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Insulating performance requirements for the coating material in the ITER DFLL electromagnetic TBM based on the MHD analysis

H. Chen *, T. Zhou, R. Lü, Z. Yang, Z. Wu, D. Xia

Institute of Plasma Physics, Chinese Academy of Sciences, School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, Anhui, China

ABSTRACT

A Chinese Dual-Functional Lithium Lead (DFLL) Electromagnetic Test Blanket Module (EM-TBM) is proposed for testing in ITER from the first day of operation for the main test objectives of the electromagnetic performances and MHD effects. The insulating coating has been designated in LiPb flow channels to reduce magnetohydrodynamic (MHD) effect. The MHD pressure drop is theoretically calculated and the influences of the coating electrical resistance and the crack fraction through the coating layer on MHD pressure drop are analyzed. The insulating performance requirements for the coating material are proposed for the EM-TBM based on above analyses. And some R&D issues about coating material and fabrication technology also have been presented in the end.

1. Introduction

The Dual-Functional Lithium Lead (DFLL) – Test Blanket Module (TBM) system [1,2] for ITER is proposed to check and validate the relevant technologies of several conceptual designs of Chinese liquid Lithium Lead (LiPb) breeder blankets including Quasi-Static Lithium Lead (SLL) and Dual-cooled Lithium Lead (DLL) blanket technology [3–6]. For consecutively validating the integrated technologies of both SLL and DLL blanket concepts, four full-scale blanket modules have been designated for DFLL–TBM during the different phases of the first 10 years of ITER operation, namely the EM (Electro-magnetic)-TBM, NT (Neutronics)-TBM, TT (Thermo-fluid and Tritium)-TBM and IN(Integrated Performances)-TBM, with as similar as possible basic structure, material and auxiliary systems.

Magnetohydrodynamic (MHD) pressure drop is a key consideration in these series liquid metal modules. To reduce MHD pressure drop of liquid metal flow, different insulating methods are proposed in these series modules. The SLL blanket technology will be tested in the EM/NT-TBM phases with relatively low flow velocity and relatively low temperature of liquid metal LiPb and the insulating coating is designated in LiPb flow channels to reduce MHD effects. The DLL blanket technology will be tested in the later TT/IN-TBM phases with relatively high flow velocity and relatively high temperature of LiPb and the flow channel inserts (FCIs) are considered to reduce MHD pressure drop and to improve the outlet temperature of LiPb.

The work on MHD pressure drop and the influences of the coating electrical resistance on liquid metal blanket have been made many years ago in Refs. [7–10]. The MHD pressure drop under coating scenario for EM-TBM is assessed in this paper. The theoretical calculations of the influence of the coating electrical resistance and the crack fraction through the coating layer on MHD pressure drop are provided. The insulating performance requirements for the coating material are proposed for the EM-TBM based on these analyses.

2. Blanket configuration

The design of EM-TBM is based on the common architecture that was developed for Chinese DEMO LiPb blankets. The structural material is made of the reduced activation Ferritic/Martensitic steel, e.g. CLAM (China Low Activation Martensitic steel) [11]. The rectangular steel structure box which has the dimensions of 484 mm (t) × 1660 mm (p) × 585 mm (r) is designed to fit the test port geometry of ITER. As schematically shown in Fig. 1. The TBM box is reinforced by one radial–poloidal (rp) and four ⌉-shaped toroidal–poloidal (tp) stiffening plates (SPs) which create 6 large liquid metal ducts oriented in the poloidal direction except for the short inlet/outlet of the ducts in the radial direction. The Al_2O_3 coating is designated as electrical insulators inside the LiPb channels to reduce the MHD pressure drop. Main characteristics and design parameters of EM-TBM are shown in Table 1.

3. MHD pressure drop in EM-TBM

MHD pressure drop is analyzed by theoretical calculation. Considering the complex geometries of the LiPb flow inside the module, the flow can be subdivided into following several components.

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* Corresponding author.
E-mail address: hlchen@ipp.ac.cn (H. Chen).

