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Thermal-Hydraulic CFD analysis of WCLL BB PbLi manifold

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ENEA CR Brasimone has developed the new design of the Water Cooled Lithium Lead Breeding Blanket (WCLL BB). In the new design Breeding Zone (BZ) water coolant flows in radial-toroidal direction, and PbLi flows in radial-poloidal direction; a gap between the Back Plate (BP) and the BZ constitutes the PbLi inlet manifold. The paper presents the CFD analysis of the WCLL BB PbLi inlet manifold, performed by ANSYS CFX-15 code. The objective of the analysis is to investigate the PbLi flow paths in the manifold region and to optimize the mass flow rate distribution in the BZ of the module. A preliminary analytical analysis is performed to evaluate pressure drop at orifices and to select the diameter of the orifices. CFD simulations are performed with the selected geometries. The optimal geometric configuration is a compromise between the need to have low PbLi velocity, to limit MHD issues and Eurofer corrosion, and to preserve the structural capability of the stiffening plates to withstand the overpressure conditions. Results demonstrate that the layout of the manifold and the size of the orifices is suitable to uniformly distribute the PbLi in the BZ, fulfilling the fluid velocity constraints. Specific MHD analyses are required to evaluate more realistic flow paths and to demonstrate the feasibility of the design.

Keywords: Breeding Blanket, CFD, DEMO, WCLL,

1. Introduction

Within the framework of EUROfusion Power Plant Physics & Technology Work Programme, the Water Cooled Lithium Lead (WCLL) is one of the four Breeding Blanket (BB) concepts considered as possible candidates for the realization of DEMO fusion power plant [1]. The WCLL BB is based on the use of reduced-activation ferritic-martensitic steel, Eurofer, as the structural material, Lithium-Lead (PbLi) as breeder, neutron multiplier and tritium carrier and water at Pressurized Water Reactor (PWR) conditions as coolant.

ENEA CR Brasimone has developed the new design of outboard segment, focusing on the equatorial outboard module, illustrated in Fig. 1 and described in detail in [2]. The new design foresees radial-toroidal tubes for water cooling of the Breeding Zone (BZ), and PbLi flowing in radial-poloidal direction. Radial-toroidal and radial-poloidal stiffening plates define the PbLi flow pattern [3]. A gap between the Back Plate (BP) and the BZ constitutes the PbLi inlet manifold. Orifices in the radial-poloidal stiffening plates and in the plate facing the BZ ensures the PbLi distribution in the BZ.

This paper presents the CFD analysis of the PbLi inlet manifold of WCLL BB equatorial outboard module, performed by ANSYS-CFX-15 [4]. The objective of the activity is to investigate the PbLi flow paths in the manifold and to achieve an homogeneous mass flow rate distribution in the BZ of the module through orifices. The first part of the activity is the analytical analysis, performed to evaluate the pressure drop at orifices and to select the diameter of the orifices. Then, the selected geometries are used to examine the PbLi flow paths through CFD simulations.

