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Thermal optimization of the Helium-Cooled Lithium Lead breeding zone layout design regarding TBR enhancement

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ABSTRACT

Within the framework of EUROfusion R&D activities, CEA-Saclay has carried out an investigation of the thermal and mechanical performances of alternative designs intended to enhance the Tritium Breeding Ratio (TBR) of the Helium-Cooled Lithium Lead (HCLL) Breeding Blanket (BB) for DEMO. Neutronic calculations performed on the 2014 DEMO HCLL baseline predicted a value of TBR equal to 1.07, lower than the required value of 1.1, necessary to ensure the tritium self-sufficiency of the breeding blanket taking into account uncertainties. In order to reach the TBR target, the strategy of the steel amount reduction inside the HCLL module breeding zone (BZ) has been followed by suppressing some stiffening/cooling plates inside the BZ, leading to this "advanced" concept. Since all the plates inside the BZ are actively cooled by helium, each change in their geometric layout has a strong impact on the thermal response of the module. Moreover, the removal of stiffening plate may impact the resistance of the box in case of in-module loss of coolant accident (LOCA).

A thermal and mechanical campaign of analyses has been carried out in order to assess a potentially optimized layout of the module which could comply with the whole set of rules foreseen for the HCLL BB design. To perform this research campaign, a theoretical-numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified Cast3M and NX FEM codes have been adopted.

Results obtained are herewith reported and critically discussed, highlighting the open issues and suggesting the pertinent modifications to DEMO HCLL module design.

1. Introduction

The design of breeding blanket able to assure the tritium self-sufficiency is one of the most challenging tasks that the EUROfusion consortium is pursuing with the DEMO project [1,2]. Within the framework of these activities, a fruitful collaboration has been established between the CEA-Saclay research centre and the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo (DEIM).

One of the principal requirements for the DEMO BB is to have a Tritium Breeding Ratio (TBR) above 1.1, in order to reach the tritium self-sufficiency taking into account uncertainties. Former studies [3] have shown that a TBR value of 1.07 has been predicted for the Helium-Cooled Lithium Lead breeding blanket (HCLL). A research campaign has been therefore launched at the CEA-Saclay in order to optimize the HCLL layout with the aim of enhancing the TBR and to verify if the thermal and mechanical requirements are still fulfilled. A theoretical-numerical approach, based on the finite element method (FEM), has been followed and the qualified Cast3M and Siemens NX FEM codes [4,5] have been adopted in the study. The methodology and loading conditions adopted, as well as the results obtained are herewith reported and critically discussed.

2. The HCLL outboard equatorial module

In the DEMO baseline used in this study [2], the DEMO blanket is divided in 16 sectors, each one formed by 2 inboard and 3 outboard segments. In order to minimize stresses from thermal loads, to facilitate the manufacturing and to be consistent with the maintenance scheme, the Multi Module Segment (MMS) design has been followed. The HCLL breeding blanket uses Eurofer as structural material, the eutectic alloy Pb-15.7Li enriched at 90% in ^{6}Li as breeder, neutronic multiplier and tritium carrier, as well as helium at the pressure of 8 MPa as coolant [6,7].

