on primary stresses and it is considered as a user input which is bounded by manufacturing constraints. One can take f_d equal to one as a starting point (square channels).

The third dimensionless parameter introduced is f_e, that is determined using the beam theory. The membrane and bending stresses acting on the thickness e_1 due to the pressure on d_2 can be evaluated considering the problem of a double-embedded beam on which, due to the coolant pressure, a distributed load acts:

$$P_m = P_{des}\cdot\frac{d_1\cdot f_d}{2\cdot e_1};\quad P_b$$

Using the criterion $\overline{P_m+P_b} < 1.5S_m$, with few steps, it is obtained the eq. (3):

$$f_{e_{1,2}} = \frac{f_d \pm \sqrt{f_d^{\,2}+12\cdot}}{6\cdot\frac{S_m}{P_{des}}}$$

The methodology, so far, provides couples of geometrical dimensions but not a unique design solution [3]. For this, the BB thermal-hydraulic aspects are introduced taking into account, in particular, the efficiency of DEMO reactor.

It is common, in system codes [6], to calculate the pumping power as a fraction of the recovered thermal power. Usually, the pumping power for helium coolant is about 8.5-10% [6], in order to keep a good efficiency of the overall system. In the current FW design of HCLL [2], the fraction of the pumping power in relation to the deposited FW thermal power is about the 3%. In the following, this fraction will be indicated with the term f_p.

Taking into account that the channels of the FW are in parallel, they will experiment the same pressure drop that is possible to calculate as shown in eq. (4) [3].

$$\frac{f_p\cdot P_{FW}}{\dot{m}_{tot}} = \frac{u_c^2}{2}\cdot\left(\frac{f}{2\cdot\frac{j}{1+}}\right.$$

The unknown factors are u_c *and* d_1. The equation necessary to solve the system is the power balance equation (eq. (5)).

$$P_{FW} = \rho\cdot n_c\cdot S_c\cdot u_c\cdot c_p$$

Combining the previous equations, it is obtained an equation of the third order in which the unknown factor is d_1, as shown in eq. (6):

$$2\cdot K\cdot f_d\cdot P_{FW}^2\cdot d_1 + -\left[\frac{Y\cdot f_d\cdot\rho\cdot c_p\cdot\left(T_{out_b}^{FW}-T_{in}\right)}{1+f_r}\right]^2 = -f\cdot\left(X+2\right.$$

The solution of eq. (6) [3] shows that only one result is real and also positive. Therefore it can be accepted as physical resolution of the problem. This equation allows determining the first dimension of the channels from which all the other characteristic are deducted. In order to calculate e_2, it is necessary to impose that it will sustain the increasing of the pressure in the BZ during an in-box LOCA [3]. Using the same approach for the calculation of the bending stress but considering, this time, a distance between two horizontal stiffening plates (H), it is possible to calculate bending stresses and applying the criteria $P_b \le 1.5\cdot S_m^D$, it is possible to estimate e_2, as follows [3]:

$$e_2 = \sqrt{P_{des}\cdot\frac{H^2}{3\cdot S_m^D}}$$

The membrane primary stress has not been taken into account because, during the LOCA, all the BZ is pressurized at the same pressure, it means that the plates will experiment the same pressure in the poloidal direction. Only the last stiffening plates may have unbalanced pressurization but it has been assumed that the caps will sustain it [3]. The allowable stress S_m^D is calculated according to the level D of RCC-MRx [5].

4. Assessment of FW structural integrity

The configuration obtained at the end of §3 is intrinsically able to withstand primary stresses. The main concern for the structural integrity of the FW are however thermo-mechanical stresses, especially because of the loss of ductility of the material in presence of neutron irradiation. To assess them, it is necessary to calculate the thermal and mechanical field.

4.1 Thermal field assessment

To determine the thermal field, a linear temperature distribution is assumed in the radial direction. This hypothesis is justified by the low thickness of the plasma-facing side, but is more delicate on the BZ side. However, temperature gradients are lower in this zone and the impact is limited. Making the balance of the conductive and convective thermal flux, it is possible to calculate the temperatures in the thickness as described in the system of equations (8) and shown in Fig. 2 [3].

$$\begin{cases} T_w^{PL} = T_{out_b}^{FW} + q''_{FW} \cdot \frac{1}{h} \\ T_p^{PL} = T_w^{PL} + q''_{FW} \cdot \frac{e}{\lambda_E} \\ T_{Armour}^{PL} = T_p^{PL} + q''_{FW} \cdot \cdot \\ T_w^{BZ} = T_{out_b}^{FW} + q''_{BZ} \cdot \frac{1}{h} \\ T_p^{BZ} = T_w^{BZ} + q''_{BZ} \cdot \frac{e_2}{\lambda_{El}} \end{cases}$$

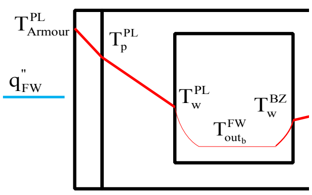

Fig. 2. Thermal field on FW.

