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CFD analysis of WCLL BB PbLi manifold

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HIGHLIGHTS

- The paper concerns the fluid-dynamics study of WCLL BB PbLi manifold of the equatorial outboard module.
- The aim of the study is the optimization of the mass flow rate distribution in the BZ of the module.
- The study is based on an analytical analysis, which is validated with CFD simulations.
- The method is used to define orifices diameter of the PbLi manifold.

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ABSTRACT

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.

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. 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 propose geometry configurations leading to uniform the mass flow rate distribution in the BZ of the module through orifices. The first part of the activity is the ana-

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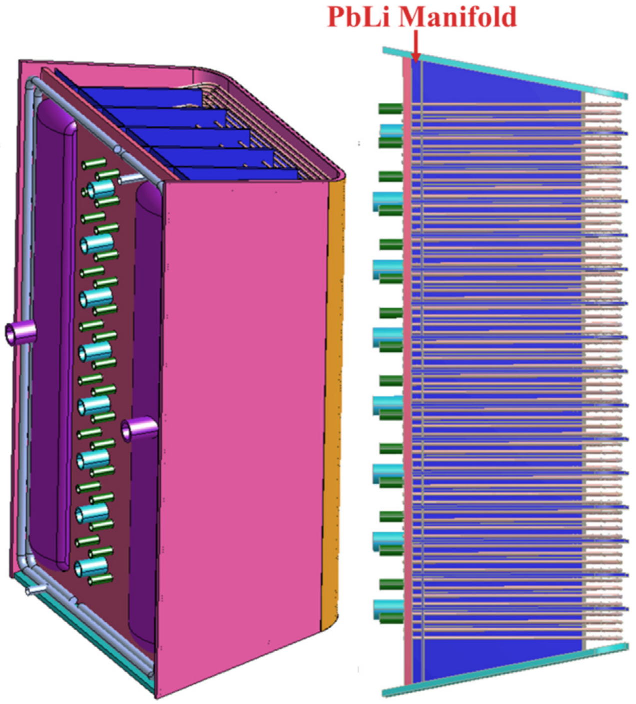


Fig. 1. WCLL BB 2015 equatorial outboard module.

lytical analysis, performed to evaluate the pressure drop in the manifold and to select the diameter of the orifices and outlets. Then, the selected geometries are used to examine the PbLi flow paths through CFD simulations.

2. Models and methods

2.1. Manifold model

The WCLL BB outboard module is characterized by 16 breeding units in poloidal direction and 6 channels in toroidal direction, defined by the radial-toroidal and radial-poloidal stiffening plates. The PbLi manifold is formed by the gap between the BP and the BZ (1.48 × 2.48 × 0.04 m), pointed out in Fig. 1. The stiffening plates divide the manifold in 96 rectangular portions, as depicted in Fig. 2. The PbLi enters in the gap from eight inlets, indicated as PbLi manifold inlet in Fig. 2. Each inlet feeds the four central portions of the manifold region, and then the PbLi spreads in toroidal direction through three small orifices realized in the radial-poloidal stiffeners (Fig. 3). The PbLi enters in each breeding unit through six orifices indicated as PbLi manifold outlet in Fig. 2.

Considering that, the breeding units are equal to each other, with the exception of the top and bottom units, and that they are symmetric with respect the poloidal direction (z-axis in Fig. 2), the computational domain, used for the calculations, is reduced at only three portions of the manifold (Fig. 3), with dimensions: 0.727 × 0.123 × 0.04 m. The orifices A, B, C indicated in the figure, are the manifold outlets. The cooling pipes of the BZ, which cross the BP, are neglected in the CFD model.

The total mass flow rate of the outboard module is 2.35 kg/s, thus the mass flow rate of the computational domain, which corresponds to half of the breeding unit, is 0.0734 kg/s.

2.2. Pressure drop analysis

A preliminary analytical evaluation of the pressure drop in the computational domain is performed to define the diameters of the stiffeners orifices and manifold outlets. The study accounts only the concentrated pressure losses and it is done considering a maximum PbLi velocity of 0.05 m/s in the whole manifold, to limit the MHD issues and to avoid corrosion of Eurofer with PbLi. Furthermore, in order to ensure the structural integrity of the stiffening plates the number of orifices on stiffening plates is preserved.

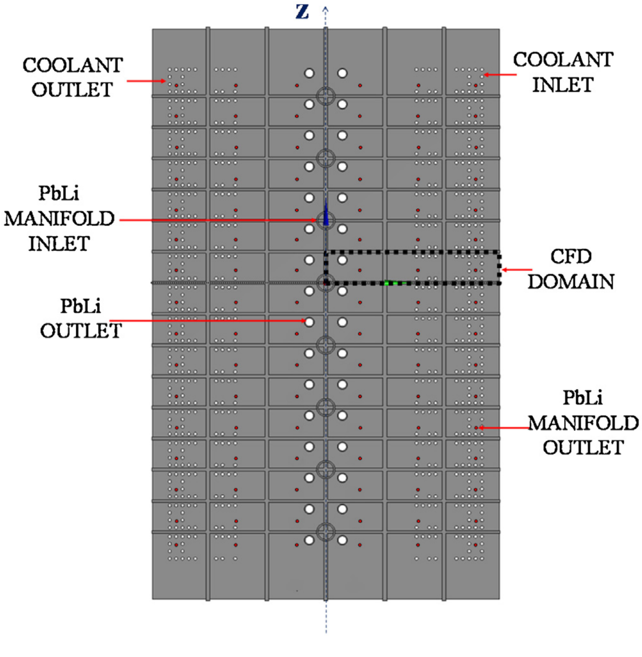


Fig. 2. PbLi manifold of WCLL equatorial outboard module.

