EUROFUSION WPBB-CP(16) 16460

T Melichar et al.

Optimization of the First Wall Helium Cooling System of the European DCLL using CFD Approach

Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Optimization of the First Wall Helium Cooling System of the European DCLL using CFD Approach

Tomáš Melichar[1], Otakar Frýbort[1], Ladislav Vála[1], Pavel Zácha[2], Iván Fernández[3], David Rapisarda[3]

[1]Research Centre Řež, Hlavní 130, 250 68 Husinec-Řež, Czech Republic
[2]Czech Technical University in Prague, Zikova 1903/4, 166 36 Prague 6, Czech Republic
[3]CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain

Dual Coolant Lithium Lead (DCLL) is one of the four breeding blanket concepts being developed within the EUROfusion project as candidates for the European DEMO. One of the most challenging components of the breeding blanket in terms of thermal-hydraulic is the first wall. In order to handle the high thermal loads that the DCLL first wall will be facing, a proper design of the helium cooling system is crucial. The present work deals with the evaluation of the first wall cooling ability under DEMO conditions and with the optimization of geometric and operational parameters of the cooling system composed of helium channels. For this purpose, a sensitivity study to evaluate dependence between the geometric and the operational parameters was performed. All studies were performed using Computational Fluid Dynamics (CFD) approach. The preparation process of the CFD analyses including geometric parametrization of a computational mesh is also described.

Keywords: CFD, DCLL, DEMO, EUROfusion, Helium cooling, Plasma facing components

---

author's email: tomas.melichar@cvrez.cz

1. Introduction

DCLL (Dual-Cooled Lead-Lithium) is one of the four EUROfusion breeding blanket concepts considered for DEMO. The breeding blanket is conceived as a multi-module segment (MMS). This concept uses a self-cooled Pb-17Li eutectic alloy functioning at the same time as a tritium breeder and a neutron multiplier. Helium is the second coolant and is used for cooling of both the first wall, which is integrated in the breeding blanket module and is directly exposed to the plasma heat flux and for cooling of the module stiffening walls. The main structural material of the breeding blanket is EUROFER. The main advantage of this material is reduced activation due to neutron interactions while having similar thermal and mechanical properties as conventional ferritic steels [Ref.1]. Hence, the EUROFER operating temperature range is limited to a maximum temperature of 550°C in order to avoid creep and to a minimum temperature of 300°C due to ductile-brittle transition temperature (DBTT). A thin protective tungsten layer is applied on the first wall surface [Ref.2].

A properly designed first wall (FW) cooling must meet the temperature requirements mentioned above. It is also important to reduce high temperature gradients in the structure to avoid unacceptable secondary mechanical stresses. In particular, the point of juncture of the two metals (EUROFER and tungsten) will be exposed to the highest stress intensity due to different thermal expansion coefficients. Moreover, the ratio of pressure drop to convective heat transfer coefficients along the channels surface has to be optimized in order to keep the power of the compressors as low as possible and to reach the high helium outlet temperature in order to attain high efficiency of a thermal cycle. If these requirements are not met, it is necessary to propose suitable modifications of either the geometry or the operational parameters of the helium cooling system.

In order to evaluate the first wall cooling ability and dependence between the thermal-hydraulic and geometric parameters, a sensitivity study of the first wall model was performed using computational fluid dynamics method (CFD). In particular, effects of the distance between the helium channels and coolant inlet velocity on the hydraulic parameters of the first wall helium system and on the maximum EUROFER temperature were assessed. These effects were detected and described in the present work to support the design of the DCLL module and to fulfil the EUROFER temperature limits by applying reasonable combinations of the channels pitch and the coolant velocity values. Heat transfer coefficients in different parts of the first wall cooling system and for various coolant velocities were also evaluated.

Geometrically parametric computational mesh is necessary to be implemented into the CFD. Process of preparation of the CFD analysis is also described below.