In order to estimate the thermal field on the ribs (Fig. 3), it is necessary to take into account that the adjacent channel are feed in counter-current, it means that there will be two different bulk temperature, $T^{FW}_{out_b}$ and T_{in}, respectively. Applying the same assumption discussed above, it is possible to figure out the temperature in the middle of the rib ($T^{PL}_{w_{1-2}}$), as reported in eq. (9).

$$T^{PL}_{w_{1-2}} = T^{PL}_p - \left[\frac{q''_{FW} \cdot \left(e \right.}{\lambda_E} \right.$$

Consequently, the assessment of the wall temperature on the ribs ($T^{AV}_{w_1}$ and $T^{AV}_{w_2}$) can be pursed thanks to the eq. (10) (Fig. 3, right-side).

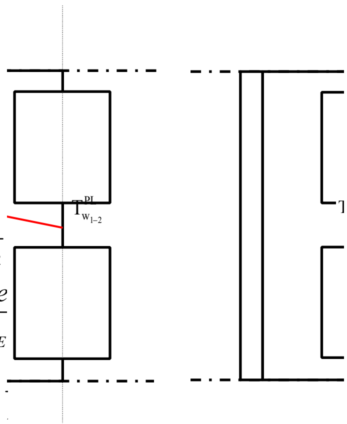

Fig. 3. Thermal field on FW rib.

$$\begin{cases} T^{AV}_{w_1} = \dfrac{\dfrac{T^{PL}_{w_{1-2}} \cdot \lambda_{EUR}}{r} + h \cdot T^{FW}_{out_b}}{h + \dfrac{\lambda_{EUR}}{r}} \\ T^{AV}_{w_2} = \dfrac{\dfrac{T^{PL}_{w_{1-2}} \cdot \lambda_{EUR}}{r} + h \cdot T_{in}}{h + \dfrac{\lambda_{EUR}}{r}} \end{cases} \quad (10)$$

4.2 Thermo-mechanical field assessment

For assessing the thermo-mechanical field on the FW according to RCC-MRx methodology, three paths (Fig. 4) have been identified in which the primary and secondary stresses have been calculated.

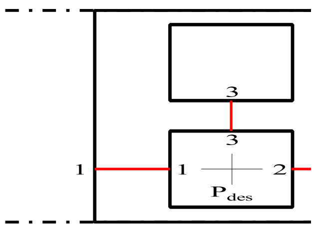

Fig. 4. FW paths for stress assessment.

In the following, the paths will be used for stress calculation as well for checking level A criteria [5].

4.2.1 Primary stress

Primary stresses are those due to external forces acting on the structure: in case of the FW this is the coolant pressure acting on the channels walls. In order to evaluate the primary stress, the beam theory has been used. Applying the force balance for each path, according to the pressure action, the membrane and bending primary stress have been estimated for Path 1-1, 2-2 and 3-3 (eq. (11)) [3]. No bending stresses have been identified for the path 3-3 due to the same pressure on the rib in poloidal direction [3].

$$P_m^{1-1} = P_{des} \cdot \frac{d_2}{2 \cdot e_1}; \quad F$$

$$P_m^{2-2} = P_{des} \cdot \frac{d_2}{2 \cdot e_2}; \quad F$$

$$P_m^{3-3} = P_{des} \cdot \frac{d_1}{2 \cdot r};$$

4.2.2 Secondary stress

Secondary stresses are those due to imposed displacements of the structure: in case of the FW those are the deformations due to the temperature field in the structures. The assessment of the secondary stresses may be very difficult due to the intrinsic 3D nature of the phenomenon [7]. For this reason, the plate theory has been selected for its study. Two thermal regimes are identified in the FW that can be separately studied and then combined [8]: a uniform temperature variation and a temperature gradient through the thickness. Referring to the Fig. 5, T_0 is the reference temperature, T_m is the average temperature on thickness, T_1 is the highest temperature on surface, T_2 is the lowest temperature on surface, ΔT_m is the difference between the average and the reference temperature and ΔT is the difference between surface temperatures.

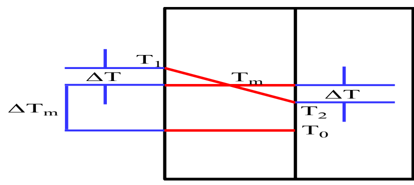

Fig. 5. Thermal gradient and averaged temperatures.

