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Optimization of the first wall helium cooling system of the European DCLL using CFD approach

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HIGHLIGHTS

- Sensitivity study of the DCLL first wall was performed using CFD approach.
- Dependence between geometric and operational parameters was evaluated.
- Heat transfer coefficients were evaluated in different parts of the first wall.
- Proposed first wall cooling system is able to absorb plasma heat flux of 0.5 MW/m^2.

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ABSTRACT

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.

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 Pb-17Li eutectic alloy functioning at the same time as a coolant, 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 [1], while having similar thermal and mechanical properties as conventional ferritic steels. 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) [2]. A thin protective tungsten layer is applied on the first wall surface [3].

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 a power of compressors as low as possible and to

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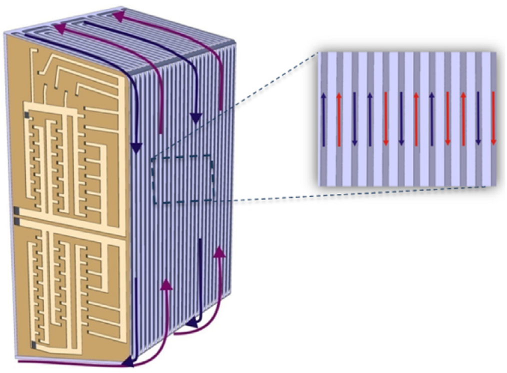

Fig. 1. First wall helium cooling system of the DCLL 2015 outboard equatorial module v1.0 [4].

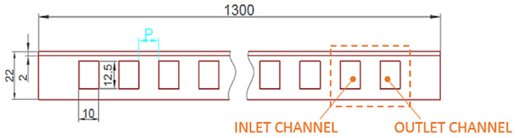

Fig. 2. First wall channels geometry.

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 outboard equatorial first wall model was performed using computational fluid dynamics method (CFD). In particular, effects of the distance between the helium channels and the 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.

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.

2.1. Geometry

A computational model of the first wall cooling system is based on the design of the DCLL 2015 module (Fig. 1) 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, 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 (Fig. 2). 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 the poloidal direction of the first wall is 1.65 m.

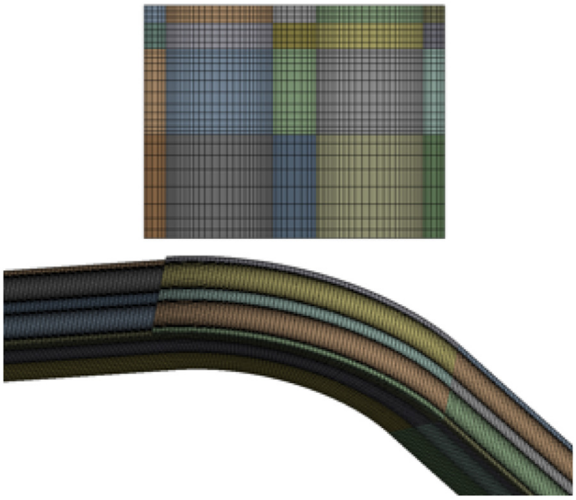

Fig. 3. Computational mesh of the helium channels (top) and the elbow domain (bottom).

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 (Fig. 3). The computational mesh consists of approx. 2 million mesh elements, values of the Y+ parameter defining the mesh suitability for turbulence models are between 25 and 125.

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, 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.

2.3. Solver settings

The boundary conditions of the computational model (Fig. 4) are based on the DEMO 2014 parameters and on results of a 1D code PLATOON [5]. A heat flux of 0.5 MW/m^2, considered as minimum requirement for the steady-state operation [4], 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 [6]. 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.

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 [7]. The k-epsilon Realizable model using the standard wall function (semi-

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