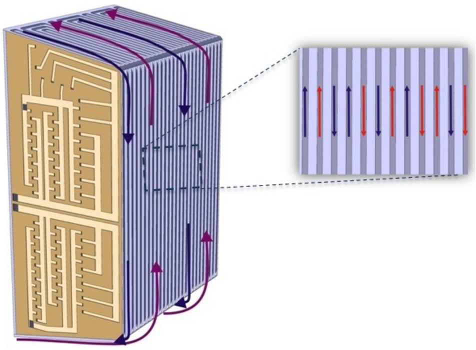
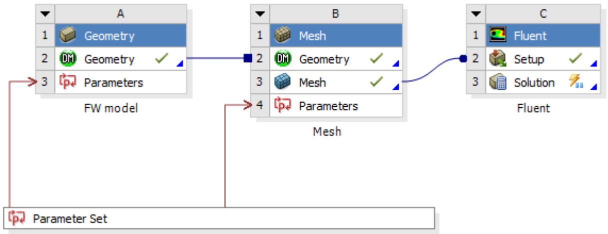


Fig.1. First wall helium cooling system of the DCLL 2015 module [Ref. 3].

2. Computational model

The preparation of the CFD study including the geometry description, computational mesh creation and the solver setting is described in the following section. ANSYS software was used for all the process of CFD analysis [Ref. 4].



2.1 Geometry

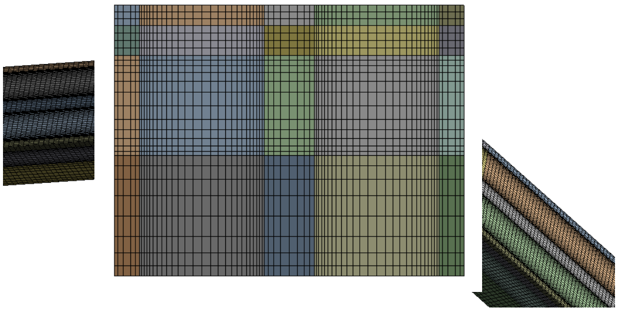
A computational model of the first wall cooling system is based on the present design of the DCLL module [Ref. 5] and is composed of one periodically repeating segment of the first wall helium cooling system including the top and the bottom wall of the module. This segment is composed of a pair of rectangular helium channels with dimensions 12.5 × 10 mm (Fig. 6), where the first one represents the inlet “cold” channel and the second one is the outlet counter-flow channel through which the heated coolant exits first wall. A thin tungsten layer of 2 mm thickness, which is directly exposed to the plasma heat flux, is applied on the first wall surface. The dimension in poloidal direction of the first wall is 1.65 m [Ref. 3].

2.2 Mesh

Thanks to the relatively simple geometry, it was possible to create a high quality structured mesh composed of hexahedral elements and which is conformal on all the interfaces. The computational mesh consists of approx. 2 million mesh elements.

Fig.2. Computational mesh of the helium channels (top) and the elbow domain (bottom).

Parameterization of the geometry and computational mesh was carried out using *ANSYS Design modeler* and *Meshing* tools. The mesh transformation is driven by



setting the mesh elements size on the appropriate edges of the computational model. This setting is maintained even after the geometry update so the coarseness of the mesh is fixed while the mesh element number is changing depending on the geometry change. The *ANSYS Workbench* environment provides coupling of the geometry modeler, the meshing tool and the solver (see Fig. 3) which automate the process of the sensitivity study. The whole process of the sensitivity study requires a high number of simulations to be carried out. The meshing automation reduces the total working time.

Fig.3. Scheme of the CFD project in the ANSYS Workbench environment.

2.3 Solver settings

The boundary conditions of the computational model are based on the DEMO 2014 parameters [Ref. 6] and on results of the analyses performed within the DCLL work package. A heat flux of 0.5 MW/m^2, considered for the steady-state operation [Ref. 7], is applied all over the first wall. Convection boundary condition, characterized by temperature profile and heat transfer coefficient, representing the liquid metal flow, is applied on the rear wall of the model. A volumetric heat source caused by neutron interactions in the solid materials is also assumed [Ref. 3]. The helium inlet temperature is set to 300°C. The helium properties were set as piece-wise linear function in terms of temperature for an operating pressure of 8 MPa. A periodic boundary condition is applied on the side walls of the model.

