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Influence of blanket structural materials on liquid metal Pb–17Li flow in the FDS

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Abstract

The Dual-cooled Waste Transmutation Blanket design of the Fusion-Driven Sub-critical System is a dual-cooled liquid metal Pb–17Li and He system with Chinese Low Activation Martensitic steel structure. The effects of the structural material on liquid metal MHD flow, including pressure drop and heat transfer, are presented. The influences of the wall conductance of the duct wall on the MHD pressure drop have been analysed and estimated. The pressure drop is too large to be accepted when Pb–17Li coolant flows in these ducts without insulating coating. This can be improved by using Al_2O_3 electrically insulating coating, while heat transfer must also be cautiously considered.

1. Introduction

The Fusion-Driven Sub-critical System (FDS), which employs the Dual-cooled Waste Transmutation Blanket (DWTB) with Chinese Low Activation Martensitic (CLAM) steel serving as the main structural material and liquid metal Pb–17Li as both coolant and tritium breeding material, provides a feasible, safe, economic and highly efficient potential method of disposing of high level waste. This system has been investigated in ASIPP (Institute of Plasma Physics, Academia Sinica) [1–5]. One of the key feasibility issues of a liquid metal blanket is the impact of the wall conductance on the liquid metal magnetohydrodynamic (MHD) flow i.e., resulting pressure drop, flow distribution, and heat transfer. It is necessary to analyze and numerically simulate the influence of the structural materials on the liquid metal MHD flow in the blanket design of FDS.

The CLAM material, a Chinese version of the low activation ferritic/martensitic steels, serves as blanket structural material in the DWTB. The compatibility of CLAM material with Pb–17Li is expected to improve by changing the contents of specific alloying elements. The influences of the structural material on liquid metal flow in the FDS blanket has been studied by considering the MHD pressure drop and heat transfer, including various finite wall conductances. Analysis and preliminary estimate about MHD flow in ducts with insulating coating Al_2O_3 have been completed.

2. Structural materials

DWTB is one of the promising candidate blankets with an excellent potential for disposing of high level waste (HLW) in the FDS [5]. The outer blanket consists of MA-zone for transmutation of the minor actinides (MA: 237Np, 241Am, 243Am, 244Cm), U-zone for breeding of 239Pu, FP-zone for transmutation (FP: 129I, 99Tc, 135Cs), graphite neutron reflector and CLAM steel structure. Liquid metal Pb–17Li flows rapidly in the square ducts of the DWTB to remove the heating energy of high nuclear power from the blanket. CLAM has been selected as the blanket structural material.

CLAM is one of the reduced activation ferritic/martensistic (RAFM) steels (9Cr1.7WVTa), which has been developed recently in China. The compatibility of CLAM with Pb–17Li is expected to improve by

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changing the contents of specific alloying elements. An insulating coating of Al_2O_3 is used on the inner surface duct wall to reduce MHD pressure drop. Concerning the compatibility of Al_2O_3 material with Pb–17Li, a study has concluded that the coating on the martensistic steel was stable against corrosion in flowing Pb–17Li at 450 °C for 10 000 h [6]. The Al_2O_3 coating has been formed on the surface of the CLAM steel by CVD means in China [7].

3. Analyses of Pb–17Li flow in a duct without insulating coating

The equations describing the steady state, incompressible MHD flow are Navier–Stokes equation, Maxwell's equations, Ohm's law and the mass conservation equation. To solve these equations, certain simplifications can be made. Inertial and viscous forces are important in the boundary layers while in the core flow they are generally negligible. So the fully developed MHD flow is assumed as inertialess, inviscid MHD flow that is governed by the balance between the pressure gradient and the Lorentz force in core of the flow.