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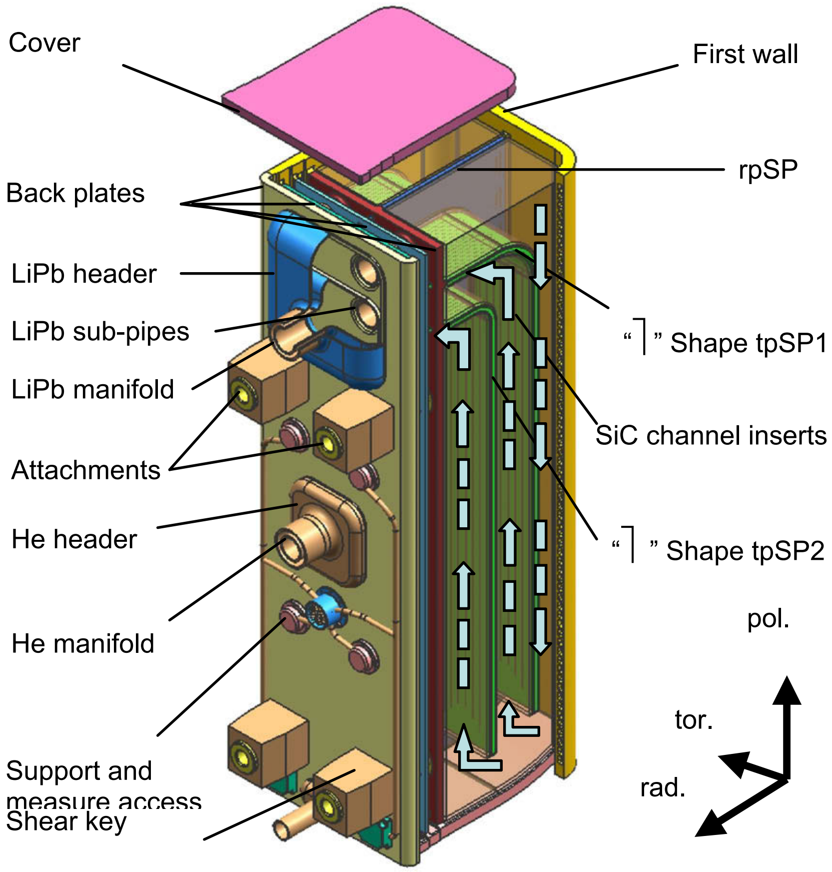

Fig. 1. 3D structure view of EM-TBM.

(1) Flow in the front channels including radial flows at the module bottom and top.
(2) Flow in the return channels.
(3) Flow in the contraction/expansion.
(4) Flow in the inlet/outlet manifold.
(5) Flow in the concentric pipe within a near-uniform magnetic field.
(6) Flow in the concentric pipe in a fringing magnetic field.

Table 1
Main characteristics and design parameters of EM-TBM.

	Parameters
Heat flux	Average 0.15, maximum 0.3 (MW/m^2)
Structural material	China low activation martensitic steel (RAFM Steel)
TBM dimensions	Poloidal 1660 mm × toroidal 484 mm × radial 585 mm Gap between TBM and frame = 20 mm
Total deposited power	Average 0.12, maximum 0. 24 (MW)
Magnetic field	4 T
He coolant	$T_{\mathrm{in/out}}$ = 300/366 °C; P_{in} = 8 MPa; Q_{tot} = 0.35 kg/s
First wall	U-shape; toroidal He cooling; 4 paths; thickness: 30 mm (5/15/10) Cooling channels: (15 × 20) mm^2, pitch 25 mm $T_{\mathrm{in/out\ He}}$ = 300/366 °C; V_{He} = 11 m/s
r–p stiffening plate	Thickness: 10 mm (3/4/3); cooling channels: (4 × 9)mm^2, pitch 12 mm $T_{\mathrm{in/out\ He}}$ = 366/366 °C; V_{He} = 14 m/s
t–p stiffening plate	Thickness: 10 mm (3/4/3); cooling channel: (4 × 8) mm^2, pitch 11 mm $T_{\mathrm{in/out\ He}}$ = 366/366 °C; V_{He} = 14.7 m/s
Cover	Thickness: 32 mm; 8 parallel cooling channels; (8 × 16) mm^2, pitch13 mm $T_{\mathrm{in/out\ He}}$ = 366/366 °C; V_{He} = 14 m/s
He collector	3-stage collector; radial direction size: 20/30/10/30/10/30/20 mm
Breeder/multiplier LiPb	2 rows poloidal flowing channel V_{LiPb} = 3/1.2/1.2 mm/s; V_{LiPb} = 1.28 kg/s; $T_{\mathrm{in/out}}$ = 366/366 °C