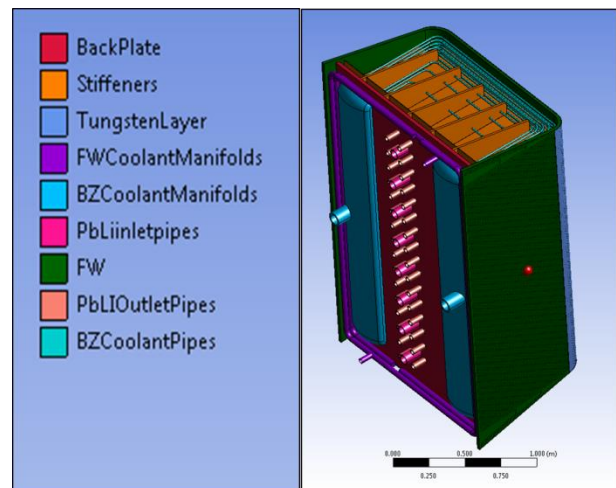


Fig. 1. WCLL BB 2015 equatorial outboard module

2. Models and methods

2.1 Manifold model

The PbLi feeding of the outboard module foresees the PbLi distribution through an inner manifold, constituted by the gap between the BP and the BZ (0.04×2.48 m), pointed out in Fig. 2. The 15 radial-toroidal stiffening plates, and the 5 radial-poloidal stiffening plates divide the manifold region in 96 square channels, as depicted in Fig. 3. The PbLi enters in the gap from eight feeding pipes, (see Fig. 1). Each pipe feeds four square channels of the manifold region. From the center the PbLi spreads in toroidal direction, in the other

channels, through three small orifices realized in the radial-polooidal stiffeners. The PbLi enters in the BZ of the module through six orifices and shares in the six channels, defined by the radial-polooidal stiffeners. The WCLL BB outboard module is divided in 16 elementary cells in poloidal direction, the central ones (14 cells) are equal and symmetric with respect to the poloidal direction. Taking advantage of this symmetry, the computational domain, used for the calculations, is reduced at only three square channels of the manifold. A schematic representation of the computational domain is shown in Fig. 4.

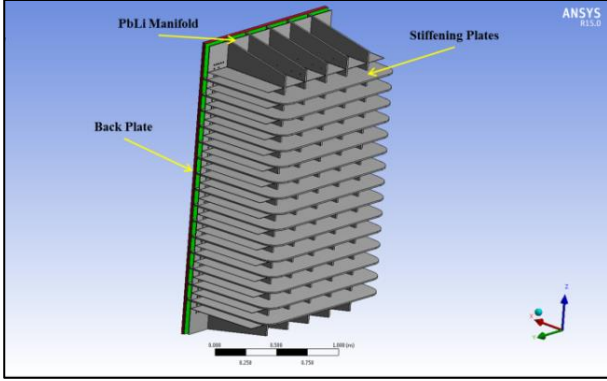


Fig. 2. Internals of WCLL equatorial outboard module

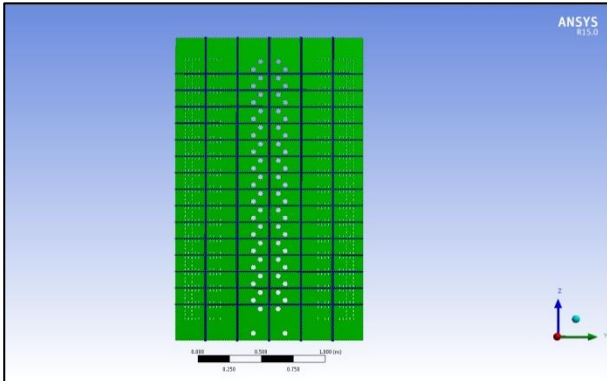


Fig. 3. PbLi manifold of WCLL equatorial outboard module

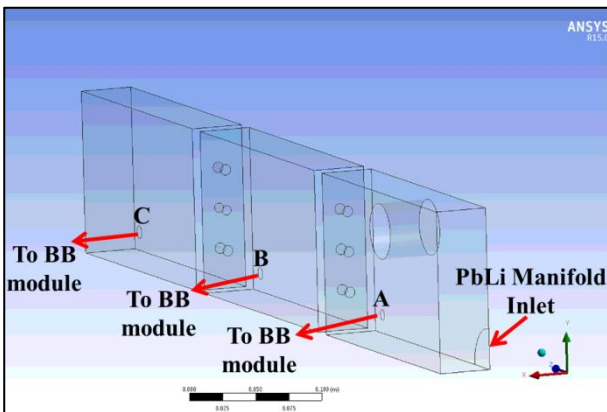


Fig. 4. CFD computational domain

2.2 Pressure drop analysis

A preliminary analytical evaluation of the pressure drop at orifices is done for different geometric configurations of the manifold. The maximum PbLi velocity is set to 0.05 m/s in order to limit the MHD issues and to avoid corrosion of Eurofer with PbLi. Furthermore, the structural integrity of the stiffening plates has to be considered as constraint, thus some parameters are preserved (i.e. the number of orifices on stiffening plates).