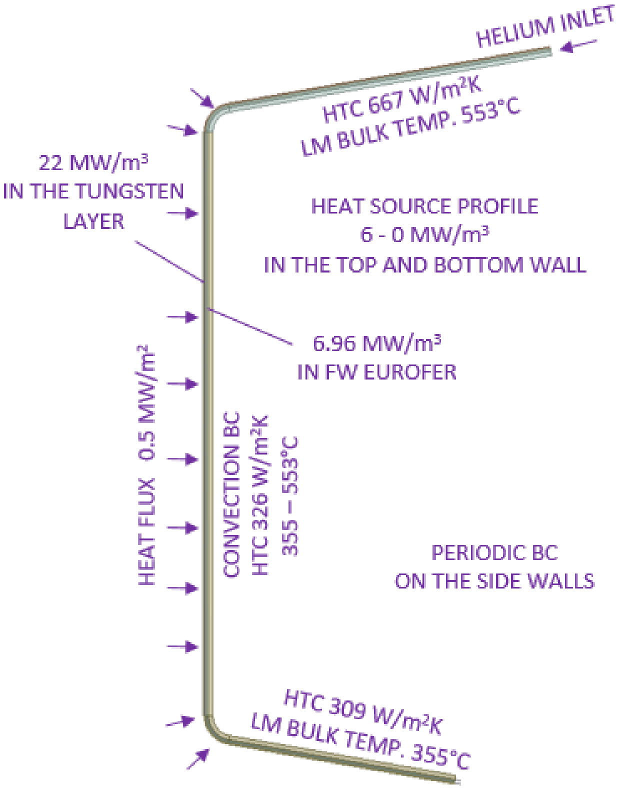


Fig.4. Boundary conditions of the first wall model.

Calculations were carried out with the commercial software ANSYS Fluent 16. Several models of turbulence and various computational meshes were tested on a simplified geometry in order to find the most suitable computational configuration [Ref. 8]. The k-epsilon Realizable model using the standard wall function (semi-empirical formulas resolving the boundary layer) was chosen. This model allows the use of a relatively coarse mesh and gives comparable results with the k-Ω model, which resolves the viscous sublayer with a mesh all the way to the wall and requires much finer grid [Ref. 9].

3. Sensitivity study of the first wall parameters

The sensitivity study to evaluate the effect of the pitch between the helium channels (the distance denoted with “P” in Fig.6) on the maximum EUROFER temperature, pressure drop of the first wall helium cooling system and on the helium outlet temperature was conducted in the range of the coolant inlet velocity from 70 to 100 m/s. Fig. 6 shows that it is possible to find a proper solution in terms of maximum EUROFER temperature with relatively high margin for the assessed channels layout under reasonable combinations of channel pitch values and coolant flow velocity. Naturally, any increase of the pitch causes a rise in temperatures in the first wall but at the same time, it causes a reduction of the helium mass flow through the breeding blanket module due to the decrease in the total number of channels. It was found that the effect of the pitch on the maximum EUROFER temperature is approx. +5°C when the pitch is increased by 1 mm and the maximal temperature grows by approx. 10°C when the inlet velocity is increased by 10 m/s. The effect of channels pitch *P* on the outlet helium temperature, which is important in terms of thermal cycle efficiency, is shown in Fig. 7.

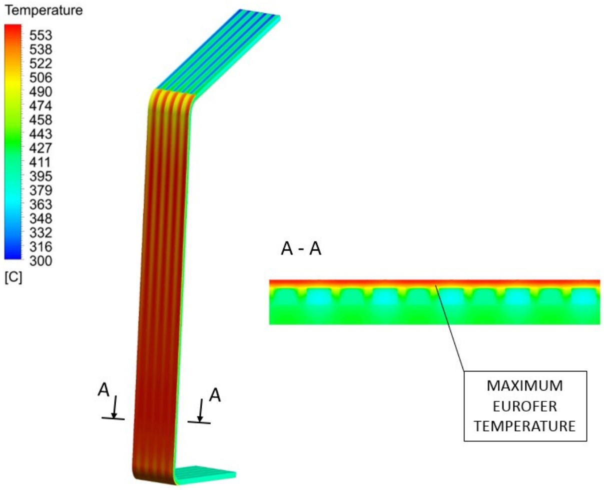


Fig.5. Temperature field in the first wall.