Flow in the poloidal front channels with radial sections. The flow in the long poloidal channels is approximately fully developed. For fully developed flow in a rectangular duct with insulating coating of uniform thickness t_i, the MHD pressure drop is given by [12,13]

$$\frac{dp}{dx} = \sigma VB^2 \frac{1}{1 + \frac{\rho_i t_i M}{p_i t_i + 2bM\rho}}, \tag{1}$$

where ρ_i and ρ are the electric resistivity of the insulating coating and coolant, respectively. σ is the liquid metal's electric conductivity, V is the average flow velocity, B is the magnetic flux density, M is the Hartmann number, b is one half the channel radial width perpendicular to B.

The electric insulation effectiveness of the coating is mainly characterized by the ratio $\rho_i t_i$ to $2bM\rho$. So the MHD pressure drop mainly depend on the ratio $k = \rho_i t_i / 2bM\rho$ and keep low level when the electrical resistance approaches high.

Flow in the poloidal return (back) channels. The analysis for the back channel is similar to that for the front channels. The MHD pressure gradient mainly depend on the ratio $k = \rho_i t_i / 2bM\rho$.

Flow in the contraction/expansion. The flow changes in the connecting components form abrupt expansion or contraction that causes strong 3D effects with associated pressure drop.

Experimental observation for MHD pressure drop in 3D elements can be correlated by the empirical relation [14]

$$\Delta p = \zeta \frac{1}{2} \rho v^2, \quad \text{with } \zeta = f(N, M), \tag{2}$$

where ζ is the coefficient of local MHD resistance, N stands for the interaction parameter. $\zeta = 0.5N$ is chosen for the present estimates.

The 3D MHD effects are not eliminated by the insulation of the flow wall because currents shortcut in the liquid metal and not only along the walls. The parameters of the coating insulating material have no influence on the 3D MHD pressure drop.

Flow in the inlet/outlet manifold. The MHD pressure losses of LiPb flow in manifold are associated with the axial currents and cannot be eliminated by insulation. This part of MHD pressure drop is analyzed by the following formula recommended in Ref. [15]:

$$\Delta p = 1/2 \rho v^2 k M^2 / Re. \tag{3}$$

For the different geometries reported in special literature [16], recommended values for k range from 0.25 to 2. Taking into account the complex fluid redistribution in the manifold, we use here $k = 1$.

Flow in the concentric pipe within a near-uniform magnetic field. Analysis for the annulus and internal concentric pipe within a near-uniform magnetic field is similar to that for the poloidal channels. MHD pressure drop can be computed by Eq. (1) and mainly depend on the ratio $k = \rho_i t_i / 2bM\rho$.

Flow in the concentric pipe in a fringing magnetic field. Reliable techniques for calculating MHD pressure drop for flows in a fringing magnetic field are not available. This part of MHD pressure loss is associated with the axial currents. Assessment of the pressure drop with 3D effect can be correlated by the empirical relation (2) and almost has nothing with the coating insulation effectiveness.

These MHD empirical relations show the MHD pressure drop has relationship not only with channel geometry, flow velocity and magnitude of magnetic field, but also with the electrical insulation effectiveness of coating, including the electrical resistivity, thickness and integrality. In order to get insulating performance requirements for the coating material, the influence of the electrical insulation effectiveness on MHD pressure drop is analyzed below.