The analytical analysis starts from the assumption of different values of the first outlet orifice (A) and the stiffeners orifices diameters. The diameter of the outlet orifices B and C is calculated with pressure drops correlations. The loss of flow through an orifice of area A_o is calculated with the following equation:

$$\Delta P = \frac{1}{2\rho} \left(\frac{\dot{m}}{A_o} \right)^2 K \quad (1)$$

Where ρ is the PbLi density at 400 °C, and is assumed equal to 9720 kg/m³; \dot{m} , is the inlet mass flow rate, A_o is the flow area; and K is the pressure loss coefficient. The pressure loss at inlet orifice is calculated considering \dot{m} equals to the total inlet mass flow rate (0.07343 kg/s), and the area of the inlet orifice equals to 0.003 m². The analysis accounts only the concentrated pressure losses, and not the friction, thus the pressure loss coefficient at inlet orifice, where there is a sharp expansion, is calculated with the following equation:

$$K_{in} = \left(1 - \frac{A_{min}}{A_{max}} \right)^2 \quad (2)$$

Where A_{min} is the inlet orifices area and A_{max} is the vertical section area of one square channel.

To obtain an uniform distribution of the PbLi flow, the mass flow rate considered is 1/3 of the inlet mass flow rate (0.0245 kg/s) in the calculation of the pressure drop at the outlet orifice A; the area of the orifice changes with the diameter, whose selected range is from 6.0 mm to 8.0 mm. The pressure drop coefficient of the orifice can be preliminarily estimated as:

$$K_o = \frac{1}{2} \left(1 - \frac{A_o}{A_{max,i}} \right) + \left(1 - \frac{A_o}{A_{max,o}} \right)^2 \quad (3)$$

where $A_{max,i}$ and $A_{max,o}$ are the flow areas before and after the orifice, respectively (in the present case are both equal to the vertical section area of one square channel).

As the pressure losses at stiffening plate orifices (3 orifices in each plate) are in parallel (considering the two plates separately) the loss of flow calculation assumes the following expression:

$$\Delta P_{o,s} = \frac{1}{2\rho} \left(\frac{\dot{m}}{3 \cdot A_{o,s}} \right)^2 K_{o,s} \quad (4)$$

where $A_{o,s}$ is the area of a single orifice in the plate; \dot{m} is equal to 2/3 of inlet mass flow rate through the first plate and 1/3 of mass flow rate for the second one. The pressure drop coefficient $K_{o,s}$ is calculated for a single orifice in the plate using the above Eq. (3) with the corresponding flow areas.

Assuming the diameter of outlet orifice A and of stiffening plates orifices, the pressure loss at orifice B and C can be calculated by difference of pressure loss from inlet and outlet, and then, the diameter of the orifices can be determined. The results of the pressure drop of different geometry configurations, calculated at outlet orifices, are reported in Table 1.

Table 1. Pressure drops at outlet orifices.

#	ΔP_{OA} [Pa]	ΔP_{OB} [Pa]	ΔP_{OC} [Pa]
1	57.77	32.77	26.53
2	88.06	63.06	56.82
3	57.77	44.40	41.07
4	31.17	17.81	14.48
5	57.77	50.02	48.09
6	18.27	10.52	8.59

The analytical analysis demonstrates that, setting the stiffener orifices diameter, the outlet orifice A diameter can assume only values lesser than or equal to the stiffening plate orifices. On the basis of the pressure drop analysis, several orifice geometries are selected to be studied with a CFD analysis. The orifices diameter are reported in Table 2, where the Φ_{SP} indicates the diameter of each stiffening plate orifice, which are three for all plates and cases; Φ_A , Φ_B , and Φ_C are, respectively, the diameter of outlet orifice A, B, C (see Fig. 4).

Table 2. Orifices diameter selected with analytical analysis.