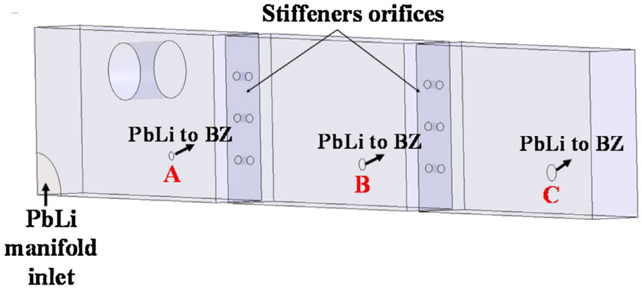


Fig. 3. CFD computational domain.

The diameter of manifold outlets B and C are defined assuming the diameter of outlet A and stiffening plates orifices, and calculating the pressure drops from inlet and outlet of the manifold. Different values of outlet A and stiffening plate orifice diameters are considered.

The loss of flow through an orifice of area A_o is calculated with the following equation [6]:

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

Where ρ is the PbLi density at 325 °C, and is assumed equal to 9808.8 kg/m^3 [5]; $\dot{m}$, is the inlet mass flow rate (0.07343 kg/s), A_o is the flow area (0.003 m^2); and K is the concentrated pressure loss coefficient, calculated with the following equation [6]:

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

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

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

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

The mass flow rate through the outlet A is 1/3 of the inlet mass flow rate (0.0245 kg/s); the area of the orifice depends on the diameter, whose range is from 6.0 mm to 8.0 mm. The pressure drop coefficient of the outlet can be preliminarily estimated as:

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

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

The loss of flow through the three stiffening plate orifices (considering the two plates separately) is calculated with the following expression [6]:

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

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.

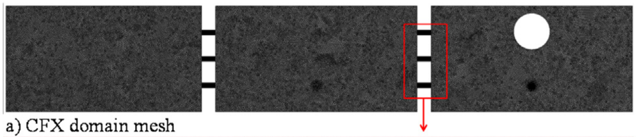
The analytical analysis demonstrates that, setting the stiffener orifices diameter, the outlet A diameter can assume only values lesser than or equal to the stiffening plate orifices. The results of the pressure drop at manifold outlets are reported, for different geometries, in Table 1.

The diameters of outlet B and C are calculated starting from the pressure drops, with the reverse equations. Several geometries are selected to be studied with a CFD analysis. The values of diameters are reported in Table 2, where: Φ_{SP} indicates the diameter of each stiffening plate orifice, Φ_A, Φ_B, and Φ_C are, respectively, the diameter of manifold outlet A, B, C (see Fig. 3).

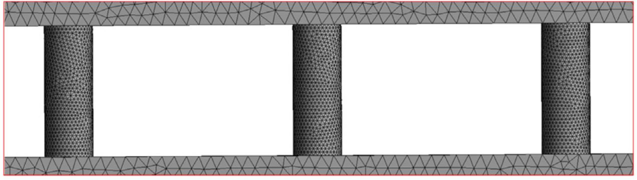
2.3. Modeling and meshing

The computational domain considered, and described in Section 2.1, is fluid. A rough mesh model is used in the calculations. The mesh is formed by tetrahedral elements and is characterized by 2×10^6 nodes and 7×10^6 elements. The selected mesh of the computational domain is used for all the calculations and is reported in Fig. 4.

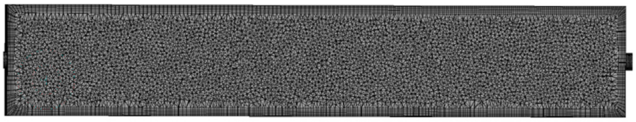
The CFD fluid-dynamic simulations are steady state and run in isothermal conditions (energy equation is turned off). The SST (Shear Stress Transport) k-ω turbulence model [4] is completely used in this context. The steady calculations were interrupted when residual RMS errors values were below an acceptable value (i.e. 10^{-4}), and monitor points for selected parameters of interest (i.e. pressure in the domain) reached constant values. The number of iterations needed to achieve steady state conditions was about 200.



a) CFX domain mesh



b) Detail of the mesh at stiffening plates orifices



c) Poloidal-toroidal section of the mesh

Fig. 4. CFX computational domain mesh.

Table 3
CFX boundary conditions.

