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Numerical analysis of MHD flow and heat transfer in a poloidal channel of the DCLL blanket with a SiC_f/SiC flow channel insert

S. Smolentsev [a,*], M. Abdou [a], N.B. Morley [a], M. Sawan [b], S. Malang [c], C. Wong [d]

[a] MAE Department, UCLA, 44-114 Engineering IV, Box 951597, Los Angeles, CA 90095, USA
[b] University of Wisconsin-Madison, 1500 Engineering Dr., Madison, WI 53706, USA
[c] Fliederweg 3, D 76351 Linkenheim-Hochstetten, Germany
[d] General Atomics, Box 85608, San Diego, CA 92186, USA

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Abstract

MHD flow and heat transfer have been analyzed for a front poloidal channel in the outboard module of a Dual Coolant Lithium Lead (DCLL) blanket, with a flow channel insert made of a silicon carbide composite. The US reference DCLL blanket module [C. Wong, S. Malang, M. Sawan, S. Smolentsev, S. Majumdar, B. Merrill, D.K. Sze, N. Morley, S. Sharafat, P. Fogarty, M. Dagher, P. Peterson, H. Zhao, S. Zinkle, M. Youssef, Assessment of liquid breeder first wall and blanket options for the DEMO design, in: Proceedings of the 16th ANS TOFE Meeting, Madison, September 14–16, 2004.] has been considered. Effectiveness of the insert as insulator was assessed via numerical simulations based on a 2D model for a fully developed flow and on a 3D model for heat transport. Parametric studies were performed at $\sigma = 5\text{–}500\,(\Omega\text{m})^{-1}$ and $k = 2\text{–}20$ W/m K. Parameters resulting in a reasonably low MHD pressure drop and almost no heat leakage from the breeder into the cooling helium flows have been identified.

Keywords: DCLL blanket; Magnetohydrodynamics; Heat transfer

1. Introduction

Using flow channel inserts (FCIs) made of a silicon carbide composite (SiC_f/SiC) for electrical insulation was proposed in [2]. This idea takes central place in several blanket concepts [1]. It is also a candidate for tests in ITER [3]. The main attraction of FCIs is that SiC_f/SiC has low electrical and thermal conductivity, allowing for sufficient reduction of the MHD pressure drop and heat loss. At the same time, the FCI does not serve as a structural element and carries only low stresses.

In the present analysis, the US reference Dual Coolant Lithium Lead (DCLL) blanket is considered [1]. Reduced activation ferritic steel is used as the struc-

* Corresponding author.
E-mail address: sergey@fusion.ucla.edu (S. Smolentsev).

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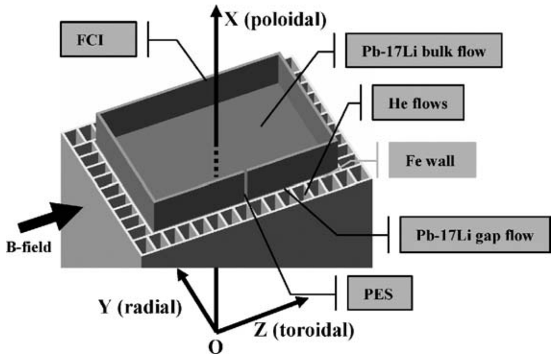

Fig. 1. Typical poloidal blanket channel with FCI and helium cooling channels. Location of some of the helium channels is different for the front and return channels.

tural material. Helium cools the fist wall and blanket structure, and the self-cooled breeder, Pb–17Li, circulates for power conversion and tritium breeding. A key element of the concept is the SiC_f/SiC FCI (Fig. 1) used as electric and thermal insulator. In the module, the Pb–17Li moves upward through the front channel, and then downward through two return channels. The Pb–17Li flow both in the gap between the FCI and the wall and inside the FCI is driven by the same pressure head. There can be openings in one of the walls of the FCI to equalize the pressure on both sides of the FCI: either pressure equalization holes (PEH) or a pressure equalization slot (PES). The basic parameters are summarized in Table 1. We will refer to the flow inside the FCI as “bulk flow”, and that in the gap as “gap flow”. The channel sizes are identified with the internal FCI dimensions.

Table 1
Parameters for the front poloidal channel of the reference DCLL blanket

Poloidal length: 2 m	Magnetic field (outboard): 4 T
Channel sizes: 0.3 m (toroidal), 0.2 m (radial)	Pb–17Li mean flow velocity: 0.06 m/s
FCI thickness: 0.005 m	He temperature: 400 °C
Gap width: 0.002 m	Inlet Pb–17Li temperature: 460 °C
Ferritic wall thickness: 0.005 m	Heat transfer coefficient in He: 4000 W/m^2 K
PES width: 0.005 m	

2. Mathematical model and computer code

The mathematical model assumes 2D fully developed flow and 3D heat transfer. The problem is formulated in terms of the flow velocity (U), induced magnetic field (B_x) and temperature (T). Details of the mathematical model and the computer code are explained in [4]. The volumetric heating q'''_T is determined from neutronics calculations using the code DANTSYS [5]. The results for the radial variation of nuclear heating are then approximated as a function of the radial depth s: $q'''_T = 30 \times 10^6 \exp(-10s)$, W/m^3. In the calculations, $Ha = 15{,}900$.

