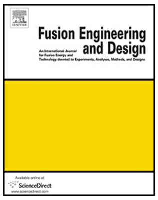
Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes



# MHD thermohydraulics analysis and supporting R&D for DCLL blanket in the FNSF

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ARTICLE INFO

*Article history:*
Received 18 January 2017
Received in revised form 11 June 2017
Accepted 11 June 2017
Available online xxx

*Keywords:*
Blanket
Lead-lithium
DCLL
FNSF
Magnetohydrodynamics
Pressure drop

ABSTRACT

A Fusion Nuclear Science Facility (FNSF) has been recognized in the fusion community as a necessary facility to resolve the critical technology issues of in-vessel components prior to the construction of a DEMO reactor (Abdou et al., 1996) [1]. Among these components, development of a reliable, low-cost and safe blanket system that provides self-sufficient tritium breeding and efficient conversion of the extracted fusion energy to electricity, while meeting all material, design and configuration limitations is among the most important but still challenging goals. In the recent FNSF study in the US (Kesel et al., 2015) [2], a Dual-Coolant Lead-Lithium (DCLL) blanket has been selected as the main breeding blanket concept. This paper summarizes the most important details of the proposed DCLL blanket design, presents the MHD thermohydraulic analysis for the PbLi flows in the blanket conduits and introduces supporting R&D studies, which are presently ongoing at UCLA. We also discuss the required pre-FNSF R&D in the area of MHD Thermofluids to support the further work on the DCLL blanket design & analysis and its integration into the fusion facility.

## 1. Introduction

The DCLL is an attractive breeding blanket concept that potentially leads to a high-temperature ($T \sim 700\,^{\circ}$C), high thermal efficiency ($\eta > 40\%$) blanket system. In this concept, a high-temperature lead-lithium (PbLi) alloy circulates slowly ($U \sim 10$ cm/s) in large poloidal rectangular ducts ($D \sim 20$ cm) to remove the volumetric heat generated by neutrons and produce tritium, while a pressurized (typically to 8 MPa) helium gas (He) is used to remove the surface heat flux and to cool the ferritic first wall (FW) and other blanket structures in the self-cooled region. The key element of the concept is a flow channel insert (FCI) that serves as an electrical or electrical/thermal insulator to reduce the magnetohydrodynamic (MHD) pressure drop and to decouple the temperature-limited RAFM (reduced-activation ferritic/martensitic) steel wall from the flowing hot PbLi.

Several designs of the DCLL blanket have been proposed in Europe [3–6], the US [7–11] and China [12–14]. At present, a module-type DCLL blanket is considered in Europe for a possible implementation in a DEMO reactor [15]. Historically, the first DCLL version, known as a low-temperature (LT) DCLL blanket [3], relied on qualified materials and existing fabrication technologies. A key component of this design is a sandwich-type FCI composed of steel/alumina/steel layers or a thin alumina layer placed on the wall to be used as electrical insulator for decoupling electrically conducting structural walls from the flowing PbLi. In the next, more advanced high-temperature (HT) DCLL blanket, which was first introduced in [8], an FCI made of silicon carbide (SiC), either composite [16] or foam [17], was further proposed as a means for electrical and also thermal insulation to provide acceptable MHD pressure drops and to achieve a high PbLi exit temperature. At present, the LT DCLL with a sandwich FCI is considered in the fusion community as a backup option in case a SiC FCI could not be developed and fully qualified prior to the start-up of the FNSF. More information about the DCLL blanket developments, blanket key features and technical characteristics as well as several design examples can be found in [18].

