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MHD and heat transfer considerations for the US DCLL blanket for DEMO and ITER TBM

Sergey Smolentsev[a,*], Neil B. Morley[a], Clement Wong[b], Mohamed Abdou[a]

[a] *University of California, Department of Mechanical and Aerospace Engineering, 43-133 Engineering IV, Los Angeles, CA 90095-1697, USA*
[b] *General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA*

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ABSTRACT

We summarize here the results of ongoing studies for magnetohydrodynamic (MHD) flows and heat transfer in the eutectic alloy lead–lithium (PbLi), which is used as a breeder and coolant, for three US Dual-Coolant Lead–Lithium (DCLL) blanket scenarios: ITER H-H, ITER D-T, and DEMO. The paper focuses on the important blanket feasibility issues, such as the MHD pressure drop, heat leakages from PbLi into the cooling helium flows, and the temperature distributions in the insulating flow insert and at the material interface. Both ITER scenarios look acceptable, i.e., all material restrictions can be easily met. In the DEMO scenario, the flow insert operates in harsh conditions causing high temperature drop in the insert and high interface temperature between the hot PbLi and the ferritic structure that may exceed the allowable material limits.

1. Introduction

The Dual-Coolant Lead–Lithium (DCLL) blanket is being considered in the US for testing in ITER and as a primary candidate for a DEMO reactor. Details of the DCLL design for ITER Test Blanket Module (TBM) are given in [1]. The reference DCLL DEMO blanket was first introduced in [2], and the design and R&D work on this blanket is currently in progress in the US. In the DCLL blanket, eutectic alloy lead–lithium (PbLi) circulates slowly (∼10 cm/s) as a breeder and coolant, while helium (He) is used for cooling the reduced activation ferritic steel (RAFS) structure. The overall geometry of the blanket modules in ITER and DEMO is similar (Fig. 1). The poloidal length of the module is ∼2 m, while the radial depth is ∼60 cm in DEMO and ∼20 cm in ITER. The module box is strengthened by vertical stiffening plates (grid plates) connecting the first wall panel with a strong back wall. There are additional stiffening plates (separation plates) to separate the two or three rows of poloidal ducts. In what follows we will refer to the poloidal ducts in the row next to the first wall as “front” ducts, while the ducts in the second or third rows are referred to as “return” ducts.

Three blanket scenarios are considered here. In the *ITER H-H scenario*, only the surface heat flux is applied. In this scenario, the PbLi enters the module at 470 °C and leaves it at a slightly lower temperature due to heat leakages from the PbLi into the He. The inlet He temperature is taken at 300 °C to provide test conditions, where the temperature difference between the PbLi and He is maximized. In the *ITER D-T scenario*, both surface and volumetric heating are applied. The peak neutron wall loading is 0.78 MW/m^2; the inlet PbLi temperature is 360 °C and the outlet temperature is 470 °C. The maximum bulk temperature of PbLi in both ITER scenarios is limited to 470 °C to avoid potential material problems, which may occur at higher temperatures. In the *DEMO scenario*, the peak neutron wall loading is 3.08 MW/m^2. Here a high-performance regime is utilized, where the inlet PbLi temperature is 500 °C, while the outlet temperature is 700 °C.

A key element of the DCLL concept is the flow channel insert (FCI) made of silicon carbide (SiC), either as a composite or as foam, which serves as an electrical insulator to reduce the magnetohydrodynamic (MHD) pressure drop, and as thermal insulator to decouple the high temperature PbLi from the RAFS structure. The FCI (typically 5 mm thick) is separated from the RAFS wall by a thin (∼2 mm) gap also filled with PbLi. Both the flow inside the FCI box (bulk flow) and that in the gap are driven by the same pressure head. The gap and the bulk flows are connected through small openings in one of the FCI walls to equalize the pressure on both sides of the FCI. The blanket thermal efficiency is strongly dependent on the insulating properties of the FCI. The desired blanket design requires minimization of heat leakages from the PbLi flows into the He streams, as well as minimization of the MHD pressure drop, while keeping the interface temperature between the PbLi and the RAFS structure below the allowable limits. Meeting all these requirements places special limitations on the FCI design

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[*] Corresponding author. Tel.: +1 310 794 5366.
E-mail address: sergey@fusion.ucla.edu (S. Smolentsev).