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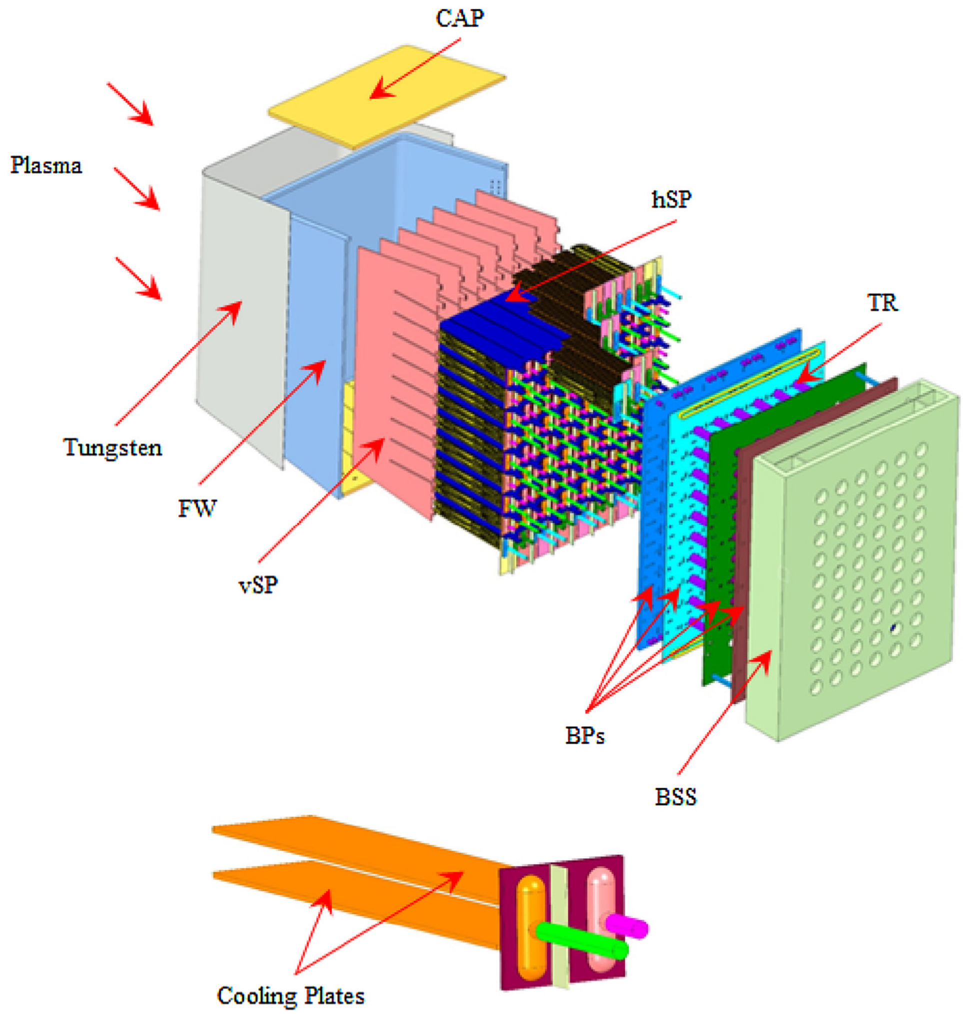

Fig. 1. Typical HCLL module.

The present study has been focused on the outboard equatorial module already described in [6,7], even though its layout has been modified in order to accomplish the goal of the research. An exploded view of the module is given in Fig. 1.

In the new "advanced" layout of the module, the First Wall (FW)–Side Wall (SW) channels are oriented in radial-toroidal-radial direction (i.e. horizontal) instead of the radial-poloidal-radial (i.e. vertical) one. In order to reduce the amount of steel and stiff the module, only the vertical Stiffening Plates (vSPs) located near the Caps have been maintained. Moreover, the dimensions of the equivalent Breeding Units (BUs) have been increased, passing from 9 to 8 BUs in toroidal direction. Since the dimension of the BU has been increased and the design pressure in case of LOCA has been raised from 8 to 10 MPa, to account for operating margins of safety devices (rupture discs), the thickness of the horizontal SPs (hSPs) has been increased from 11 mm to 14 mm.

The helium coolant, entering the module at the temperature of 300 °C, is collected in Manifold 1 and then it is distributed in the SW-FW channels where a counter-current heat exchange takes place. The helium exiting the SW-FW channels is collected into Manifold 3 where it splits itself into SP and Cap channels. A mixing between the different coolant streams exiting the aforementioned channels occur in Manifold 2 before the helium enters the Cooling Plate (CP) channels. The He outlet pipe from each BU is then connected to a common collecting chamber in the manifold/supporting structure and routed outside the Vacuum Vessel through pipes crossing the upper ports. A detailed scheme of the coolant path is proposed in Fig. 2.

Table 1
FW and hSP channels geometry.

	FW	hSP	CP
Number	72	3	7
Radial dimension [mm]	10	–	–
Poloidal dimension [mm]	15	6	4.5
Toroidal dimension [mm]	–	8	4
Rib [mm]	5.2	6.5	2.2

It has to be underlined that modifications made on both the number of CPs and SPs have a great impact on the helium mass flow rates and heat transfer coefficient values. Moreover, since the toroidal dimension of the equivalent BU has been increased from 154 mm to 174.13 mm the number of CP channels has been also increased from 6 to 7. Hence, the verification of the thermo-hydraulic requirements for the new set up configurations has to be performed. Table 1 resumes the main geometric parameters of the FW, hSP and CP channels.