The location of the maximum EUROFER temperature is at the EUROFER/tungsten interface and between the helium channels. The cross section with the highest temperatures (shown in Fig. 5 on the left) is located 0.35 m from the bottom edge of the first wall. The obtained temperature field can be implemented into the finite elements method solver to evaluate the stress intensity in the first wall structure.

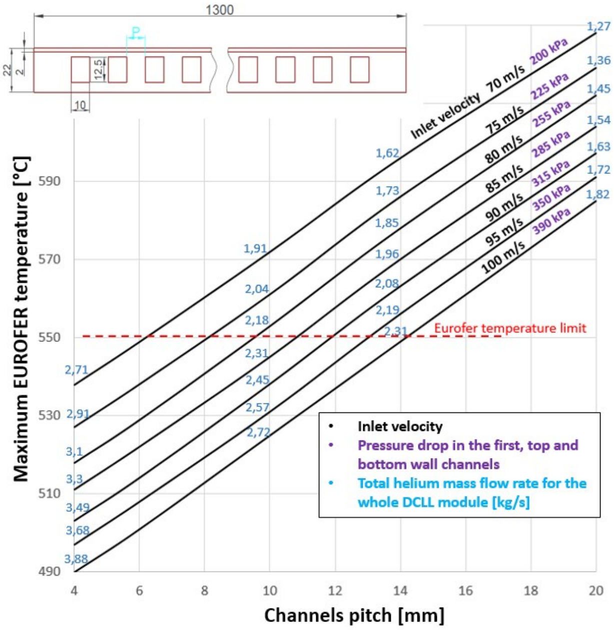


Fig.6. Sensitivity study of the first wall – dependence of the channel pitch on the maximum EUROFER temperature.

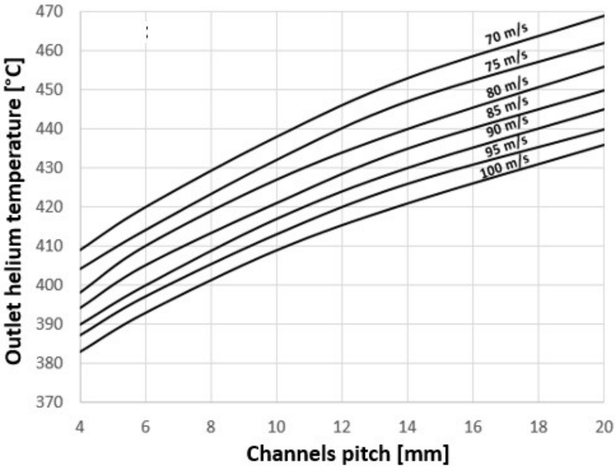


Fig.7. Sensitivity study of the first wall – dependence of the channel pitch on the helium outlet temperature.

The distance between the helium channels and the EUROFER/tungsten interface was assumed to be 2.5 mm in this study. However, due to the mechanical issues, the thickness was later increased to 3. This measure has a significant effect on the maximum EUROFER temperature which grows by 10°C.

4. Heat transfer

Heat transfer coefficients (HTC) were estimated in 10 different sections of the first wall helium system to characterize convective heat transfer between the fluid and solid domains. Due to the unavailability of suitable tools evaluating accurate values of the HTC directly in the CFD solver, values were estimated manually according to Newton´s law:

$$HTC=\frac{q_w}{T_w-T_{bulk}}$$

where HTC [W/m^{2}K] is the local heat transfer coefficient, q_w [W/m^2] is the wall heat flux, T_w [K] the is wall temperature and T_{bulk} [K] is the bulk temperature of the helium. The wall heat flux and temperature profiles were obtained directly from the CFD solver. In order to obtain more accurate values of the HTC, several temperature profiles were depicted in different cross-sections of each observed location. Then these values were averaged to obtain the representative heat transfer coefficient.