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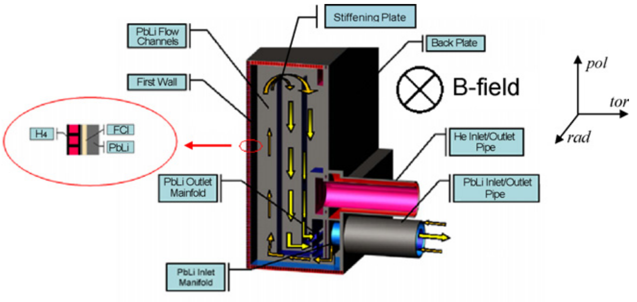

Fig. 1. Sketch of the DCLL DEMO blanket with the flow channel inserts made of silicon carbide. The PbLi flows are shown by arrows.

and SiC material properties: in particular, on its electrical (σ_{SiC}), and thermal (k_{SiC}) conductivity [4]. Preliminary MHD and heat transfer considerations for the DCLL blanket with the FCI are given in [3,4]. In this paper, we present more details based on the most recent numerical calculations, and also extend our analysis to the two ITER scenarios described above. Regarding the DEMO scenario, only the outboard module at the reactor mid-plane (where the thermal load is highest) is currently considered.

2. MHD pressure drop

In all three scenarios, the applied magnetic field is about the same, ∼4 T, while the blanket dimensions and flow rates are larger in DEMO resulting in slightly higher MHD pressure drops compared to ITER. In the ITER TBM, PbLi enters the module at its bottom from the outer annulus of the concentric pipe (details of the concentric pipe design are seen in Fig. 1). From the inlet manifold it is distributed into the three front poloidal rectangular ducts, where it flows upwards. At the top of the module, the PbLi makes a 180° turn and then flows downwards through the return ducts at the back of the module. At the bottom of the module, the liquid is collected and leaves the module from the outlet manifold through the internal tube of the concentric pipe. Electrical insulation of the module is provided via FCIs. The PbLi flows in the blanket can be subdivided into the following components: (A) counter-current flow in the concentric pipe within a near-uniform magnetic field; (B) flow in the concentric pipe in a fringing magnetic field; (C) flow in the inlet manifold; (D) flow in the front ducts, including radial flows at the module bottom and top; (E) flow in the return ducts; (F) flow in the outlet manifold.

Detailed estimations of the MHD pressure drops for all the flows under ITER TBM conditions are given in [5]. Brief description of the numerical procedure for solving MHD equations is given in the next section. The overall MHD pressure drop in the module is ∼0.45 MPa and mostly contributed by 3D flows, such as those in manifolds, where the pressure losses occur due to axial electric currents. These currents close their circuit mostly in the flow domain and cannot be reduced significantly by the FCI, whose main function here is thermal insulation. In the poloidal flows, the MHD drag is caused by cross-sectional electric currents, which close their circuit through the conducting walls, so that electrical insulation via FCIs can be very effective as a means for reducing the MHD pressure drop (Fig. 2). Fig. 2 shows the MHD pressure drop reduction factor *R* defined as the ratio between the MHD pressure drop calculated without the FCI and that with the FCI. The computations were performed for the case without a pressure equalization slot whose effect on the MHD pressure drop was found insignificant [4]. Taking into account that the magnetic field for ITER TBM and the outboard DEMO blanket is not very high (∼4 T), no special requirements on the insulating properties of the FCI are needed for these two DCLL blanket scenarios. As shown earlier [4] even relatively high σ_{SiC} around 500 S/m provides the reduction of the MHD pressure drop in the poloidal flow by a factor of 10. More severe requirements are, however, applied to inboard modules where the magnetic field is about three times higher and effective electrical insulation of the poloidal flows is thus necessary. The computed value of 0.45 MPa is well within the permissible limits (usually <2 MPa).

