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Influence of thermal performance on design parameters of a He/LiPb dual coolant DEMO concept blanket design

E. Mas de les Valls[a,b,*], L. Batet[a,c], V. de Medina[a,d], J. Fradera[a,c], M. Sanmartí[e], L.A. Sedano[f]

[a] *Technical University of Catalonia (UPC), Jordi Girona 1-3, 08034 Barcelona, Spain*
[b] *Technology for Fusion (T4F) Research Group, GREENER, Department of Heat Engines, Barcelona, Spain*
[c] *Technology for Fusion (T4F) Research Group, GREENER, Department of Physics and Nuclear Engineering, Barcelona, Spain*
[d] *Sediment Transport Research Group, Department of Engineering Hydraulic, Marine and Environmental Engineering, Barcelona, Spain*
[e] *bFUS-IREC, Jardins de les Dones de Negre 1, 08930 Sant Adrià del Besòs, Spain*
[f] *EURATOM-CIEMAT Association, 28040 Madrid, Spain*

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ABSTRACT

Spanish Breeding Blanket Technology Programme TECNO_FUS is exploring the technological capabilities of a Dual-Coolant He/Pb15.7Li breeding blanket for DEMO and studying new breeding blanket design specifications. The progress of the channel conceptual design is being conducted in parallel with the extension of MHD computational capabilities of CFD tools and the underlying physics of MHD models. A qualification of MHD effects under present blanket design specifications and some approaches to their modelling were proposed by the authors in [1]. The analysis was accomplished with the 2D transient algorithm from Sommeria and Moreau [2] and implemented in the OpenFOAM CFD toolbox [3]. The thermal coupling was implemented by means of the Boussinesq hypothesis. Previous analyses showed the need of improvement of FCI thickness and thermal properties in order to obtain a desirable liquid metal temperature gain of 300 °C. In the present study, an assessment through sensitivity and parametric analyses of the required FCI thickness is performed.

Numerical simulations have been carried out considering a Robin-type thermal boundary condition which assumes 1D steady state thermal balance across the solid FCI and Eurofer layers. Such boundary condition has been validated with a fluid–solid coupled domain analysis.

Results for the studied flow conditions and channel dimensions show that, in order to obtain a liquid metal temperature gain of about 300 °C, the required FCI material should have a very small effective heat transfer coefficient ($(k/\delta) \leq 1\,W/m^2K$) and fluid velocities should be about 0.2 m/s or less. Moreover, special attention has to be placed on the temperature difference across the FCI layer. However, for a maximised liquid metal thermal gain, higher velocities would be preferable, what would also imply a reduced temperature difference across the FCI layer.

1. Introduction

Spanish Breeding Blanket Technology Programme TECNO_FUS is exploring the technological capabilities of a Dual-Coolant He/Pb15.7Li breeding blanket for DEMO and studying new breeding blanket design specifications. Channel conceptual design is being done based on different analyses (from neutronics to structural studies) always giving priority to maximum thermal efficiency. Such analyses include MHD studies, mainly concerning to liquid metal MHD thermofluid issues such as MHD pressure drop, Q2D turbulence and buoyancy, among others. In this direction, a preliminary study was carried out by the authors [1], where a qualification of MHD effects under TECNO_FUS blanket design specifications and some approaches to their modelling were exposed. The analysis first summarised the main flow parameters and characteristics by means of a dimensionless study, then, some preliminary numerical results were shown. The numerical simulations were obtained with the 2D MHD model from Sommeria and Moreau [2] implemented in the OpenFOAM CFD toolbox [3]. The thermal coupling was implemented by means of the Boussinesq hypothesis. Numerical results indicated the need of improvement of FCI thickness and thermal properties in order to obtain a desirable liquid metal temperature gain of 300 °C.

Previous results [1] correspond to a FCI thermal conductivity of 15 W/m K FCI (taken from Shinavski [4]) and a FCI thickness of 2 mm. However, according to Smolentsev et al. [5], the thermal conductivity of SiC FCI (k_{FCI}) can lay between 1 and 20 W/mK,

* Corresponding author at: Dept. of Heat Engines, Technical University of Catalonia (UPC), Av. Diagonal 647, 08028 Barcelona, Spain.
E-mail address: elisabet.masdelesvalls@gits.ws (E. Mas de les Valls).

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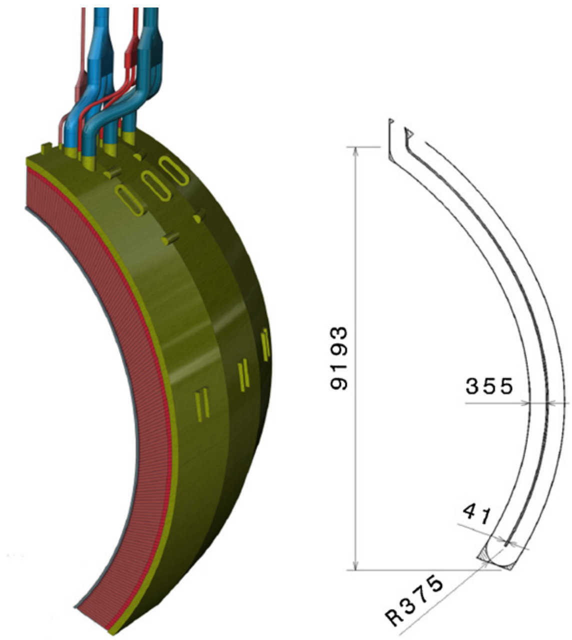

Fig. 1. Three outboard blanket modules forming a segment (left) and module dimensions in mm (right) for the TECNO_FUS proposal from [8].

depending on the fabrication technique, whereas the minimum available depth of the FCI layer (δ_{FCI}) is 5 mm [6]. The chosen FCI and its depth can alter considerably the thermal behaviour of the blanket. In the present study, an assessment through sensitivity and parametric analyses of the required FCI effective heat transfer coefficient, $(k/\delta)_{FCI}$, is performed. The case set up is the same as in the previous study. The chosen inlet velocity is 0.2 m/s since it has been previously found to be optimal in terms of the chosen three critical design parameters. Such parameters are: (1) ΔT_{LM}, liquid metal temperature increment between inlet and outlet (~300°C), (2) ΔT_{FCI} maximum temperature difference across the FCI layer (≤200°C, [7]), and (3) q_{LM} thermal liquid metal gain (as high as possible).