#	Φ_{SP} [mm]	Φ_A [mm]	Φ_B [mm]	Φ_C [mm]
1	6.0	6.0	6.9	7.3
2	6.0	5.4	5.9	6.0
3	7.0	6.0	6.4	6.6
4	7.0	7.0	8.1	8.5
5	8.0	6.0	6.2	6.3
6	8.0	8.0	9.2	9.7

2.3 Modeling and meshing

The computational domain considered, and described in Section 2.1, is fluid. The selected mesh is a non-structured mesh, the discretization is realized using a patch conforming method. The number of nodes and elements is of the order of 2×10^6 and 9×10^6 , respectively. The selected mesh of the computational domain is used for all the calculations and is reported in Fig. 5.

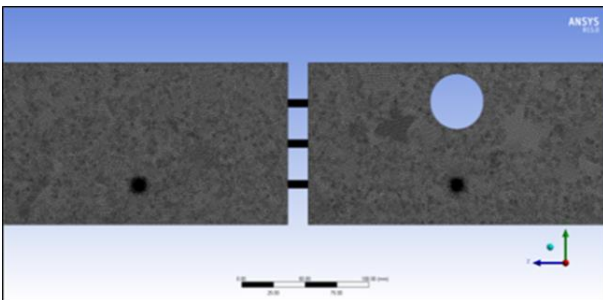


Fig. 5. CFX computational domain mesh.

Simulations are performed in isothermal condition (25 °C) and run until the steady state solution is achieved. The SST (Shear Stress Transport) $k-\omega$ model [4] is completely used in this context. The total PbLi inlet mass flow rate is 0.0734 kg/s, the static pressure at the outlet is 0 Pa. The material properties of PbLi are implemented: PbLi density is 9720 kg/m^3 , calculated at 400 °C, and specific heat capacity is 189.5 J/kg K . The boundary conditions and the material properties are summarized in Table 3.

Table 3. CFX boundary conditions

Parameter	Units	Value
Density	$[\text{kg/m}^3]$	9720
Specific Heat Capacity	$[\text{J kg}^{-1} \text{ K}^{-1}]$	189.5
Mass flow rate	$[\text{kg s}^{-1}]$	0.0734
Outlet pressure	[Pa]	0.0

3. Results and discussion

Simulations are performed with different orifices flow area, obtained from the selected geometries of the analytical analysis and reported in Table 2.

The simulations are run to investigate the PbLi behavior in the manifold and to optimize the PbLi mass flow rate distribution, maintaining the PbLi velocity below the assumed limit of 0.05 m/s. Results of the CFD analysis will be discussed hereafter.

In Table 4, the mass flow rate at outlet orifices in each CFD calculation are reported. The CFD analysis confirms the analytical results: a good mass flow rate distribution is achieved (Run 5) when pressure drop at outlet orifices are similar and considerably greater than pressure drop at stiffening plates orifices. In Fig. 6 a poloidal-toroidal view of the PbLi velocity field in Run 5 is depicted. It can be observed that PbLi is distributed in all regions, even if stagnant regions are evidenced, in particular the last one, near orifice C. PbLi velocity respects the assumed limit in the manifold with the exception of orifices where it reaches the maximum value of 0.113 m/s, due to the sharp reduction of flow area. The results of Run 6 demonstrate that PbLi velocity is maintained below the limit when the orifice hydraulic diameter is greater than 0.008 m, as shown in Fig. 7.

Table 4. CFX mass flow rates at outlet orifices.

#	A [kg/s]	B [kg/s]	C [kg/s]
1	0.0252	0.0243	0.0239
2	0.0250	0.0242	0.0241
3	0.0248	0.0243	0.0243
4	0.0254	0.0241	0.0239
5	0.0247	0.0244	0.0243
6	0.0252	0.0243	0.0239

The CFD analysis proves that an homogeneous mass flow rate distribution can be achieved assuming a greater PbLi velocity limit. The evaluation of Eurofer corrosion rate with Sannier equation [6] demonstrates that PbLi

velocity can be increased without deteriorating corrosion effect. The corrosion rate is calculated as function of velocity, considering different hydraulic diameters and constant temperature, which is the design PbLi inlet temperature (325 °C), as shown in Fig. 8. The corrosion rate is less than 1 $\mu\text{m}/\text{yr}$ increasing PbLi velocity up to 0.1 m/s.

