Thermal-hydraulic design of a DCLL breeding blanket for the EU DEMO

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The thermal-hydraulic design of the breeding blanket, as the main thermal source for power conversion, reveals itself as a key issue to counteract the influence of the foreseen low overall plant availability on the cost of electricity. In the case of the Dual Coolant Lithium-Lead (DCLL), the decreased contribution of helium (non-breeding coolant) as thermal source in comparison with lithium-lead (breeding coolant) presents clear advantages, like less dependence on the long-term availability of He and lower recirculating power (recompression). The short operational range of temperature (300-550ºC) imposed by the use of RAFM steel is handled by adopting the Multi-Module Segment concept. This allows lower PbLi velocities by arranging in parallel the circuits of different modules. In consequence, the magnetohydrodynamic pressure drop and corrosion rates may be diminished. On the other hand, the high Péclet numbers validate the use of simpler computational codes to couple thermally both coolants, taking advantage of assuming that the heat transfer between the structure and the fluids is one-dimensional. A thermal-hydraulic one-dimensional code (PLATOON) has been developed for sensitivity analyses. The paper also addresses an assessment of the cooling of the radial stiffening plates and a preliminary study of the effects of the high heat generation gradient in the front poloidal PbLi channels.

Keywords: DEMO, blanket, DCLL, thermal-hydraulics.

1. Introduction

A conceptual design of a Dual Coolant Lithium-Lead (DCLL) breeding blanket is being developed within the EUROFUSION Power Plant Physics and Technology Programme. This paper describes the thermal-hydraulic (TH) design of the so-called version 2.0, which supposes an optimization of the previous version 1.1 [1] in terms of the helium cooling system and its influence over the structural behavior. Like in the v1.1, the v2.0 is based on the CAD baseline and operational parameters of the EU DEMO 2014 (16 sectors, 1572 MW of fusion power).

The TH design deals with the limitations imposed by the use of RAFM steel (short thermal operation window, corrosion under PbLi flow, etc.) as structural material. Thus, the temperature range of the main coolant (eutectic PbLi) is established to accomplish the thermal requirements of EUROFER: 300-550ºC [1]. Together with the general description on the main characteristics of the cooling circuits, the paper addresses the characterization of the global TH performance of the outboard (OB) central equatorial module by using one-dimensional models. Specific studies about the cooling of the radial stiffening plates and a preliminary characterization of the PbLi flow in the front poloidal channels are also included.

2. Description of the cooling circuits

The DCLL v2.0 follows the Multi-Module Segment (MMS) arrangement, in which each segment is composed by a series of modules (OB: 8; inboard (IB): 7) attached to a common Back Supporting Structure (BSS) (Fig. 1). The BSS integrates the service connections for all the modules and accomplishes shielding and supporting functions. This allows arranging individual cooling/breeding circuits for the different modules in parallel and, in consequence, reducing the segment pressure drop. The liquid metal bulk velocity inside the modules (1-2 cm/s), which is much lower than the expected in a single module segment, involves important benefits from the point of view of magnetohydrodynamics (MHD) phenomena and corrosion. The following subsections describe the PbLi and He circuits inside the OB equatorial module in detail.

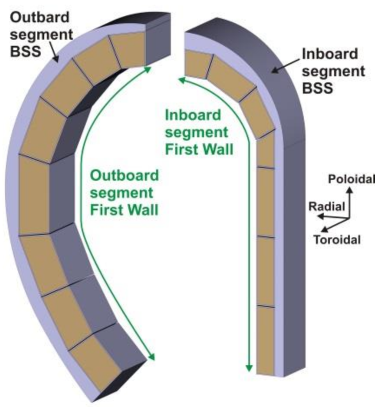

Fig. 1. Shape of the outboard and inboard MMS.

2.1 Lead-lithium

Lead-lithium enters into each module from the BSS through the external ring of coaxial inlet-outlet pipes located at the upper part of the module (Fig. 2). Each module is toroidally divided into 6 parallel circuits separated by radial stiffening plates. The routing of the

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parallel circuits is configured so that PbLi turns in planes perpendicular to the toroidal magnetic field, as well as to maximize the amount of thermal power extracted by PbLi and to avoid reverse flows due to the intense volumetric heating in the channels closer to the first wall (FW).

