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Optimization of the first wall for the DEMO water cooled lithium lead blanket

Julien Aubert[a,*], Giacomo Aiello[a], Christian Bachmann[b], Pietro Alessandro Di Maio[c], Rosario Giammusso[d], Antonella Li Puma[a], Alexandre Morin[a], Amelia Tincani[d]

[a] *CEA Saclay, F-91191 Gif-Sur-Yvette, France*
[b] *EFDA, Boltzmannstraße 2, 85748 Garching, Germany*
[c] *Università di Palermo, Viale delle Scienze, 90128 Palermo, Italy*
[d] *ENEA C.R. Brasimone, 40032 Camugnano, Bologna, Italy*

HIGHLIGHTS

- This paper presents the optimization of the first wall of the water cooled lithium lead DEMO blanket with pressurized water reactor condition and circular channels in order to find the best geometry that can allow the maximum heat flux considering design criteria since an estimate of the engineering limit of the first wall heat load capacity is an essential input for the decision to implement limiters in DEMO.
- An optimization study was carried out for the flat first wall design of the DEMO Water-Cooled Lithium Lead considering thermal and mechanical constraint functions, assuming $T_{\text{inlet}}/T_{\text{outlet}}$ equal to 285 °C/325 °C, based on geometric design parameters.
- It became clear that through the optimization the advantages of a waved First Wall are diminished.
- The analysis shows that the maximum heat load could achieve 2.53 MW m^{-2}, but considering assumptions such as a coolant velocity $\leq$8 m/s, pipe diameter $\geq$5 mm and a total first wall thickness $\leq$22 mm, heat flux is limited to 1.57 MW m^{-2}.

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ABSTRACT

The maximum heat load capacity of a DEMO First Wall (FW) of reasonable cost may impact the decision of the implementation of limiters in DEMO. An estimate of the engineering limit of the FW heat load capacity is an essential input for this decision. This paper describes the work performed to optimize the FW of the Water Cooled Lithium-Lead (WCLL) blanket concept for DEMO fusion reactor in order to increase its maximum heat load capacity.

The optimization is based on the use of water at typical Pressurised Water Reactors conditions as coolant. The present WCLL FW with a waved plasma-faced surface and with circular channels was studied and the heat load limit has been predicted with FEM analysis equal to 1.0 MW m^{-2} with respect to the Eurofer temperature limit.

An optimization study was then carried out for a flat FW design considering thermal and mechanical constraints assuming inlet and outlet temperatures equal to 285 °C/325 °C respectively and based on geometric design parameters such as channel pitch, diameter of pipes and thicknesses. It became clear through the optimization that the advantages of a waved FW are diminished. Given the manufacturing issues of that concept, the waved FW was therefore not pursued further. Even if the optimization study shows that the maximum heat load could in principle be as high as 2.53 MW m^{-2}, it is reduced to 1.57 MW m^{-2} when additional constraints are introduced in order not to affect corrosion, manufacturability and Tritium Breeding Ratio in normal condition such as a coolant velocity $\leq$8 m/s, pipe diameter $\geq$5 mm and a total FW thickness $\leq$22 mm.

However it is important to note that the FW channels currently fulfill additional functions and are therefore not optimized "at all cost" regarding heat load capacity and the paper points out some recommendations against missing assumptions.

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* Corresponding author. Tel.: +33 169089656.
E-mail address: julien.aubert@cea.fr (J. Aubert).

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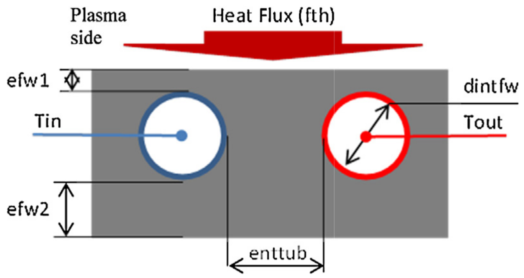

Fig. 1. FW geometric parameters.

1. Introduction

In a fusion power plant, the 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.

Within the EU the Water Cooled Lithium Lead (WCLL) blanket, using Pressurized Water Reactor (PWR) condition which is based on near-future technology requiring small extrapolation from present-day knowledge both on physical and technological aspect is considered as one of possible candidates for DEMO in present EU fusion roadmap [1].