In the case of FW, a state of "co-action" will be aroused, in which the stress/deformation are associated to zero active force [8]. Using the Hooke's law and considering a temperature difference between the two plate surfaces, it is possible to write the eq. (12) [8]:

$$Q_m = \frac{E \cdot \left[\varepsilon_y + \nu \cdot \varepsilon_x - (1+\nu) \cdot \alpha \cdot \Delta \right.}{(1-\nu^2)}$$

For bending secondary stresses the governing equation is [7]:

$$Q_b = \pm \frac{E}{2 \cdot (1-\nu)} \cdot \alpha \cdot \Delta$$

The estimation of the ε_x and ε_y assumes an important relevance for a good calculation of the membrane secondary stress. In order to evaluate the differential expansion of the FW back and front, it has been studied a methodology [3] whereby, considering the front and the back of the FW displayable as two plates with different average temperatures T_{m_1} and T_{m_2} and indicating with ε_1 and ε_2 the "theoretical" expansion in absence of restraints, it is possible to determine the real deformation ($\Delta\varepsilon$), as shown in Fig. 6, imposing a plane deformation to the boundaries.

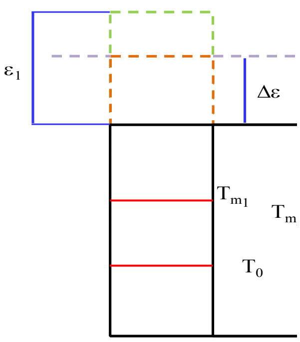

Fig. 6. Differential expansion of FW plates.

The two plates will exert a force according to the forbidden/imposed displacements. Imposing the force equilibrium, it is possible to calculate the real deformation, $\Delta\varepsilon$ (eq. (14)).

$$\Delta\varepsilon = \frac{E_1 \cdot \varepsilon_1 \cdot A_1 - E_2 \cdot \varepsilon}{E_1 \cdot A_1 - E_2 \cdot}$$

Assuming that ε_x and ε_y in eq. (12) are equal to $\Delta\varepsilon$ in eq. (14) , it is possible to assess the membrane secondary stress for the three identified paths [3].

5. Methodology application

5.1 Design Rules

The design rules contained in RCC-MRx [5] with respect to the specificities of the BB operating conditions, and the allowable limits [9] have been implemented in SYCOMORE. In particular, for the type-P [9] damages: Immediate Excessive Deformation and Immediate Plastic Instability, Creep Differed Excessive Deformation, Immediate Plastic Flow Localization and Immediate Fracture due to Exhaustion of Ductility. While for the type-S [9] damages: Ratcheting in Negligible Creep end Fatigue in Non-Singular Zones.

5.2 Benchmark

The methodology, the thermal and structural field assessment as well as the design rules of C&S have been coded in SYCOMORE using Python language [3]. In order to compare the results of Python script, a 3D geometric model has been created using CAST3M [10]. The simplified FEM model is shown in Fig. 7 [3] based on the model used in [11] replacing circular water channels by rectangular helium channels.

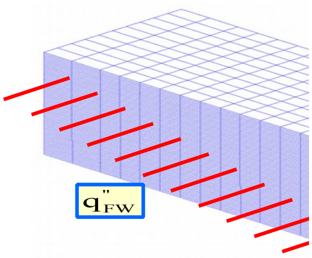

Fig. 7. 3D FEM model of FW.

Several cases have been analysed varying the HF coming from the plasma. Considering a pumping power equal to 3% of the thermal power released into the FW, seven different heat fluxes have been studied from 0.1 MW/m^2 to 0.7 MW/m^2. While three cases (0.77, 0.82 and 1.0 MW/m^2, respectively) have been studied considering a pumping power equal to the 10% of the FW thermal power [3]. Very satisfying results have been found for the thermal results with maximum error of 6.06% in all the cases with respect to the simplified FEM model [3]. Concerning the primary and secondary stresses, for the paths 1-1 and 3-3 the maximum error is about the 20%. When the thickness starts to be greater, the 3D effects have a strong impact on the results for path 2-2. In general, the most important zone, for the verification of the criteria, is the front plasma side thickness [3]. For the path 1-1, considering the reference case at 0.5 MW/m^2 [2], the results obtained with the Python script show a satisfactory agreement with the FEM calculation, with a maximum error of 14.54% [3]. A comparison has been also pursued with the detailed FEM models reported in [12] and [13]. Satisfactory results have been found comparing the maximum FW temperature (error lower than 1.01% [12]) as well as for Immediate Plastic Flow Localization and Ratcheting in Negligible Creep criteria with deviations comprised between the 5.88% and the 15.28% [13], respectively. The benchmark has demonstrated that the developed methodology reproduces the same behaviour of 3D model providing a tool useful for preliminary design [3].

6. Conclusion

Within the framework of EUROfusion activities, a research activity has been conducted in collaboration with KIT and CEA. It has been aimed to the improvement of HCLL BB module of SYCOMORE and, in particular, it has been focused on the FW geometrical design starting from thermal-hydraulic and structural considerations and taking into account, also, the criteria coming from C&S. It has been set-up a methodology for determining the FW geometric characteristics and the thermal and structural field. For the first time, the design criteria have been implemented in a system code providing important information to the designers from the early stage of the investigation. As future activities, the proposed approach might be extended to the other BB components such as stiffening plates, caps and cooling plates, providing, in this way, a powerful design tool for screening the possible reactor configuration.

Acknowledgments

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