The wall material conductance ratio, $c_w = (\sigma_w t_w)/(\sigma_f a)$, is scaled by the fluid conductivity and the dimensionless ratio between the wall material thickness t_w and characteristic length of duct a, where σ_w and σ_f are the conductivity of the wall material and coolant fluid, respectively (see Fig. 1). In general, i.e., $0 < c_w \ll 1$ and $Mc_w \gg 1$ (Hartmann number $M = Ba(\sigma/\eta)^{1/2}$, compared with the coolant the resistivity of the structural material are rather low and finite. Because of the very large electrical resistance of the boundary layers adjacent to these walls, the induced current in the liquid metal coolant flows through the duct wall material. The total current through the wall equals the total current inside the coolant ($tJ_w = -bJ_f$). The thin wall boundary condition is applied as the electrical boundary [8]

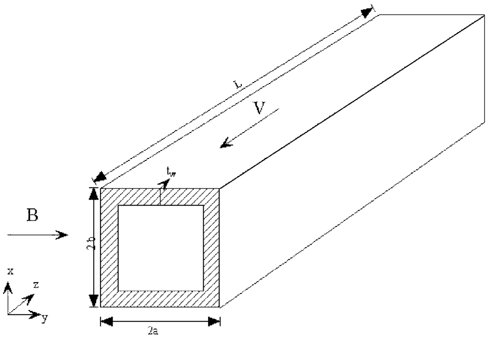

Fig. 1. Schematic of the MHD flow duct in FDS.

$$j \cdot \mathbf{n} = c_w \nabla_w^2 \Phi, \tag{1}$$

where $\mathbf{n}$ is the inward normal unity vector at the wall, ∇_w^2 is the Laplacian in the wall only, and Φ is the electrical potential in the duct wall. This boundary condition enforces the electric charge conservation in the fluid–wall interface and is integrated across the duct wall thickness. The induced current inside the liquid metal is related not only to the duct wall thickness but also to the wall conductance ratio. For a square duct with each side of length a, the electrical potential difference E_x in the duct wall is given by $E_x \sim \frac{J_w}{\sigma_w} \sim \frac{aJ_f}{t\sigma_w} \sim \frac{J_f}{c_w \sigma}$. Then the MHD pressure drop caused by the Lorentz force in liquid metal MHD flow in a square duct is

$$\frac{dp}{dz} = \sigma v B^2 \frac{c_w}{4/3 + c_w}. \tag{2}$$

Fig. 2 shows the dependence of the pressure gradient on the wall conductance ratio c_w. It is important to note that MHD pressure drop mostly depend on the electrical resistivity of the wall material, when the coolant velocity and magnet field are both fixed. The pressure drop reduction becomes significant for the wall material conductance ratio less than 1 ($c_w < 1$). The lower the structure material conductance is, the less the MHD pressure drop is, which is always expected. For the much lower values of the wall conductance ratio, the MHD retarding effects become less important.

In a recently improved DWTB design, the CLAM steel, a RAFM steel, replace the SS316 as structure material. The conductance ratios of structure materials, SS316 and CLAM steel, at various temperatures, are shown in Fig. 3 and it also shows the different pressure drop of MHD flow in ducts with SS316 and CLAM steel wall materials at different temperatures. It is clear that the CLAM steel is superior to SS316 in the high temperature range. However, the CLAM resistivity still is

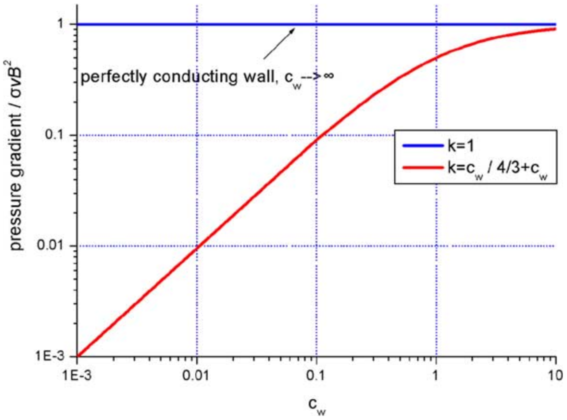

Fig. 2. The dependence of pressure gradient on the wall conductance ratio c_w.

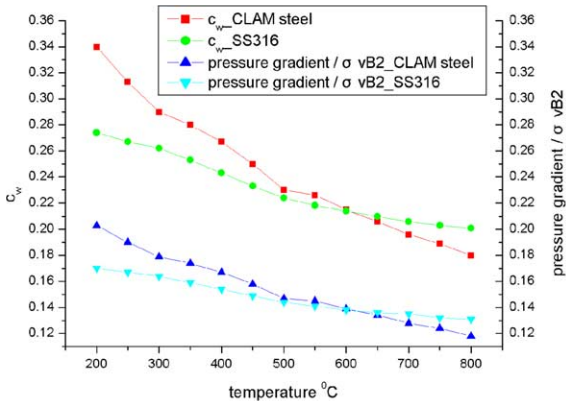

Fig. 3. c_w and pressure gradient on the walls of either SS316 or CLAM at various temperatures.