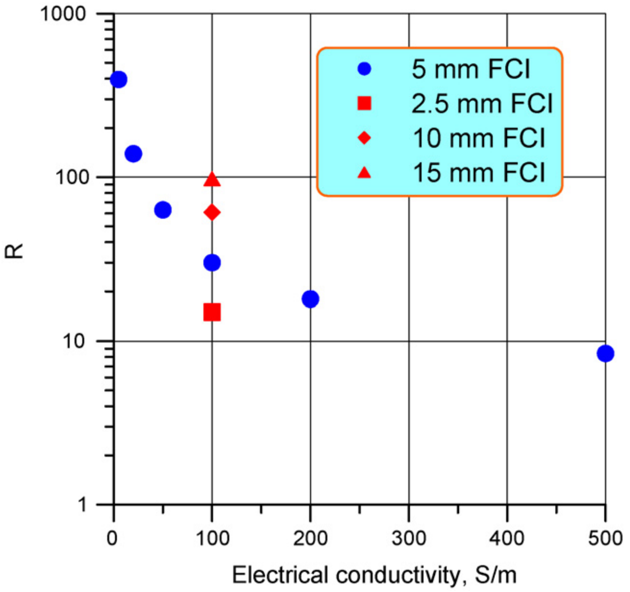

Fig. 2. Effect of the SiC electrical conductivity and the FCI thickness on the MHD pressure drop reduction factor *R* in the poloidal flow for DEMO scenario.

3. Heat leakages into He

Heat leakages into helium can reduce the bulk temperature in the PbLi and degrade blanket's thermal efficiency. A parametric study was performed for the DEMO blanket scenario via numerical simulations to assess heat leakages through the FCI by calculating a ratio $\eta = Q_{PbLi}/Q_{total}$, where Q_{PbLi} is the amount of heat deposited in the PbLi and Q_{total} is the total thermal load per module, including the surface heat flux and bulk heating. The mathematical model used in the computations assumes a fully developed flow [7], either laminar or turbulent [8]. The numerical procedure is similar to that in [4]. First, the velocity is calculated in both the bulk and gap flow, and then the velocity profile is used as input data for the 3D finite-difference heat transfer code to compute the temperature field and heat fluxes in the multi-material domain, which includes the PbLi flows, SiC FCI, and the RAFS structure. The velocity distribution is calculated using a multi-material MHD code [6], which solves the momentum equation for a fully developed flow along with the induction equation by a finite-volume technique. The calculated induced magnetic field is used to calculate the electric current components and then the Lorentz force term entering the momentum equation. Fig. 3 shows the bulk temperature as a function of the poloidal distance as the liquid proceeds through the front duct at the first wall and then through the two return ducts at the back of the module. In the case of ideal thermal insulation, all heat generated in the PbLi remains in the flow resulting in a continuous temperature increase. In the "real" case (where the thermal conductivity is finite), the bulk temperature in the two return ducts can drop due to heat losses through the FCI. Fig. 4 summarizes numerical data for η for various flow conditions. The maximum achievable η is ∼60%. As computations show, at $k_{SiC} = 1$ W/m K, the heat losses become almost independent of the electrical conductivity of the

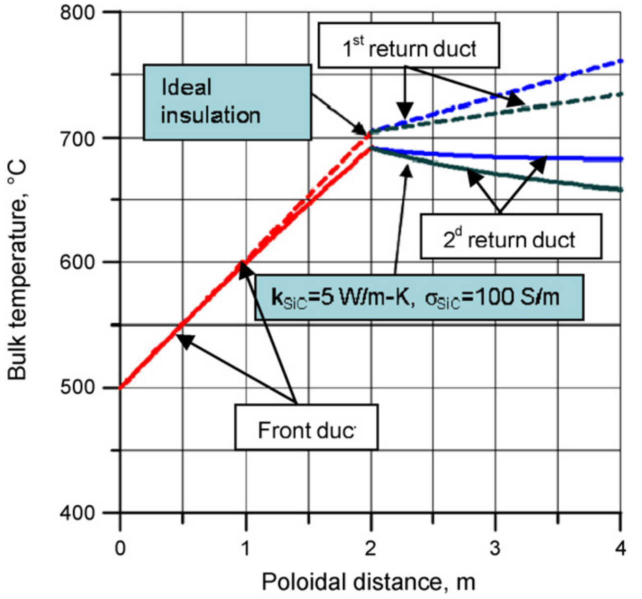

Fig. 3. Bulk temperature variations in the PbLi for the DEMO scenario as the PbLi proceeds through the front and then two return ducts.

FCI and the flow regime. In these conditions $\eta = 55\%$. The possibility to achieve $k_{\mathrm{SiC}} = 1$ W/m K in the blanket environment should be addressed via material studies.