In the recent FNSF study in the US [2], a DCLL blanket was designed for both inboard and outboard regions (Fig. 1). The entire machine is subdivided into 16 toroidal sectors, such that there are

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http://dx.doi.org/10.1016/j.fusengdes.2017.06.017
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Please cite this article in press as: S. Smolentsev, et al., MHD thermohydraulics analysis and supporting R&D for DCLL blanket in the FNSF, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.06.017

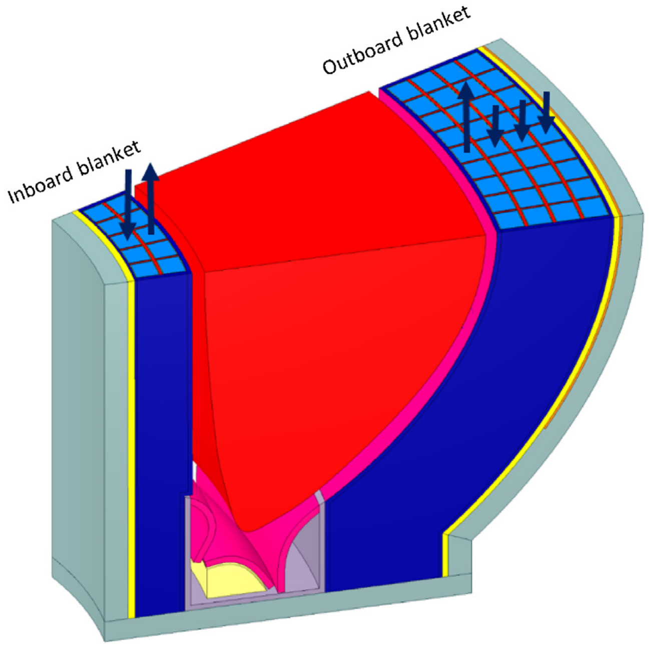

**Fig. 1.** Cross-cut of one of the 16 toroidal sectors in the FNSF with the IB and OB blankets. The arrows show the PbLi flow path in the poloidal ducts.

16 inboard (IB) and 16 outboard (OB) blankets. Each sector with the blankets can be removed via an individual port using a horizontal maintenance scheme. In the IB blanket, the liquid metal flows upwards in the five front ducts facing the plasma, makes a U-turn at the top of the blanket and then flows downwards in the five rear ducts. There are two manifolds at the bottom of the blanket to feed the poloidal ducts and to collect the hot PbLi at the exit of the blanket. The OB blanket has a similar structure but the number of the ducts and blanket dimensions are different to fit into a larger space at the OB. In the designed blanket, the liquid first flows upwards in the front nine ducts and then downwards through the three rows of return ducts (totally, 3 × 9 = 27 return ducts). The thickness of the inboard blanket (including the front wall, back wall, stiffening plates, FCI, He flows and PbLi flows) is 0.5 m. The thickness of the OB blanket is 1 m. The poloidal length of the IB blanket is ~7 m, while the OB blanket is ~ 10 m. The characteristic magnetic field at the IB is ~ 10 T and that at the OB is ~ 5.5 T. Each poloidal blanket duct has a 5-mm thick FCI. The FCI is separated from the RAFM wall with a thin 2-mm gap to accommodate possible thermal expansions of the flow insert. The space inside the FCI box and that in the gap is filled with the flowing PbLi. The most important blanket parameters in this design for two blanket version, LT and HT DCLL, are summarized in Table 1.

In this study, a conservative variant of the HT blanket is considered, where the maximum PbLi temperature is restricted to 550 °C. This temperature choice gives a conservative match to the RAFM steel limits and a reasonably large temperature window. The last parameter in Table 1, the fraction of volumetric heat absorbed by the flowing PbLi, was estimated using a simplified thermal analysis under the assumption that the volumetric heat generated in the FCI and the 2-mm PbLi gap goes to He. A full 3D analysis may find different.