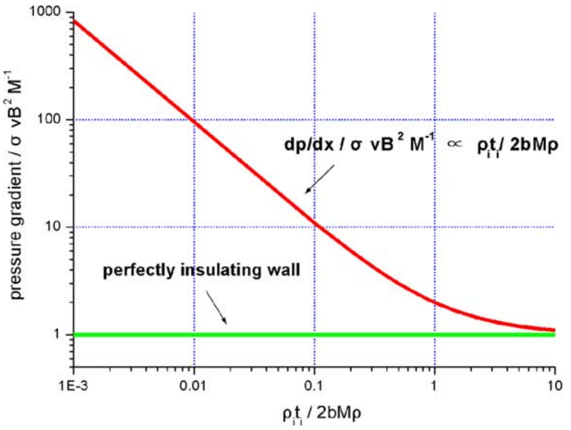

Fig. 4. The pressure gradient in a duct with insulating coating is characterized by the ratio λ.

not high enough that the MHD pressure drop is maintained in an acceptable range for the DWTB, because the coolant Pb–17Li, with velocity about 1.7 m/s, flows perpendicularly to the 5T magnet field. To have acceptable pressure drops it is necessary to decouple the liquid metal coolant from the electrically conducting wall materials.

4. Insulating coating considerations

To reduce the MHD pressure drop, an electrical insulating coating, Al_2O_3, between the wall CLAM material and the liquid metal Pb–17Li coolant, is required for DWTB design. For effective insulation, the coating usually is used on the inner surface of the wall material, which can prevent current circuits from closing through the conducting walls and reduce the total current. For the coating with finite resistance, Hua and coworkers [9] gave the fully developed flow pressure gradient in a duct with insulator coating of uniform thickness t_i as

$$\frac{dp}{dz} = \sigma v B^2 \frac{1}{1 + \dfrac{\rho_i t_i M}{\rho_i t_i + 2bM\rho}}, \tag{3}$$

where ρ_i and ρ are the resistivity of the insulating coating and coolant, respectively. From Fig. 4, the MHD flow pressure gradient mainly depends on the ratio of the insulating coating resistance to the Hartmann layer resistance $\lambda = \rho_i t_i / 2bM\rho$ [10].

When the resistance of the insulating coating is very high ($\lambda > 10$), the MHD pressure drop approaches that in the duct with perfectly insulating wall material. several values of required electrical resistivities properties and the thickness of the insulating coating for different ratios λ are given in Table 1.

However, the reliability of the insulating coating under the fusion reactor blanket conditions remain uncertain because of thermal cycles, corrosions and irradiation, and included cracks, spots and local flaws, which can lead to the resistivity decrease of coating. In practical blanket design, if $\lambda > 0.1$, the MHD pressure drop can be reduced to manageable and acceptable levels. The electrical resistivity of Al_2O_3 without irradiation ranges from 1.0×10^{14}(Ω m) at 20 °C to 3.0×10^{10} (Ω m) at 400 °C [11]. The Al_2O_3 coating has been formed on the surface of the CLAM steel by means of CVD, and its electrical resistivity reaches about 10^3–10^4 ($\Omega\,m^2$) [7]. In the DWTB design, the insulation coating thickness is assumed to be in the range 10–20 (μm), then λ is several orders of magnitude higher than the minimum requirement, which leave a large margin for degradation by radiation, corrosion and thermal cycles. For the above conditions assumed for DWTB design, the total MHD pressure drop in ducts with Al_2O_3 insulating coating is about 0.15 MPa, which corresponded to 1.7 m/s average velocity of liquid metal flow without consideration of 3D effects in inlet/outlet, manifold and bend segments.