Parameter	Units	Value
Density (@325 °C)	[kg/m^3]	9808.8
Dynamic viscosity (@325 °C)	[Pa × s]	1.94×10^{-3}
Inlet mass flow rate	[kg s^{-1}]	0.0734
Outlet pressure	[Pa]	0.0

The material properties of PbLi [5], implemented in CFX, are calculated at constant temperature of 325 °C. The PbLi density is 9808.8 kg/m^3, and the dynamic viscosity is 1.94×10^{-3} Pa × s. The total PbLi inlet mass flow rate is 0.0734 kg/s, the static pressure at the outlet is 0 Pa. The boundary conditions and the material properties are summarized in Table 3.

3. Results and discussion

Several 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, with focus on Run 5 and Run 6 that present better results in terms of mass flow rate distribution and velocities.

The CFD analysis confirms the analytical results as shown in Figs. 5 and 6, where the pressure and velocity fields are reported for Run 5 and Run 6, respectively. In Run 5, the difference of pressure between the manifold and the outlet surfaces A, B, and C, is of the same order of magnitude and equal to 52 Pa. In this case a good mass flow rate distribution is achieved, as the pressure drop between inlet and outlet is greater than the pressure drops at stiffening plate orifices. While, in Run 6, the pressure loss at stiffening plate orifices are not negligible, and bring to have less flow at outlet B and C. In Table 4, the mass flow rate at manifold outlets are reported for each CFD calculation.

The PbLi is distributed in all regions, even if stagnant regions are evidenced, in particular near the manifold outlet C. PbLi velocity, represented by the arrows in Figs. 5 and 6, respects the assumed limit in the manifold. The average velocity at manifold outlets is in the range 0.055–0.075 m/s in Run 5, and lower than 0.05 m/s in Run 6. Maximum local values are reached at manifold outlet A.

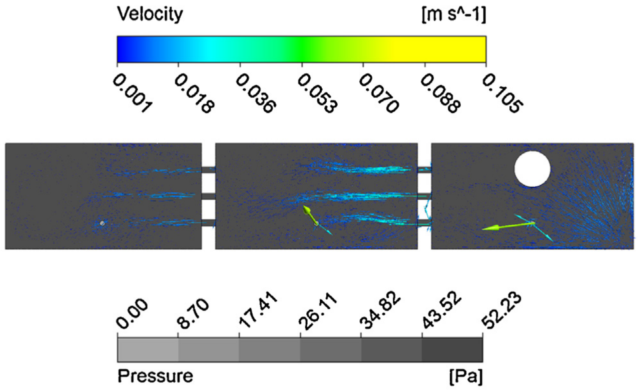


Fig. 5. CFX results: poloidal-toroidal view of pressure and velocity fields in Run 5.

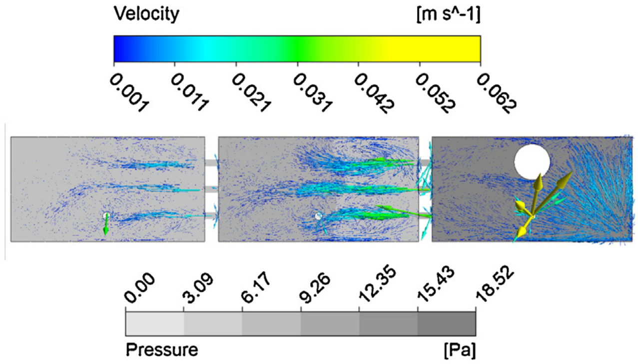


Fig. 6. CFX results: results: poloidal-toroidal view of pressure and velocity fields in Run 6.

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

Considering the stiffening plate orifices, the average PbLi velocity is 3.3 m/s for in the first set of orifices and 1.7 m/s in the second.

The CFD analysis proves that a homogeneous mass flow rate distribution can be achieved assuming a greater PbLi velocity limit. The evaluation of Eurofer corrosion rate with Sannier equation [7] demonstrates that PbLi velocity can be increased without deteriorating corrosion effect. The corrosion rate for PbLi at 325 °C, which is the WCLL BB design inlet temperature, is less than 1 $\mu m/yr$ 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.

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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References

[1] L.V. Boccaccini, et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. 109–111 (2016) 1199–1206.
[2] A. Del Nevo, et al., WCLL breeding blanket design and integration for DEMO 2015: status and perspectives, Fusion Eng. Des. 124 (2017) 682–686 http://dx.doi.org/10.1016/j.fusengdes.2017.03.020.
[4] ANSYS CFX 15.0. User's Guide, November 2013.
[5] E. Mas de les Valls, et al., Lead-Lithium eutectic material database for nuclear fusion technology, J. Nucl. Mater. 376 (2008) 353–357.
[6] I.E. Idelchik, Handbook of Hydraulic Resistance, second edition, Hemisphere, Washington, 1986, translation of a Russian edition (1975).
[7] S. Smolentsev, et al., Numerical study of corrosion of ferritic/martensitic steels in the flowing PbLi with and without a magnetic field, J. Nucl. Mater. 432 (2013) 294–304.