## 2. MHD thermohydraulics analysis

The goal of this analysis is to evaluate the MHD pressure drop for each blanket component and to eventually calculate the overall pressure drop for the entire blanket through the summation of the individual pressure drop contributions. Similar to the MHD analysis for the IB DCLL DEMO blanket in [19], in this study we identified and then computed five major pressure drops. These five main components of the PbLi loop, which are expected to have the greatest impact on the MHD pressure drop are the following (Fig. 2): (1) flows in the poloidal blanket ducts with FCI; (2) flows at the blanket inlet and outlet (i.e. manifolds); (3) flows in the PbLi access pipes with FCI in a near-uniform magnetic field region; (4) flows in the access pipes in the fringing magnetic field; and (5) flows at the top of the blanket (“U-turn”) where changes in the flow direction and flow redistribution occur.

**Table 1**
The most important blanket parameters used in the present MHD thermohydraulic analysis.

| PARAMETER | IB BLANKET | OB BLANKET |
|---|---|---|
| Blanket length, m | 7.04 | 10.28 |
| Toroidal length of the FW per sector, m | 1.69 | 2.28 |
| Characteristic B-field, T | 10.0 | 5.5 |
| NWL (averaged), MW/m$^2$ | 0.86 | 1.34 |
| Neutron multiplication in PbLi | 1.15 | 1.15 |
| PbLi Inlet/Outlet $T$, °C | 350/550 (HT DCLL)<br>350/470 (LT DCLL) | 350/550 (HT DCLL)<br>350/470 (LT DCLL) |
| FCI thickness, mm | 5 (HT DCLL) 3 RAFM+1.5 Alumina + 0.5 RAFM (LT DCLL) | 5 (HT DCLL) 3 RAFM+1.5 Alumina + 0.5 RAFM (LT DCLL) |
| Fraction of volumetric heat absorbed by PbLi | 0.78 | 0.78 |

In the long poloidal ducts, the MHD pressure drop originates from the nearly fully developed flows where the flow opposing electromagnetic forces arise from the interaction between the induced cross-sectional currents closing in the toroidal-radial plane and the strong plasma-confining toroidal magnetic field. These currents can significantly be reduced by the insulating FCI compared to a flow in a fully conducting duct without an FCI. To serve well its insulating functions, the FCI has to have sufficiently low electrical and thermal conductivity. The requirements on SiC materials for the DCLL blanket under conditions of ITER TBM and DCLL DEMO were formulated in [19,26]. For a 5-mm FCI, the goal was to provide low thermal conductivity of 1–2 W/m-K and electrical conductivity of about 1 S/m for inboard blankets. Higher electrical conductivities of about 50 S/m were found to be sufficient in lower magnetic field outboard blankets.

The degree of the pressure drop reduction is the highest (a few orders of magnitude [19]) when a low-conductivity SiC FCI is used. The sandwich FCI utilized in the present LT DCLL design (Fig. 3) is less effective as an electrical insulator because the induced electric current from the bulk flow can close through a thin 0.5 mm RAFM liner. Correspondingly, the pressure drop reduction by a sandwich FCI is significantly lower compared to the SiC FCI. The difference can especially be important for IB blankets for which the magnetic field is about two times higher. In the present study, the MHD pressure drop in the poloidal flows with the FCI, SiC or sandwich, was computed with the help of a fully developed flow model and a 2D numerical MHD solver developed in [20]. In these recent computations the electrical conductivity of the SiC FCI was chosen at 10 S/m. This relatively low value is needed to minimize the pressure drop in the IB blanket. For the OB blanket, higher (up to 50 S/m) electrical conductivities seem to be acceptable.

Computed velocity distributions in the poloidal flow with the FCI for the IB blanket are shown in Fig. 4. The PbLi flow in the duct with a sandwich FCI demonstrates very high velocity jets at the two side FCI walls (walls parallel to the applied toroidal magnetic field) (Fig. 4a). The maximum velocity in the jets in the bulk flow is about twenty times higher than the mean bulk velocity, i.e. around 2.5 m/s. In practice, such a jet flow will likely demonstrate instabilities and vortex formation [22] resulting in a turbulent flow regime.

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