3. The finite element models

A preliminary campaign of neutronic analyses allowed the TBR of different geometric HCLL module layouts to be calculated. Among the solutions assessed, the cases foreseeing a module equipped

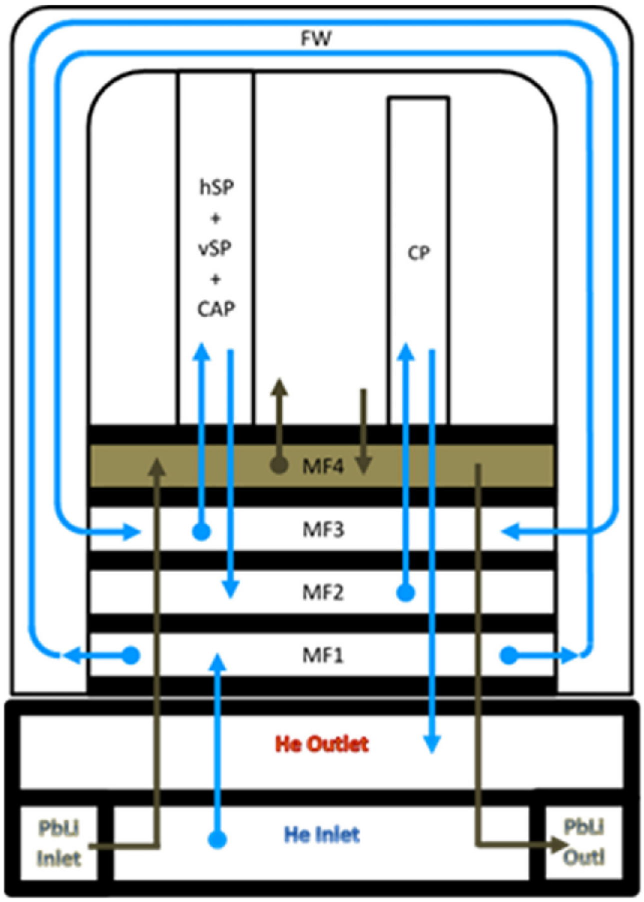

Fig. 2. The helium flow path scheme.

Table 2
The different thermal models set up.

	Number of CPs	TBR
Model 1	1	1.15
Model 2	2	1.13
Model 3	3	1.11

with 1, 2 and 3 CP per equivalent BU have been taken into account. For the thermal optimization of the module, a geometric model of each configuration, reproducing half central toroidal-radial slice of the "advanced" DEMO HCLL outboard equatorial module (i.e. slice), has been set up. The three models set up will be named in the following as Model 1, Model 2 and Model 3, respectively (Tab. 2).

Concerning the mechanical behaviour of the module in case of LOCA, a first design iterative process led to modify the most stressed area by increasing the small vSP welded to the Cap up to 27 mm thick and the Cap up to 30 mm thick. Moreover, an integrated Cap with fillet has been considered. A FE model has been developed to analyse this most stressed area by modelling only the two last slices integrating the Cap. (Fig. 3).

Finite Element (FE) models for each geometry have been set up adopting the Siemens NX 10.0 software [5]. A mesh composed of 470 k, 640 k and 1.48 M nodes connected in 1.83 M, 2.48 M and 5.17 M linear tetrahedral elements has been adopted for Model 1, 2 and 3, respectively. As it can be observed the number of nodes and elements is strongly dependent on the number of CPs per BU.

The mechanical FE model is composed of 2.23 M nodes connected in ~10 M linear tetrahedral elements. Linear elements have been adopted also in mechanical calculation to save calculation time. An overview of the FE models adopted is reported in Fig. 3.