In each blanket's module, the first part that interfaces directly the plasma is called the First Wall (FW). Its main function is to contribute to electrical production by removing high Heat Flux (HF) from the plasma with an effective coolant system. The maximum heat load capacity of a DEMO FW of reasonable cost may impact the decision of the implementation of limiters in DEMO. An estimate of the engineering limit of the FW heat load capacity is an essential input for this decision.

This paper describes the work performed to optimize the FW of the WCLL blanket concept for DEMO in order to increase its maximum heat load capacity with respect to limits and which is the easier to manufacture.

2. FW optimization methodology

2.1. Geometry

Flat FW against waved FW have been compared in [3]. The results showed that the flat FW has higher maximum temperature and reaches 522 °C (against 448 °C for the waved one) which is near the Eurofer maximum temperature limit (550 °C). Nevertheless, in order to avoid manufacturing issue or complexity due to the waved FW shape, the optimization was performed considering a flat FW. Geometric parameters that can be modified in order to optimize the FW design are presented in Fig. 1. As for the initial design [3], we assume that the fluid in the FW is in opposite direction every channel. Since maximum temperature in Eurofer occurs in the area where maximum water temperature is, only inlet and outlet temperatures are modeled. Only two channels are represented since the pattern is the same along the poloidal direction. Inner channels tubes are due to the presently assumed manufacturing technics with a copper layer between (not meshed; 80% of conduction between the two tubes in contact is assumed). Their thicknesses, called ETFW1 in the following, are designed to withstand twice the pressure. Number of channels is deduced from the pitch and assuming that the poloidal dimension of the FW is constant.

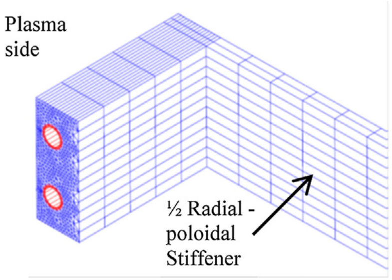

Fig. 2. FEM mesh of the initial flat FW for optimization.

2.2. Mesh

Due to the considerable number of calculations and CPU time, the FEM model used for the optimization is reduced in toroidal direction to half a cell as shown in Fig. 2. Since a full analysis was carried out on the waved FW in the report [1], the representativeness of the simplified FEM model has been previously verified with respect to the waved FW shape. However, this geometry is relevant only for the straight part of the module.

2.3. Thermal efficiency and thermo-hydraulic

To ensure thermal efficiency with PWR condition, Intel and outlet temperatures are fixed respectively to 285 °C and 325 °C.

Mass flow rate Q and water velocity v is calculated through Eqs. (1) and (2) according to power to be extracted Pt, thermal efficiency ($T_{\text{out}} - T_{\text{in}}$) and the geometry of the FW channels characterized by the sum of section S.

$$Q = \frac{Pt}{Cp(T_{\text{out}} - T_{\text{in}})} \tag{1}$$

$$Q = v \times S \times \rho \tag{2}$$

Heat Transfer Coefficient (HTC) is calculated with Dittus–Boelter correlations to perform thermal analysis [1] and pressure drops are evaluated with analytic formulae from [4].

2.4. Loads and boundary conditions

Two Load Cases are studied during the optimization: one in normal condition (LC1) and the other in faulted condition (LC2). The LC1 considers thermal loads such as the neutron power density distribution explained in [1] and the HF on the plasma faced surface that as to be evaluated. No HF comes from the PbLi pool. Mechanical loads are added such as a pressure of 15.5 MPa inside the water tubes and 0.5 MPa on the back face of the FW which is in contact with the PbLi. The LC2 considers a pressure on the back face of the FW equal to 15.5 MPa and none inside the tubes. End loads are applied on the top and on the right of the FEM FW to represent the cap and side wall of the module.

Bottom plan nodes are fixed in poloidal direction, and since the stiffener is assumed to have infinite rigidity, the nodes where the stiffener is welded are fixed in radial direction as boundary condition.

2.5. Thermal constraint

The recommended Eurofer operating temperature window is between 350 °C and 550 °C in order to prevent embrittlement under irradiation for minimal temperature and drop of strength because of creep for maximum temperature [8], thus maximum Eurofer temperature has to be limited:

$$T_{\text{FW}_{\text{max}}} < 550\,^{\circ}\text{C} \tag{3}$$

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