4. Temperature difference across the FCI; interface temperature

The temperature data were also used to evaluate the temperature difference across the FCI walls (ΔT_{FCI}) and the interface temperature between the PbLi in the gap and the RAFS wall (T_{int}). The former is responsible for the thermal stress in the FCI and should be kept within ~200 K, while the latter is limited to ~(470–480) °C based on the allowable corrosion rate. As the present calculations show, both ITER scenarios in normal conditions look to be acceptable, i.e., all restrictions on the interface temperature and the thermal stress in the FCI can be easily met. Even in abnormal conditions (for the ITER D-T scenario), when the flow rate in one of the ducts is reduced by a factor of two, all the parameters are well within the allowable limits.

In the ITER H-H scenario, the goal is to establish "test" conditions by maximizing the temperature difference between the cooling helium and the PbLi. This temperature difference drives heat leakages into the helium streams, resulting in ~(20–30) K decrease in the PbLi bulk temperature at the exit. At the same time the maximum calculated ΔT_{FCI} is ~100 K. All calculated temperature variations are very pronounced and can be measured easily when doing experiments in ITER.

In the DEMO scenario, where volumetric heating and the PbLi operation temperature are sufficiently higher, the FCI operates in harsh conditions that may result in intolerably high thermal stresses. The FCI electrical conductivity, which is responsible for the shape of the velocity profile and even for the flow regime, has a very strong effect on ΔT_{FCI}. Increasing σ_{SiC} results in higher flow velocities at the front and back FCI walls and lower velocities over the central area and at the lateral walls. As a result, the temperature difference decreases across the front FCI wall, but it increases across the lateral walls. For example at $\sigma_{\mathrm{SiC}} = 1$ S/m, maximum ΔT_{FCI} for the front FCI wall in the front duct is 320 K, while for the side wall it is 190 K. At $\sigma_{\mathrm{SiC}} = 100$ S/m, corresponding temperature differences are 140 and 500 K. A parametric study (using σ_{SiC} and k_{SiC} as parameters) was performed to find σ_{SiC} leading to reasonably low ΔT_{FCI} for all FCI walls in both front and return ducts. It was found that at $\sigma_{\mathrm{SiC}} = 20$ S/m the maximum temperature differences are 200 and 240 K correspondingly (Fig. 5). These values are still high and

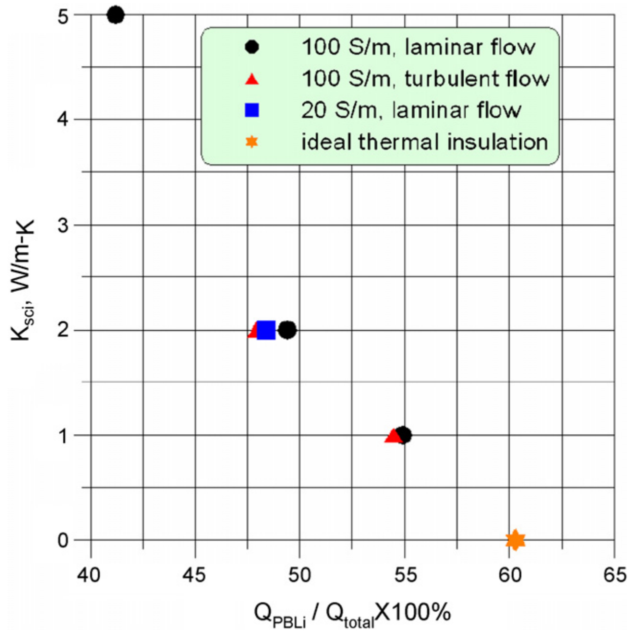

Fig. 4. Effect of the electrical and thermal conductivity of the FCI and the flow regime on heat losses in the DEMO blanket.