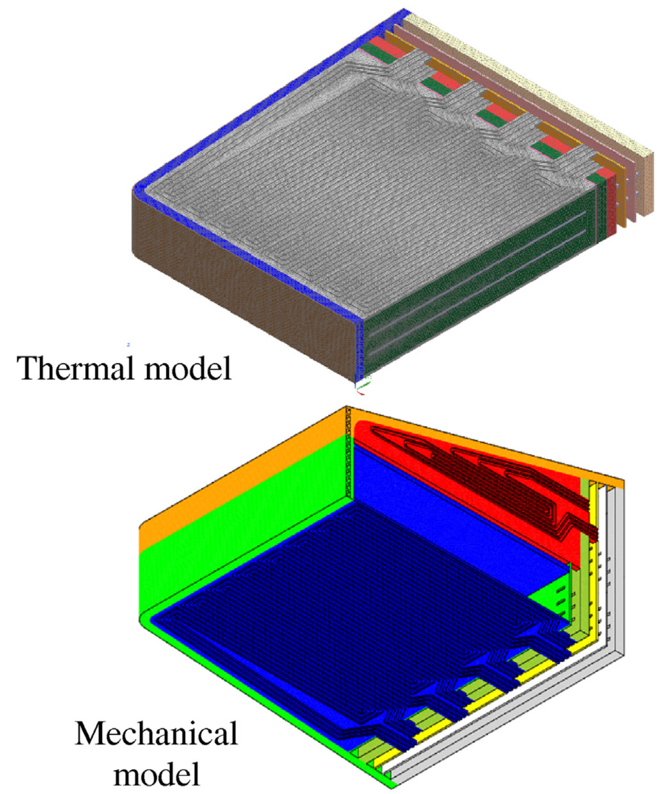

Fig. 3. Typical FE models.

A proper set of loads and boundary conditions has been applied in order to reproduce the loading conditions typical of a flat-top plasma operational scenario. Concerning the thermal optimization campaign, a heat flux value equal to 0.5 MW/m^2 has been imposed on the FW surface, while the non-uniform volumetric heat power distribution calculated in [3] has been taken into account. A coupled 1D-advection/3D-thermal formulation has been used to model the helium flow inside SW-FW, SP and CP channels. The Gnielinski correlation [8] has been adopted in order to calculate the heat transfer coefficient (HTC) between the coolant and the structure, taking into account also the influence of the channel roughness (ε) on the HTC by means of the Chen equation [8] for the determination of the Darcy-Weisbach friction coefficient. In particular, the value of ε = 25 μm has been considered. Mass flow rate (G) values have been computed taking as reference a thermal rise of 200 °C for the helium coolant, from 300 °C to 500 °C and assuming that the helium flow is equally split between the different channels fed by each manifold. Values of G and HTC values are reported in Table 3. Finally, a symmetry boundary condition has been imposed on the toroidal mid-plane of the model, while a thermal coupling between the two poloidal model surfaces has been imposed in order to take into account the continuity of the module.

From the mechanical point of view all the calculations have been performed considering a pressure of 10 MPa inside the box. This pressure has been applied only on the FW, Cap and first-BP internal surfaces. No pressure has been applied on hSP and vSP external surfaces since they are in equilibrium. A symmetry boundary condition has been imposed on the toroidal mid-plane of the model as well as on back and the bottom poloidal surface. The box has been analysed in faulted condition according to the RCC-MRx §RB3251.13 [9]. The maximum temperature resulting from the normal operation in the area of interest is 500 °C, thus, the Eurofer mechanical properties have been taken at 500 °C for stresses calculations and

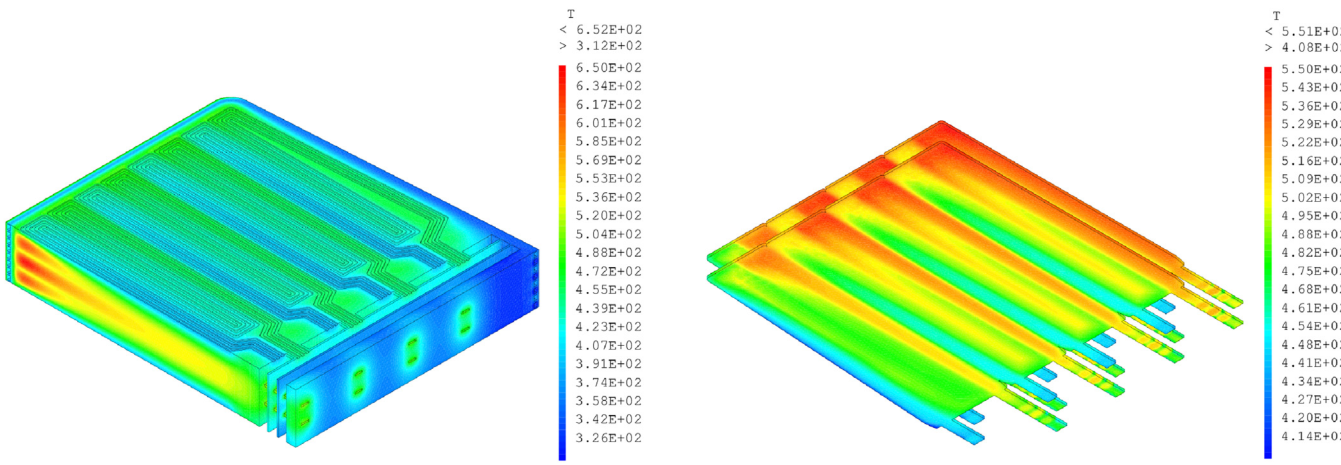

Fig. 4. Model 2 thermal results.