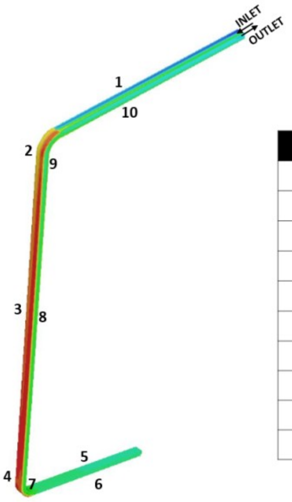
As it can be seen from the table in Fig. 8, values of the heat transfer coefficients grow approximately by 1 000 W/m^{2}K when the coolant inlet velocity is increased by 10 m/s in the explored velocity range (75 – 95 m/s). It is also evident that the HTC grows significantly in sections located behind the elbow domains (positions 2 and 7 in Fig. 8). This is provided by the enhancement of turbulence intensity and by the mixing of the coolant. According to the CFD study and the heat transfer evaluation, it is essential to maintain the DCLL first wall structure in the required temperature limits to achieve the HTC of 6 000 W/m^{2}K or higher.

The channels wall roughness was considered 25 μm in this study.

Fig.8. Heat transfer coefficients in the first wall.

5. Conclusion and further work

The computational model representing the first wall of the DCLL breeding blanket module was created using the CFD method to obtain a temperature field in the first wall structure. Using this parametric model, a sensitivity study of the geometric and operational parameters was performed. It was found that it is possible to absorb the steady-state plasma heat flux of 0.5 MW/m^2 and to fulfil the required temperature limits under the specific combination of the pitch values between the helium channels and the helium inlet velocities. Heat transfer coefficients were evaluated in different sections of the cooling system to characterize the convective heat transfer. Values of 6 000 W/m^{2}K or higher are required to maintain the structure in the temperature limits.



Heat transfer coefficient values [W/m²K]

	75 m/s	85 m/s	95 m/s
1	6000	6500	7500
2	7000	9000	12000
3	5500	6500	7500
4	5500	6500	7500
5	5000	5500	6000
6	5000	5500	6000
7	7500	8000	10000
8	6000	7000	8000
9	6000	7000	8000
10	6500	8000	10000

The next step within the DCLL first wall development will consist of recalculating the model for the new DEMO2015 specifications [Ref. 10] in terms of both thermal-hydraulic and structural analysis. Different channels layouts (single parallel and counter flow channels) will be explored and compared with the current proposal. Another objective of the further work is the evaluation of the helium mass flow distribution into the individual channels from the helium manifold located upstream the first wall cooling system and eventually to propose measures to reach uniform cooling of the structure. Implementation of turbulencing elements applied on the channels walls is another promising issue which might be also investigated by the DCLL design team. As mentioned in section 4, even a small geometrical element causing mixing of the coolant may cause a significant enhancement of the heat transfer. Implementation of proper turbulencing elements would allow the use of lower coolant velocities and deal with higher values of the plasma heat flux which may occur during unsteady operational regimes. However, the ratio of the heat transfer coefficients and pressure drop should be optimized.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This work has been also supported by a grant no. MSMT-41274/2014-2 from Ministry of Education, Youth and Sports of the Czech Republic.

References

[1] F. Gillemot, et al., Material property handbook pilot project on EUROFER97, EFDA_D_2LDMEK, 2016.

[2] D. Rapisarda, et al., Status of the engineering activities carried out on the European DCLL, this conference.

[3] I. Fernández, et al., Design Engineering / DCLL Design Report 2015 , EFDA_D_2MYHGZ, 2016.

[4] T. Melichar, et al., Thremal-hydraulic and Thermal-mechanic Analysis of First Wall of DCLL Breeding Blanket Concept, EFDA_D_2MSTXM, 2015.

[5] D. Rapisarda, Conceptual design of the EU-DEMO Dual Coolant Lithium Lead Equatorial Module, IEEE Transactions on Plasma Science, pg. 1603-1612, 2016.

[6] R. Kemp, DEMO1_JULY_12, Summary parameter set for 2012 single-null DEMO1 design, EFDA_D_2LBVXZ, 2012.

[7] D. Carloni, System Requirements Document – Breeding Blanket, EFDA_D_2MCZZF, 2015.

[8] T. Melichar, First Wall Cooling of the DEMO Fusion Reactor by Using of Helium Ducts (Master thesis), Czech Technical University, 2015. [In Czech language]

[9] ANSYS Fluent Theory Guide Release 15.0, ANSYS, 2013.

[10] G. Federici, et al., Overwiev of the design approach and priorisation of R&D activities towards an EU DEMO, Fusion Engineering and Design, 109-111, pg. 1464-1474, 2016.