4. Coating influences on MHD pressure drop and performance requirements

4.1. Effect of electrical resistance

MHD pressure drop in the channels or pipes within the uniform or near-uniform magnetic field strongly depends on the coating electrical resistance $\rho_i t_i$ while the 3D MHD effect almost has nothing to do with it. Fig. 2 gives the total MHD pressure drop of EM-TBM as a function of $\rho_i t_i$. It shows that the MHD pressure drop is reduced as the electrical resistance increases, and it can be reduced to the level with perfect electrically-insulated wall when $\rho_i t_i$ is higher than 0.01 $\Omega\,\text{m}^2$.

So the sufficiently high electrical resistance is an important requirement for the coating performance. The electrical resistivity of the coating should be higher than $10^3\,\Omega\,\text{m}$ corresponding to 10 μm thickness under irradiation. The Al_2O_3 coating is recommended as candidate electrical insulator for EM-TBM. The electrical resistivity of Al_2O_3 without irradiation ranges from $1.0 \times 10^{14}\,\Omega\,\text{m}$ at 20 °C to $3.0 \times 10^{10}\,\Omega\,\text{m}$ at 400 °C [17]. However, under irradiation, the electrical resistivity will be degraded. For the ionizing radiation levels in the blanket modules, Al_2O_3 has resistivity in the range of about 1 to $10^7\,\Omega$ m. i.e. about 3–4 orders of magnitude less than without radiation. This is only the RIC (Radiation Induced Conductivity), and does not take into account RIED (Radiation Induced Electrical Degradation) which further reduces the resistivity within irradiation time at high temperatures [18]. The thickness of the coating can be assumed to be in the range 10–20 μm. So $\rho_i t_i$ can reach the level of about $10^2\,\Omega\,\text{m}^2$ under irradiation, several orders of magnitude higher than the minimum requirement, which can leave a large margin for degradation while considering RIED or other irradiations and corrosion.

4.2. Effect of crack

The reliability of the insulating coating remains uncertain because of the thermal cycles, corrosion, irradiation or mechanical stresses, which can lead to small cracks through the coating. This can cause significantly higher pressure drop due to the electric currents flowing the conducting wall through the cracks. To keep MHD pressure drop on a low level, the capability of self-healing is necessary for the insulating coating. So the influences of these crack fraction and regenerated capability of self-healing on MHD pressure drop should be considered.

Hua and Gohar [12] have given the detailed study of these influences. They assumed that the cracks are uniformly distributed over the duct wall surface, and at any given time the regenerated layer inside the cracks has been reached a certain fraction of the original coating thickness. The regenerated thickness t is treated as a parameter while t_c is the original coating thickness. The electrical resistivity of the regenerated layer is assumed to be the same with that of original coating, which satisfies the good insulating requirement of 0.01 $\Omega\,\text{m}^2$. Fig. 3 shows the magnitude of the increase in pressure drop as a function of the crack fraction in the case of EM-TBM. It is seen that the pressure drop will increase with the enlargement of crack fraction. But the increase also lies on the regenerated self-healing thickness in the crack area. The more regenerated thickness is, the less the increase. The increase in pressure drop is insignificant even for large crack fraction if thin layers of 1/100 of the original coating thickness are formed inside the cracks in the case of EM-TBM.

So the capability of self-healing in-suit to repair any cracks is another important requirement for the coating performance. Regenerated coating layer can prevent the electrical currents from flowing through the conducting structure and keep MHD pressure

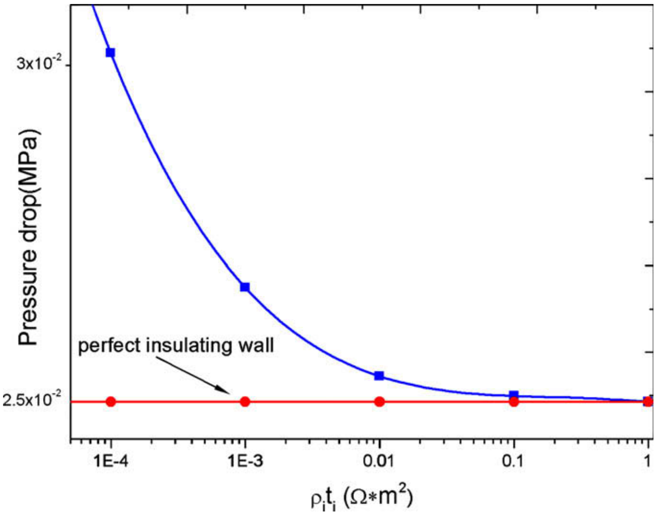

Fig. 2. MHD pressure drop as a function of the coating electrical resistance $\rho_i t_i$.