Structural analyses are needed to evaluate if the presence of the orifices in the stiffening plates may compromised the structural integrity of the BB box, in normal operation and overpressure conditions. Furthermore, specific MHD analyses are required to evaluate more realistic flow paths in the PbLi manifold and to demonstrate the performances of the selected design

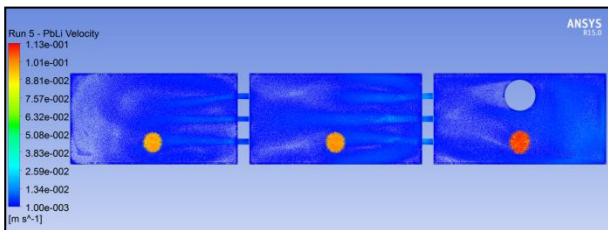


Fig. 6. CFX results: Run 5: poloidal-toroidal view of PbLi velocity.

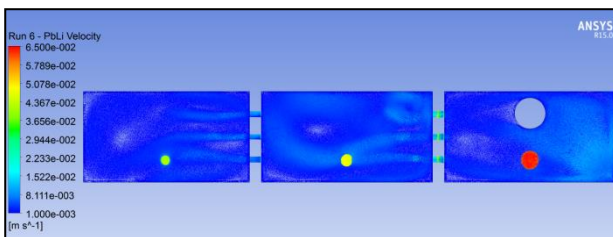


Fig. 7. CFX results: Run 6: poloidal-toroidal view of PbLi velocity.

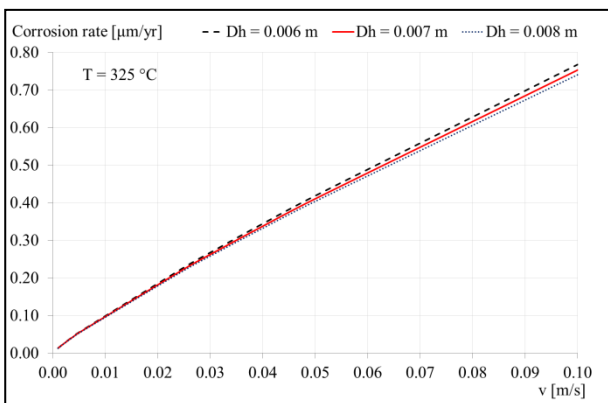


Fig. 8. Eurofer corrosion rate vs PbLi velocity, at different hydraulic diameter and constant temperature.

4. Conclusion

The activity, carried out in the frame of EUROfusion Power Plant Physics & Technology Work Programme, aims at supporting the preliminary design of the PbLi manifold, evaluating the size of the orifices suitable to uniformly distribute the breeder in the BZ. The objective is pursued calculating the pressure drops through the outlet and stiffening plate orifices of the manifold, and defining the allowed orifices diameters. Several geometries are selected and investigated through CFD predictive calculations, using ANSYS CFX – 15 code.

The main outcomes from the analysis are the following:

- The analysis of the results demonstrates that ANSYS-CFX code has the capability of examining and predicting the PbLi flow paths in WCLL BB manifold, confirming the results obtained with the analytical analysis.
- CFD results show that it is possible to achieve an homogenous mass flow rate distribution, even if PbLi velocity exceeds the assumed limit at outlet velocity.
- The evaluation of Eurofer corrosion rate demonstrates that PbLi velocity can be increased without deteriorating corrosion effect
- The best solution is a compromise between the need to have slow PbLi velocity, to avoid MHD issues and limit Eurofer corrosion by PbLi, and to preserve the structural integrity of the stiffening plates.
- Specific MHD analyses are required to evaluate more realistic flow paths in the manifold and to demonstrate the performances of the selected design.

Acknowledgments

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