Table 1
The thickness requirement for Al_2O_3 insulating coating ($\rho_i = 2.5 \times 10^3$ μΩ)

λ	10	10^3	10^5	10^6	10^7	10^8
$\rho_i t_i$($\Omega\,m^2$)	6.175×10^{-3}	6.175×10^{-1}	6.175	61.75	617.5	6175
t_i(μm)	2.47×10^{-6}	2.47×10^{-4}	2.47×10^{-2}	2.47×10^{-1}	2.47	24.7

5. Heat transfer considerations

The electrical properties of wall materials not only influence the MHD pressure loss but lead to the velocity pattern of MHD flow, and further affect on heat transfer. For the liquid metal MHD flows in the square duct of DWTB, the results of numeral simulation showed that the M-shaped velocity profiles in side layers are formed in the plane perpendicular to magnet field, while this M-shaped velocity doesn't appear in Hartmann layers (see Fig. 5). The velocity structure is strongly dependent on the wall material conductance ratio c_w, and therefore on the current induced in liquid metal. The larger the wall conductance ratio, the higher the high jet velocities are in the side layers.

However, when the insulating coating is used on the inner surface duct wall, the high-velocity jets can be reduced. It is clear that the electrical insulation of wall materials alters the velocity distribution, and the gradual diminution of the high-velocity jets near the side walls depends on increasing the resistivity of the insulation [12]. This reduces heat transfer of liquid metal coolant. It is assumed that the average power density is 100 MW/m^3 in MA-zone and 10 MW/m^3 in U-zone, respectively. From the results on heat transfer, the average side-wall Nusselt number of the perfectly insulated duct is much more than that of the perfectly conducting walls. A 3D computational fluid dynamic code will be used to simulate heat removal in the future work.

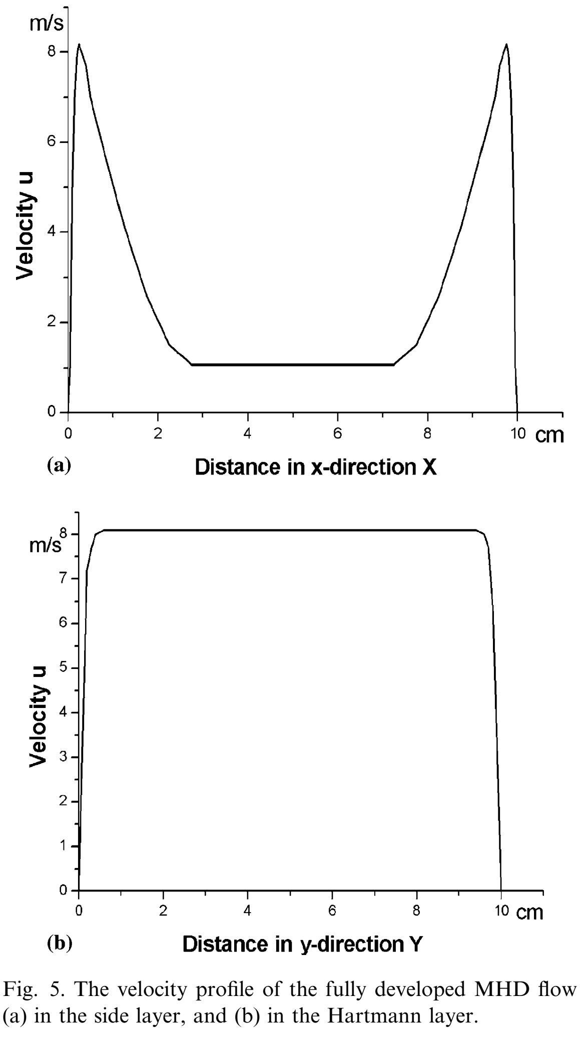

Fig. 5. The velocity profile of the fully developed MHD flow (a) in the side layer, and (b) in the Hartmann layer.

The question then become, is it possible to reduce the pressure drop as well as improve the coolant heat transfer capability? In the DWTB conceptual design, different resistance coatings are used on Hartmann walls and side walls, respectively. This is technically challenging goal, as is the avoidance of cracks, spots and flaws in the insulating coating.

6. Conclusions

The effects of structure material, duct wall conductance ratio, and insulating coating on liquid metal MHD pressure drop and heat transfer have been discussed. The results show the different velocity profiles between the side layer and Hartmann layer in duct with electrical conducting wall materials. The effective insulating coating by Al_2O_3 on the CLAM duct walls can reduce the MHD pressure drop and leave a large margin for degradation in DWTB design of FDS. But it also changes the velocity profile, which may affect the liquid metal heat transfer capability. Further 3D numerical modeling is needed for researching the influence of structure material on coolant velocity and heat transfer.

Acknowledgements

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