After the inlet, PbLi flows downwards through two parallel poloidal channels separated by a toroidal stiffening plate, where it is preheated. It turns 90º and moves in radial direction towards the FW. Then it flows upwards while receives the highest neutron and photon power deposition. Near the top of the module PbLi turns again and flows in radial direction to be extracted through the inner duct of the coaxial pipes. It must be underlined that, at the release date of the v2.0 design, all the breeding blanket pipes were required to be routed through the vacuum vessel upper ports to make easier the remote maintenance procedure.

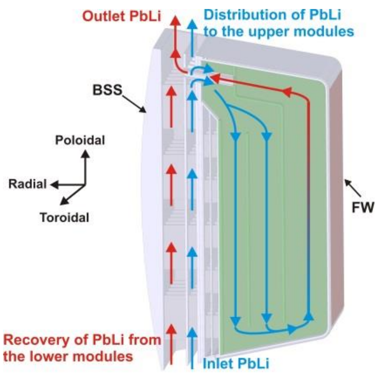

Fig. 2. PbLi routing in the OB equatorial module.

2.2 Helium

The design of the He circuit has been considerably simplified with respect to v1.1 by suppressing the toroidal stiffening plates cooling channels. The key mission of the He circuit is the cooling of the FW, which receives 59% of the total power deposited in the equatorial module EUROFER structure (including the plasma-facing tungsten layer). Since the mass flow rate needed to cool the FW is much bigger than the one needed for the radial walls (mainly because of the considered heat flux of 0.5 MW/m^2), the He scheme is arranged as a series of different parallel circuits with common source and sink (Manifolds 1 and 2, Fig. 3).

The FW He circuit carries 94% of the total mass flow rate in the equatorial module (2.74 kg/s). He circulates in counter-flow from the bottom to the top along the FW and returns following the opposite direction in order to increase the He outlet temperature and minimize the thermal stresses in the structure. A dedicated sensitivity analysis has been carried out to know the influence of parameters like channel size, pitch, distance from He to the tungsten layer and He inlet velocity. Results from CFD analyses indicate that the selected configuration (10x15 mm^2 channels with pitch of 5 mm) allows maintaining the FW structure under 550ºC for acceptable inlet velocities (~80 m/s) [2].

The circuits of the side walls and radial stiffening plates are much less important in terms of mass flow rate, but they are necessary to maintain the EUROFER temperature under 550ºC and contribute appreciably to increase the He outlet temperature.

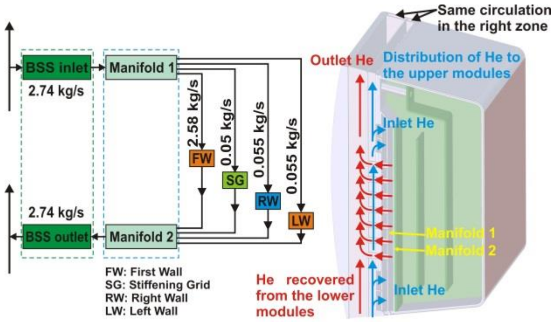

Fig. 3. He cooling scheme in the OB equatorial module.

Fig. 4 (left) shows the new configuration of the He channels in the radial stiffening walls, which is conceived to cool fundamentally the area closest to the FW and the top radial PbLi duct.

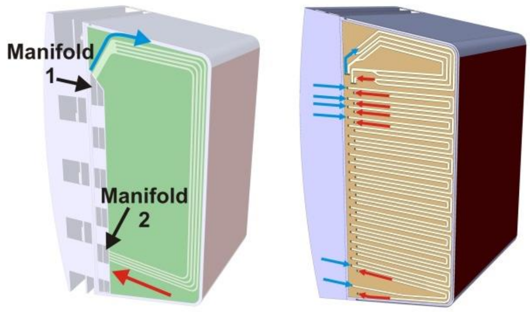

Fig. 4. He cooling channels in the radial stiffening plates (left) and side walls (right).