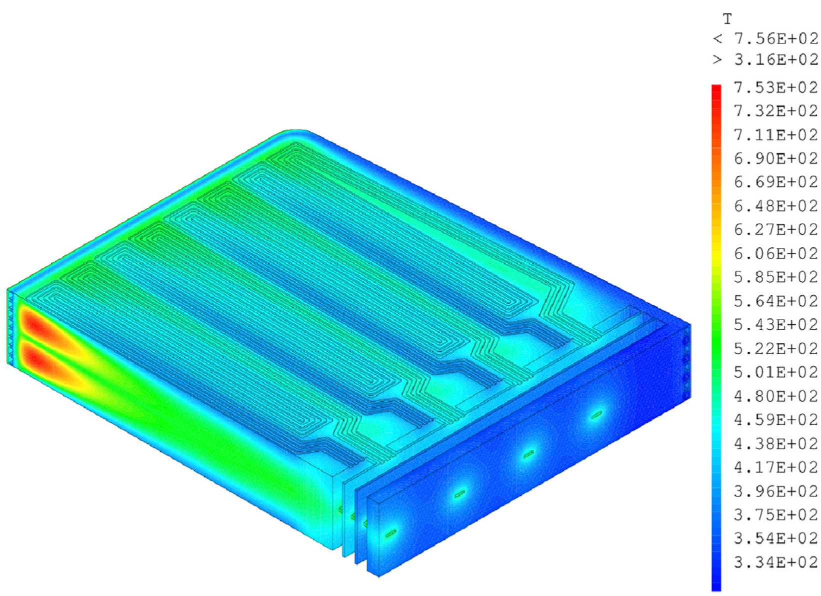

Fig. 5. Model 1 thermal results.

these stresses have been compared to the stress limit criterion $S_m{}^D$ (at 500 °C) equals to 274 MPa.

4. Results

The research campaign has been organized in two main phases. The former has regarded the investigation of the thermo-hydraulic behaviour of the three set up FE models of the slice. The latter has been focussed on the assessment of the mechanical performances of the model representing a corner of the HCLL outboard equatorial module. Both thermal and mechanical calculations have been performed adopting the Cast3M FEM code.

The maximum Eurofer temperature of 550 °C and a total pumping power of 200 MW (10% of the total fusion power) are the two thermo-hydraulic parameters that have led the thermal optimization campaign. As far as mechanical requirements are concerned, the fulfilment of the pertinent RCC-MRx codes safety rules have been analysed.

Results of thermal analyses performed on the three FE models of the slice have shown that the Eurofer limit temperature of 550 °C is exceeded in all models if roughness effects on the HTC are neglected. Whereas they are taken into account, Model 2 results (2 CPs) show Eurofer temperatures above 550 °C in a really narrow area of the central BU (Fig. 4), probably due to the conservative adiabatic condition imposed on this surface, while Model 1 fully satisfies the thermal criterion on the maximum steel temperature, even though very high temperatures are foreseen within the breeder domain (Fig. 5). High temperature values achieved within the breeder could be probably reduced when considering buoyancy effects. From the hydraulic point of view, a first rough estimation of the distributed pressure drops [10] inside the cooling channels has shown that only Model 2 is acceptable, with a total demanded pumping power of 195.9 MW.

Concerning the mechanical behaviour of the module in case of LOCA, even with a thicker and more optimized integrated Cap with reduced vSPs, the resistance of all the components of the modules in case of in-box LOCA at 10 MPa cannot be entirely justified regarding Level D RCC-MRx criteria in the module corner zone (even with a linearization of stresses). However, a good withstanding of the Cap, the hSPs, the BP and the Tie Rods can be particularly noticed (Fig. 6). Nevertheless, some design improvement in the module corner zone are needed in order to demonstrate the good behaviour of the reduced vSPs and the FW.