3. Physical properties

Physical properties of a composite depend on the fabrication techniques, impurities, dopants, and interphase materials. The electrical conductivity for a sample fabricated by polymer impregnation pyrolysis is $\sigma = 22\,(\Omega\text{m})^{-1}$, while for samples made by chemical vapor infiltration $\sigma = 650\,(\Omega\text{m})^{-1}$ [6]. For typical 3D low porosity composites, $k = 15$ W/m K [6]. Lower values can be achieved with a 2D woven, lower density composite. Some reduction in σ and k has been reported under neutron irradiation [7]. One should also take into account differences in physical properties along and across the fibers. In the present study, we perform calculations in a parametric form. The electrical conductivity of SiC_f/SiC varied from 5 to 500 $(\Omega\text{m})^{-1}$ and thermal conductivity from 2 to 20 W/m K. Advice from material experts indicates that the lower values are in fact achievable. A thin sealing layer of crystal SiC was assumed at all surfaces of the FCI to prevent penetration of liquid metal.

4. MHD flow

Computations were performed for two types of pressure equalization openings. The discrete holes in the PEH case are placed along the channel axis, far apart. In the PES case, the axial slot is located at the center of one of the FCI walls, going over the whole poloidal length of the channel. Here, we consider PES in the side wall of the FCI (the wall parallel to the magnetic field).

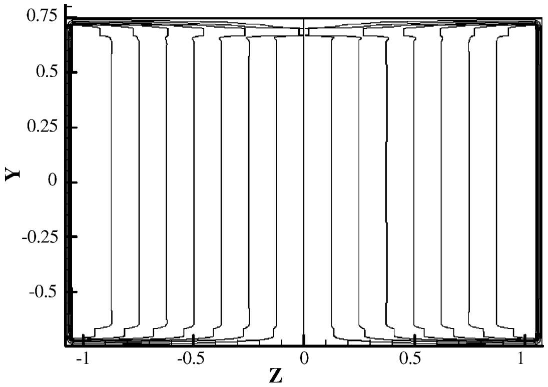

Fig. 2. Induced magnetic field distribution in the domain with PES.

Electric currents generated in the bulk flow leave the internal domain through one of the FCI side walls and the opening, and return back through the opposite wall (Fig. 2). When interacting with the toroidal magnetic field, the induced currents create Lorentz force, which is responsible for special "M-type" velocity profiles (Fig. 3). In all figures, the velocity is scaled by the mean flow velocity of the bulk flow. The high velocity jets near the side walls reduce strongly as σ decreases. However, even at $\sigma = 5\,(\Omega\mathrm{m})^{-1}$, the jets do not fully disappear, indicating that electrical insulation is not perfect. In the flows with PES, reverse flows appear in the vicinity of the slot caused by high concentration of the induced currents in this region. The velocity is different in the two sections of the gap. In the "Hartmann gap" (the gap with a longer side perpendicular to the magnetic field), the flow is almost stagnant. In the other gap section ("side gap"), the electric current flows parallel to the magnetic field resulting in no Lorentz force and thus allowing for much higher velocities.

Reduction of the MHD pressure drop by the FCI is significant: a factor of 10 reduction at $\sigma = 500\,(\Omega\mathrm{m})^{-1}$, and a factor of 200–400 reduction at $\sigma = 5\,(\Omega\mathrm{m})^{-1}$, as compared to the case without insulation. The case with PEH suggests better reduction of the MHD pressure drop. The difference in the MHD pressure drop between these two cases becomes more important as σ decreases, reaching two times at $\sigma = 5\,(\Omega\mathrm{m})^{-1}$.

5. Heat transfer

Heat transfer simulations were performed for the case with PEH. The key points in the heat transfer optimizations are: minimization of heat losses from the liquid metal; reduction of temperature stresses in the FCI; and ensuring the temperature at the interface is below its corrosion limit. Temperatures at the edges