Fig. 4 also depicts (right) the radial design of the side walls channels. The density of channels is larger than in the stiffening plates because the walls are thicker (30 vs 17 mm). The central part of the wall includes a pattern of U-shaped channels running on counterflow, whereas the channels of the lower and upper parts are adapted to the position of the top and bottom walls, as well as to the geometry of the internal manifolds. On the other hand, the number and size of the ducts communicating the internal manifolds and the BSS have been enlarged and relocated to favor the feeding of the FW circuit.

2.3 Back Supporting Structure

The BSS consists in a long 'C-shape' (OB segments) or 'cane-shape' (IB segments) structure (Fig. 1) with a series of poloidal ducts covering the whole length of the segment. Both PbLi (central ducts) and He (side ducts) circulate along the BSS according to similar schemes. The BSS channels are designed to maintain a low and constant flow velocity in order to limit the pressure drop and the corrosion. Since the mass flow changes along the BSS channels because of the distribution or collection, such goal is achieved by varying the hydraulic diameter. In the case of the PbLi channels, the cross-section of the hot one (550ºC) is considerably larger (average velocity: 9 cm/s) than the cold one (300ºC, average velocity: 24

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cm/s) because of corrosion. Despite the previously commented requirement of remote maintenance, the possibility of routing some OB segments pipes through the vacuum vessel lower ports has been anticipated. In such case, the OB inlet and outlet pipes can be located in the opposite ends of the segment and both hot and cold streams circulate upwards. Thus it is possible to maximize the cross section of each channel at the expense of the other in the different sections of the BSS.

3. Thermal-hydraulics 1D model of the outboard equatorial module

The first phase of the TH analyses has been focused on determining the key parameters affecting the performance of the DCLL blanket (mass flows, outlet temperatures, pressure drops, etc.). For that reason, a 1D TH model of the OB equatorial module has been developed. The model couples thermally the different PbLi and He circuits, as well as the structure walls and the tungsten layer, and allows a fast evaluation of the TH behaviour with enough accuracy to improve the operational and geometrical parameters, to identify possible thermal issues and to obtain input data for successive more detailed analyses. It has been created in the PLATOON code (PLAtform for Thermal-hydraulic One-dimensional OutliNe). PLATOON is a steady-state code written in MATLAB Simulink. It uses correlations to calculate Nusselt numbers and pressure drops. Regarding Nusselt, Gnieliski's is used for He and Ji&Gardener [3] for PbLi (assumption of electrically insulated walls instead of Flow Channel Inserts, FCI). Two different approaches have been followed to model the pressure drop in the PbLi circuits: 1) for straight channels with FCI [4] and 2) for 3D complex geometries, with a simplified approach based on the proportionality between the pressure drop and the fluid kinetic energy [5].

The most relevant parameters obtained for the DCLL v2.0 are shown in Table 1.

Table 1. TH parameters obtained from PLATOON.

He parameters	OB Eq. Module	OB Segment
Mass flow rate	2.74 kg/s	16.4 kg/s
Inlet temperature	300ºC	300ºC
Outlet temperature	425.2ºC	425.2ºC
Pressure drop	2.53 bar	3.38 bar
% Extracted power	44	44
PbLi parameters	OB Eq. Module	OB Segment
Mass flow rate	49.2 kg/s	295.8 kg/s
Inlet temperature	300ºC	300ºC
Outlet temperature	542.8 ºC	542.8 ºC
Pressure drop (insulated)	0.92 bar	0.94 bar
% Extracted power	56	56

The temperature evolution along the different segments in which each PbLi circuit has been discretized is depicted in Fig. 5 (left). Fig. 5 (right) shows the He temperature at several points in one of the side walls.

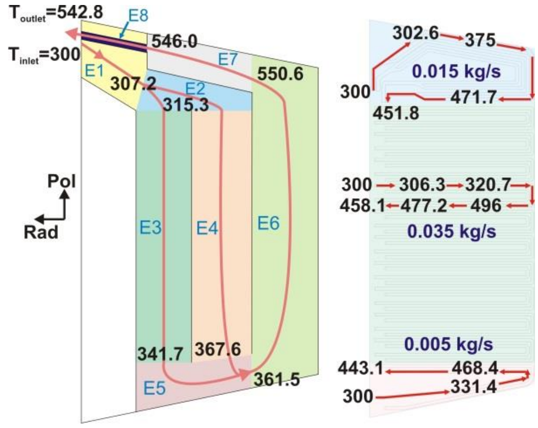

Fig. 5. Evolution of PbLi temperature (ºC) along the circuit (left). He temperature (ºC) in different locations of a side wall (right).