An explanation of the TECNO_FUS blanket concept is given (Section 2) along with a brief overview of the implemented model and boundary conditions (Section 3). The sensitivity to FCI thermal properties is then analysed (Section 4) and main conclusions are summarised (Section 5).

2. The TECNO_FUS blanket concept

According to Juanas and Fernández [8], the reactor is split in 12 segments, each one consisting of two inboard and three outboard blanket modules, the latter shown in Fig. 1. Initially, each module consists of four banana-shaped (poloidal) channels, two in the front and two in the back, connected at the bottom of the module. Liquid metal (Pb-15.7Li) flows from the inlet manifold at the top, down through the front channels and returns through the back channels up to the outlet manifold. The blanket poloidal length *L* is 9193 mm, so it covers almost all the poloidal dimension of the reactor. Each channel has a radial depth 2*b* of 355 mm and a toroidal width 2*a* of 610 mm. More details of the geometry are given in Fig. 1.

The present status of the design considers, with 3450 MW of fusion power, a neutron wall loading for the blanket of 2.1 MW/m^2. The amplification factor is estimated to be 1.16. The thermal load for the TECNO_FUS blanket geometry has been obtained from a 2D-axisymmetric neutronic assessment using a simplified, onion layer-like, isometric model from Catalán et al. [9]. From their results, the thermal load can be expressed following an exponential curve (Eq. (1)), where *r* stands for the distance to the First Wall.

$$S_{\text{thermal}} = 12\exp(-4.8r) + 40\exp(-20r) \qquad \text{MW/m}^3 \qquad (1)$$

Improvements on the above-mentioned neutronic load and channel geometry are currently being carried out, however, minor changes are expected on MHD thermofluid properties. The data used for the present study coincides with the one considered in [1].

As liquid metal (LM) flows, it experiences a huge thermal load caused both by thermal deposition from plasma's reaction and by neutron reactions in PbLi. At the same time, the large magnetic field, responsible for plasma confinement, interacts with the flow velocity inducing electric currents and, thus, generating the Lorentz force that opposes the flow. All of this results in a considerable increase of fluid temperature at the inlet channel only diminished by helium cooling channels at the walls. Preliminary TECNO_FUS blanket characterisation considers a helium average temperature of 400 °C and an inlet LM temperature of 450 °C. A LM temperature gradient of 300 °C would be desirable to permit efficient heat extraction through a super-critical CO_2 heat exchanger. Thus, the flow rate should be high enough to avoid excessive thermal stresses on the structure but, at the same time, able to provide a high LM outlet temperature. MHD pressure drop is not an aspect of major concern due to the presence of flow channel inserts (FCIs). Indeed, the present TECNO_FUS blanket concept considers the FCIs to be directly in contact with the steel, using Hot Isostatic Pressure technique, so that no pressure equalisation openings are needed. Thus, a reasonable reduction of the MHD pressure drop can be achieved with relatively low values of the FCI electrical conductivity.

Considering a toroidal magnetic field of 7 T, the Hartmann number for the previously defined blanket is $Ha_a = 51390$, while the Reynolds number is $Re_a = 4.5 \times 10^5$. Therefore, parameter $R = Re_a/Ha_a = 8.8$ for the present design lays in the range of US DCLL and self-cooled blanket designs. For the estimation of the Grashof number (*Gr*), a characteristic temperature scale has been defined as $\Delta T = \overline{S}_{\text{thermal}}\ b^2/k$, which is associated with the average radial thermal load $\overline{S}_{\text{thermal}}$ and the liquid metal conductivity *k*. For the TECNO_FUS blanket, $Gr_b = 2.8 \times 10^9$ is obtained, which is in accordance with the dual-coolant concept [10]. All dimensionless numbers have been calculated using the PbLi database [11].

Under the above mentioned flow conditions, and considering the large poloidal length of each banana-shaped channel, the flow can be modelled using the two-dimensional set of equations from Sommeria and Moreau [2] (SM82) which includes a linear friction term in the momentum equation due to the contribution of Hartmann boundary layers. Moreover, under the above mentioned Re_a, MHD turbulence is expected to exist. Following the Ha_a–Re_a diagram in Smolentsev and Moreau [12], the liquid metal flow would correspond to the Q2D region. This implies that all three dimensional effects are confined in the thin Hartmann layers at the walls perpendicular to the magnetic field, where almost all Ohmic and viscous forces occur.

3. Model and boundary conditions

Due to its large poloidal dimension, full 3D modeling of the complete TECNO_FUS blanket is hardly possible with the existing CFD tools and, when possible, it is highly time consuming. Taking profit of the MHD flow conditions, which allow using the two-dimensional set of equations from Sommeria and Moreau [2], the studied geometry is reduced to a 2D toroidal plane of the blanket. Such configuration permits modeling the flow all along the blanket with the aim of predicting heat extraction ratios and, hence, efficiencies.