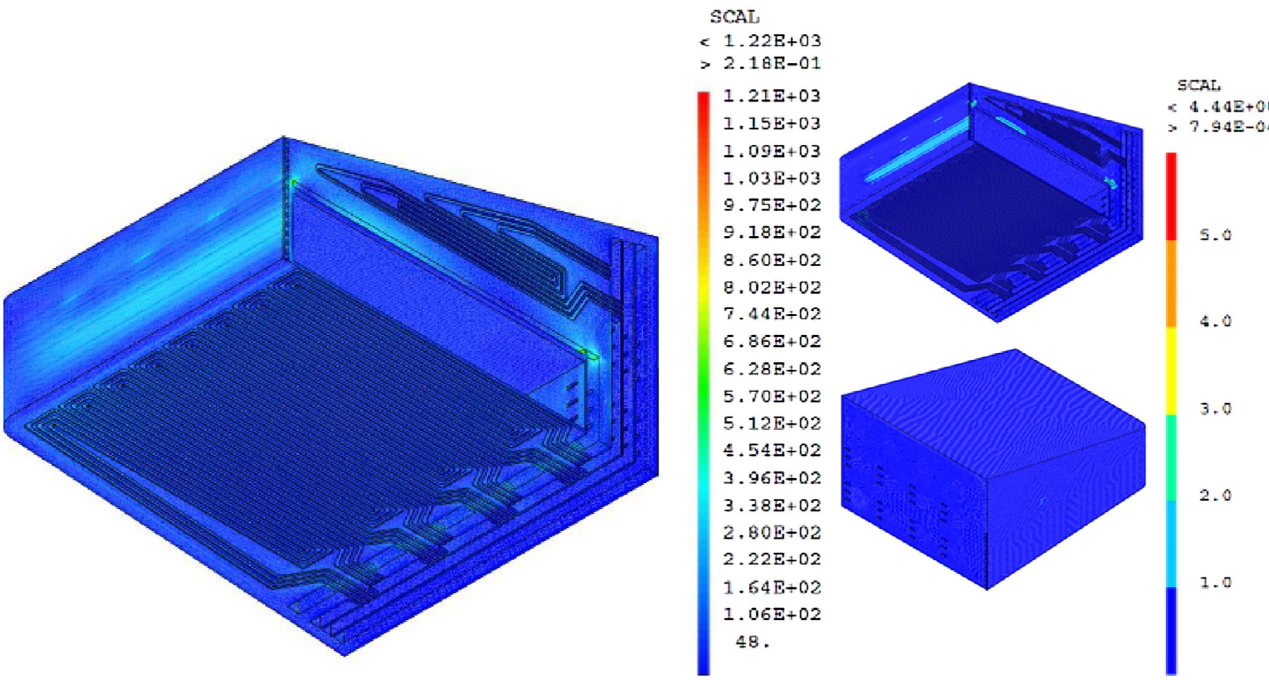

Fig. 6. Mechanical results: stresses and ratios vs. $S_m{}^D$.

Table 3
G and HTC values adopted in the calculations.

Model 1			
Component	G [kg/s]	HTC [W/m² °C]	
		$\varepsilon = 0$	$\varepsilon = 25\,\mu m$
FW channel	0.0786	5.83×10^3	1.02×10^4
hSP channel	0.0181	5.43×10^3	8.82×10^3
CP channel	0.0101	8.38×10^3	1.52×10^4
Model 2			
Component	G [kg/s]	HTC [W/m² °C]	
		$\varepsilon = 0$	$\varepsilon = 25\,\mu m$
FW channel	0.0771	5.74×10^3	9.96×10^3
hSP channel	0.0178	5.35×10^3	8.66×10^3
CP channel	0.0050	4.92×10^3	7.62×10^3
Model 3			
Component	G [kg/s]	HTC [W/m² °C]	
		$\varepsilon = 0$	$\varepsilon = 25\,\mu m$
FW channel	0.0756	5.66×10^3	9.77×10^3
hSP channel	0.0174	5.27×10^3	8.49×10^3
CP channel	0.0032	3.55×10^3	5.08×10^3

5. Conclusions

This paper shows one of the alternative design studied for the DEMO HCLL BB in order to enhance the TBR. The one detailed in this paper, called the "advanced" concept, is consisting mainly of horizontal Stiffening Plates only plus Cooling Plates.

Even if this "advanced" concept shows some benefits regarding TBR enhancement, there are some non-acceptable drawbacks such as a loss of stiffness in case of LOCA, especially on the Caps area. Moreover, an increase of pressure drop could occur for the most advantageous models from TBR point of view, in order to keep the maximum Eurofer temperature under 550 °C. The configuration with 2 CPs seems to be the best compromise, even though further investigations should go deeper in order to justify this concept, especially regarding the behaviour of the modules in case of LOCA.

Acknowledgments

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