It is important to notice that the highest temperatures obtained in each type of wall included in the model do not raise the considered limit of 550ºC.

4. Radial stiffening plates cooling

The results of the v1.1 TH model in PLATOON [1] suggested the possibility of suppressing the internal He channels of the stiffening toroidal plates and simplifying the circuit of the radial plates, which consisted in a poloidal pattern of U-shape channels. Subsequent FEM steady-state thermal analyses (Fig. 6 left) have confirmed the capability of flowing PbLi to cool the thin stiffening grid plates (17 mm). There is only a small area of the radial plates where He cooling is needed, where the maximum values of heat deposition and PbLi temperature coincide. The toroidal wall closest to the plasma is clearly identified in the map by a temperature range notably far from the limit of 550ºC. Such results have led to propose a cooling scheme focused on that critical area, which is extended from the upper part of the PbLi front channels to the rear limit of the upper radial channel (enclosure 7 in Fig. 5 left). The final design of the cooling channels has been adapted following several mechanical requirements, like positioning the outlet above the lower limit of the 2nd toroidal stiffening plate to counteract the lower section modulus, and the results of a CFD assessment of the cooling channels configuration. It has been carried out considering different numbers of channels (3 or 4), pitch (10, 20, 30 and 45 mm) and He inlet velocity (10, 20, 30 and 40 m/s). As shown in Fig. 6 (right), the presence of 4 channels with a pitch of 30 mm and an inlet velocity of just 20 m/s is enough to keep the maximum temperature in 537ºC. A pretty uniform temperature is ensured in the critical zone, taking into account its effect on the thermomechanical behavior.

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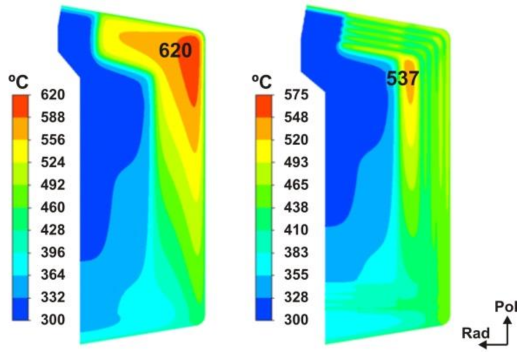

Fig. 6. Temperature map of a radial stiffening plate without He channels (left). Temperature map for 4 channels, 20 m/s and 30 mm pitch (right).

5. Preliminary characterization of the PbLi flow in the front poloidal channels

A main concern about the behavior of the PbLi flow in the breeding zone is related to the non-uniform volumetric heating in the front poloidal channels. The buoyancy forces affect the velocity profiles significantly and create recirculating flows, whose magnitude of velocity can even overcome that of the forced flow. Under some conditions such flows exhibit inflectional instability and eventually become turbulent. There is a risk of locally reversed flows and associated hot spots at the solid wall, which may occur in those channels where the forced and buoyant flows are opposite [6].

Since Grashoff numbers (Gr) around 10^{12} are expected in the PbLi front channels of the OB equatorial module, with a huge heat generation gradient along their radial length, the characterization of the flow under such conditions becomes mandatory. Up to date, simulations coupling Navier-Stokes and Maxwell equations with heat and mass transport equations are far from the characteristic dimensionless numbers of a DCLL front poloidal channel (e.g. $Gr=4\cdot10^{8}$). For that reason, a very preliminary CFD transient calculation without magnetic field has been carried out in order to give a basic idea of the PbLi buoyancy-driven flow under such heat generation profile. The selected 3D geometry has been adapted from one of the internal PbLi circuits of the OB equatorial module (toroidal length: 192.5 mm, radial length: 300 mm). The model is composed of part of the lower radial channel (enclosure 5, Fig. 5), where it is located the inlet; the poloidal channel (enclosure 6, Fig. 5) and part of the upper radial channel (enclosure 7, Fig. 5), where it is located the outlet.