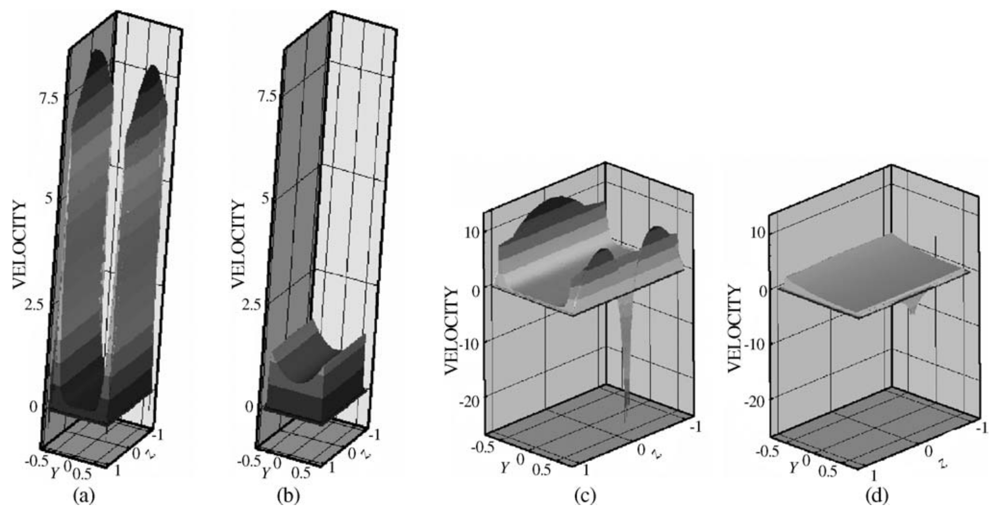

Fig. 3. Velocity profiles in the reference MHD flow: PEH, $\sigma = 500\,(\Omega\mathrm{m})^{-1}$ (a); PEH, $\sigma = 5\,(\Omega\mathrm{m})^{-1}$ (b); PES, $\sigma = 500\,(\Omega\mathrm{m})^{-1}$ (c); PES, $\sigma = 5\,(\Omega\mathrm{m})^{-1}$ (d). The velocities are scaled with the mean velocity in the bulk flow.

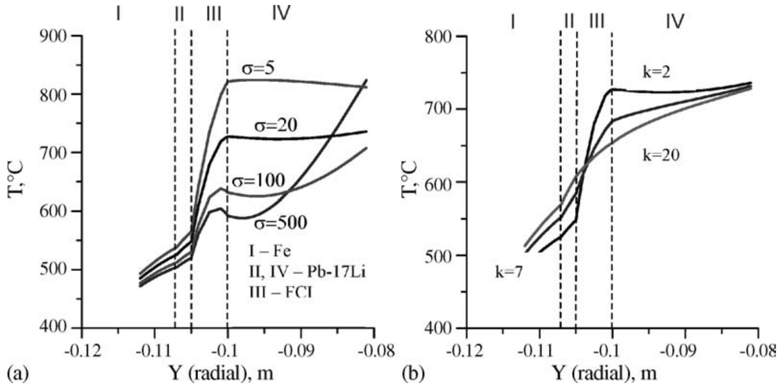

Fig. 4. Radial temperature variations in the vicinity of the front wall at the flow exit calculated at $k = 2$ W/m K (a); $\sigma = 20\,(\Omega\text{m})^{-1}$ (b).

of the domain are mostly controlled by the helium flows, while the temperature field in the central part is affected by the liquid metal flow. Fig. 4 shows the effect of σ and k on the radial temperature distribution at the channel top in a narrow region facing the first wall. The effect of k is obviously thermal insulation of the bulk flow region. The influence of σ is not so simple, since its variations result in significant changes of heat transfer through modifications of the liquid metal flows. Reduction of σ causes bigger temperature difference across the FCI, and hence higher thermal stresses. It also leads to higher interface temperatures between the ferritic wall and liquid metal. At the same time, reduction of σ is desirable because of smaller pressure losses. Therefore, reduction of σ may lead to ambiguous consequences on the blanket performance.

Heat losses from the bulk flow region through the FCI into the helium can be minimized by changing k and σ from the relevant range. At $k = 2$ W/m K almost no leakage from the bulk flow occurs, indicating ideal thermal insulation conditions. Thus, the only heat losses into the helium flow in this case occur from the external sub-domain that includes the ferritic wall, gap and the FCI. The heat losses from the external sub-domain were calculated as 23% of the total heat generated in the channel. Small reduction of heat losses from the external sub-domain can be achieved through higher σ by providing conditions wherein some amount of heat generated in the FCI will be taken by the bulk flow. However, such a reduction seems to be too small to be useful.

6. Concluding remarks

Basic characteristics of MHD flow and heat transfer in the front poloidal channel of the DCLL blanket were studied. Parameters of the SiC_f/SiC FCI have been identified that result in low MHD pressure drop and almost no heat leakage from the breeder into the helium flows. The results show that the MHD pressure drop can be reduced by 400 times as compared to the case without insulation if electrical conductivity of a silicon carbide composite is $5\,(\Omega\text{m})^{-1}$. This conclusion, however, does not apply to liquid metal flows in other sections of the blanket module, where the MHD pressure drop is mostly associated with the axial currents. It has been observed that if the thermal conductivity of SiC_f/SiC is 2 W/m K or lower, the FCI acts as an ideal thermal insulator. However, these values should be corrected if the design parameters are different. More improvements should be included in the future for better estimation of the blanket performance. These modeling efforts should be accompanied with a broad materials program to develop fabrication techniques for the silicon carbide inserts and characterize their properties. Development of broad experimental MHD studies is also necessary.

Acknowledgements

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