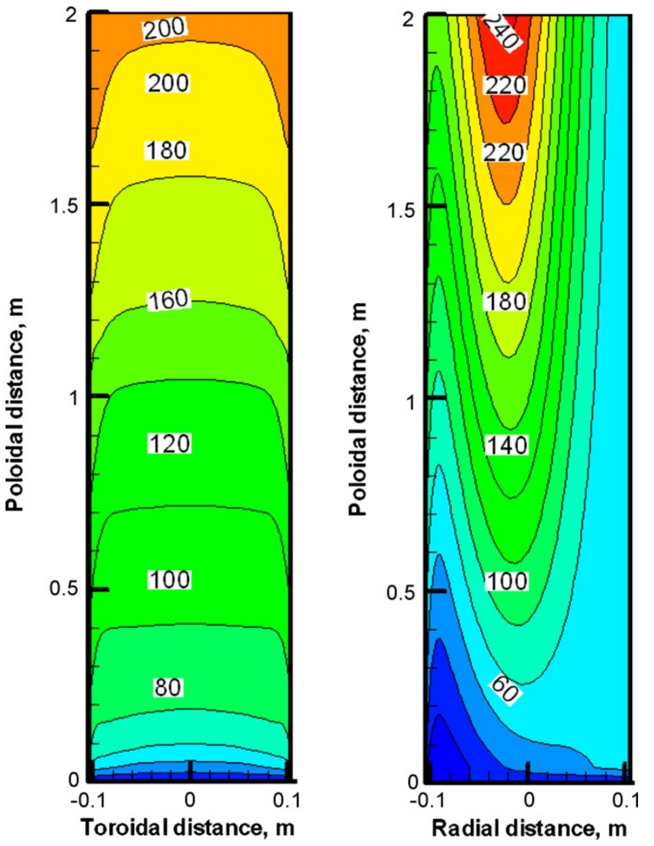

Fig. 5. Temperature difference across the FCI. Front duct. Left: front FCI wall. Right: side FCI wall. $\sigma_{\mathrm{SiC}} = 20$ S/m. $k_{\mathrm{SiC}} = 2$ W/m K.

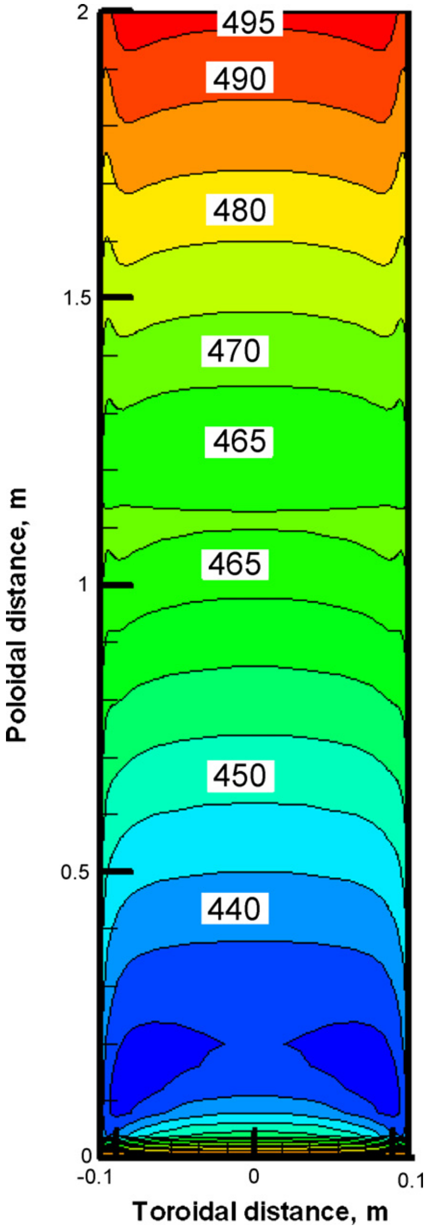

Fig. 6. Interface temperature. Front duct. Front surface. σ_{SiC} = 20 S/m. k_{SiC} =2 W/m K.

further design optimizations are needed. There are also concerns regarding the interface temperature (Fig. 6), which is also higher than the allowable limit at some locations.

5. Concluding remarks

Excessively high ΔT_{FCI} and T_{int} seem to be a critical issue for the existing US DEMO blanket design. Some design improvements can, however, be suggested to mitigate these potential problems. The interface temperature at the locations where it is too high can be reduced by increasing locally the heat transfer coefficient in the He flow by increasing its velocity or applying a heat enhancement technique, e.g. artificially roughened walls. To decrease the temperature difference across the FCI, a “nested” (double-layer) FCI will be considered. Another possible approach is using a variable thickness (or variable electrical conductivity) flow insert to reduce ΔT_{FCI} by affecting the velocity profile.

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