As boundary conditions, a velocity of 4.3 cm/s has been imposed at the inlet to obtain a representative bulk velocity in the poloidal channel of 2 cm/s, whereas null pressure has been set at the outlet. Convective heat transfer has been set in the rest of faces, whose temperatures and film coefficients have been taken from the results of PLATOON. The volumetric heat generation has been introduced as an energy source term through a user-defined function. The PbLi density has been introduced as a linear function while the gravity effect has been activated. The selected viscous model has been laminar, in order to simulate the laminarization of the core of the flow due to the effect of the strong toroidal magnetic field if buoyancy forces were not involved.

The numerical model has been created and solved in ANSYS FLUENT. The generated structured mesh consists of $3.1\cdot10^{5}$ elements (hexahedra) with boundary layers.

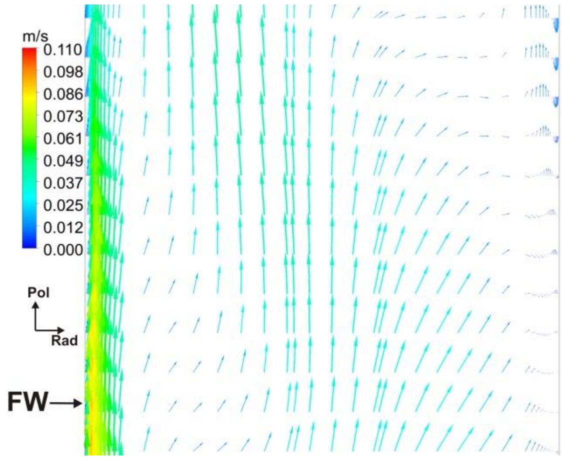

Fig. 7. Velocity vectors in a central vertical plane of the poloidal PbLi channel (t=153 s). Detailed view of the equatorial region.

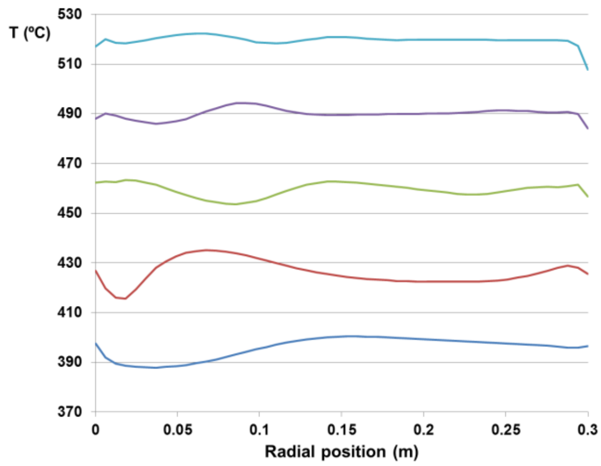

Fig. 8. Temperature profiles along the radial length of the PbLi channel at different poloidal positions (t=153 s). Central vertical plane (r=0 indicates the position of the first wall).

Due to the buoyancy effects, PbLi velocity decreases from the FW (5-10 cm/s) to the rear limit of the channel (1 cm/s), where reversed flows appear in the upper half of the poloidal channel (Fig. 7). Nevertheless, they do not apparently involve the existence of hot spots. The temperature radial profiles in the poloidal channels are almost flat instead of the very high heat generation gradient (Fig. 8). This can be explained by the mentioned differences in the velocity module across the radial direction due to buoyancy effects. On the other hand, the poloidal profile is almost linear, with a mass-weighted average temperature of 533ºC at the outlet. This involves an increment of 183ºC along the circuit, which is very similar to the gain calculated with PLATOON for the v2.0 model (around 185ºC).

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Although these results seem to be quite encouraging because the absence of large temperature gradients and convection plumes, they must be considered as very preliminary until MHD effects are considered.

6. Conclusions

This paper presents an overview of the thermal-hydraulic design of the DCLL breeding blanket for the EU DEMO. A 1D tool has been developed to obtain a global thermal-hydraulic model of the outboard equatorial model, whereas more detailed approaches have been used to assess and correct localized issues. The results of these preliminary calculations suggest that the DCLL v2.0 design is efficient enough to limit pressure drop in both coolants and to extract the deposited power while the temperature limit of the structural material (550 ºC) is fulfilled.

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