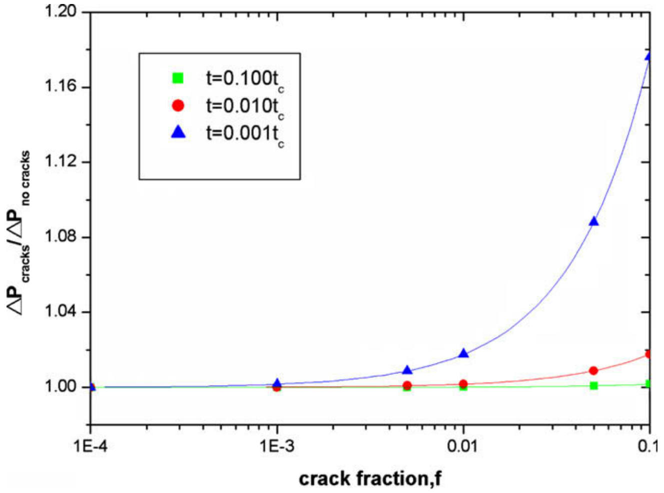

Fig. 3. Influences of the crack fraction on MHD pressure drop.

drop on a low level. The 1/100 self-healing capability which can keep low MHD pressure drop should be needed for the coating material in EM-TBM design.

5. R&D issues

The requirements of the electrical insulator coating material to reduce MHD have been addressed based on the theoretical analyses. However, some R&D issues should be focused on the coating itself. Firstly, the technical feasibility of achieving a stable Al_2O_3 coating inside the blanket channels is a challenge. The thermodynamically stable is reduced under the conditions of elevated temperature, irradiation or corrosion, and the electrical performance is also reduced under these conditions. Secondly, although the capability of self-healing is critical to the coating performance, the regeneration of Al_2O_3 on CLAM in flowing LiPb has so far not been demonstrated experimentally. And moreover, considering the mechanical stability, the coating may not only crack, but flake off the metal surface, which would cause a big MHD pressure drop in the flowing LiPb. The third issue is about the coating fabrication technology and method. Currently, hot dip aluminizing (HDA), physical vapor deposition (PVD), and chemical vapor deposition (CVD) including the APCVD (Atmospheric Pressure CVD), LPCVD (Low Pressure CVD), PECVD (Plasma Enhanced CVD), etc. are being widely studied in the world. For the better film stability, uniformity, and fewer defects, the effective methods, such as HAD and PVD, are being investigated and experimented for the coating fabrication of EM-TBM and liquid metal blanket [19].

6. Summary

EM-TBM will be installed in ITER from the first day of operation for the main test objectives of the electromagnetic performances and MHD effects. The SLL blanket technology will be test in EM-TBM phase with relatively low flow velocity and relatively low temperature of LiPb. To reduce the MHD pressure drop the insulating coating, such as Al_2O_3, is considered as electrical insulators inside the LiPb channels. The MHD pressure drop and the influences of insulating coating electrical resistance and crack fraction through the coating layer on MHD pressure drop are analyzed by the theoretical calculation. The results show the MHD pressure drop may be reduced to the level with perfect electrically-insulated wall if the $\rho_i t_i$ of the insulating coating is higher than 0.01 $\Omega\,m^2$, and the 1/100 self-healing capability should be needed for the coating material when large crack fraction appears in the coating layer. And at last some R&D issues about coating material and fabrication technology have been presented, which will be focused on in the future theoretically and experimentally.

Acknowledgements

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