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Pressure drop and velocity changes in MHD pipe flows due to a local interruption of the insulation

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ABSTRACT

In liquid metal blanket concepts, such as the dual coolant lead lithium (DCLL) blanket, in which the PbLi serves to cool the breeding zone, the liquid metal has to flow with sufficiently large velocity to guarantee a suitable removal of the volumetric heat generated in the fluid. Large velocities lead to a high pressure drop caused by magnetohydrodynamic (MHD) interactions of the liquid metal with the plasma confining magnetic field. In order to reduce MHD pressure losses in DCLL blankets, it is foreseen to decouple electrically the PbLi from the conducting wall of the ducts. This can be achieved by inserting insulating layers inside pipes and channels. In this paper we investigate MHD flows in well-conducting pipes with flow channel inserts (FCI). The influence on the pressure drop of the finite electric conductance of the layer and of the presence of an interruption in the insulation is analyzed. Numerical results show that under realistic operating conditions, i.e. for sufficiently small electric conductance of the insert and large magnetic fields, the ensuing additional MHD pressure losses are still acceptable. However, the discontinuity of the insulation causes significant modifications of the velocity distribution in the pipe, which have to be taken into account, since they can affect heat and mass transfer phenomena.

1. Introduction

In the dual coolant lead lithium (DCLL) blanket concept the liquid metal serves both as tritium breeder and as coolant of the breeding zone [1]. In order to ensure a suitable extraction of the volumetric heat generated by neutrons, the liquid metal has to flow at sufficiently large velocity (~ 10 cm/s) in long poloidal channels. This may lead to increased pressure losses that are related to the magnetohydrodynamic (MHD) interaction of the moving liquid metal with the magnetic field that confines the fusion plasma. As a result electric currents and intense electromagnetic Lorentz forces are induced in the PbLi [2]. In MHD duct flows in strong magnetic fields, as typical in fusion reactors, Lorentz forces result in high pressure heads and they tend to slow down the fluid in the core of the channel.

In electrically insulated ducts currents close exclusively in the thin boundary layers that form along the walls and this yields a much smaller total current density compared to the case in which electrically conducting walls provide a closing path for the current. For that reason the feasibility of the DCLL blanket concept is strictly related to the possibility of realizing a suitable insulation in the channels. The use of so-called flow channel inserts (FCIs) has been proposed in order to decouple thermically and electrically the conducting duct wall from the high temperature liquid metal [3]. They could be fabricated by using the ceramic material SiC [4]. Alternatively, sandwich-type FCIs consisting of a thin ceramic layer between two steel sheets, which are welded at all edges to avoid contact between the insulating layer and the liquid breeder, can be used [3]. The latter technical solution is the one considered in the present study and to be inserted in a test-section for an upcoming experimental campaign [5].

Two dimensional MHD flows in ducts with FCIs have been already investigated in long channels in which fully developed conditions are achieved [6]. However, it has to be taken into account that FCIs could be shorter than the long poloidal ducts forming the blanket breeding zone and therefore it could be necessary to insert several pieces in the channels. This could lead to the presence of gaps between the inserts, namely to local interruptions of the electrical insulation. MHD flows in circular pipes with cracks in insulating coatings or with small uninsulated regions have been analyzed for ideal cases in which the insert provides a perfect insulation and the wall of the duct is perfectly electrically conducting [7] [8]. The present work aims at complementing previous investigations by considering MHD flows in pipes with discontinuous insulation and realistic values of the conductivity of walls and inserts. Due to the present uncertainty about the fabrication procedure of FCIs, parametric studies are carried out to cover a large range of electrical properties of the internal insulation. Pressure and velocity distributions, as resulting from the 3D MHD effects near the

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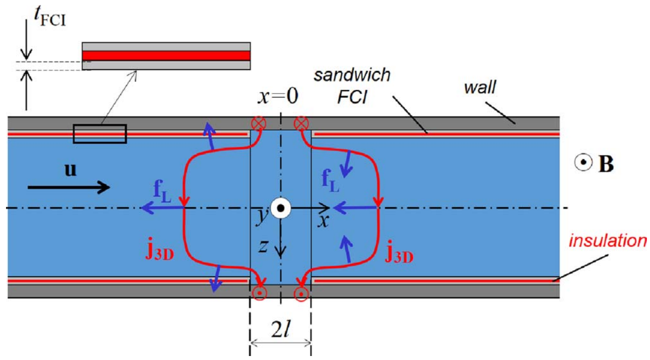

Fig. 1. Sketch of the model geometry and coordinate system. Distribution of current and electromagnetic forces is schematically displayed.

gap between inserts and from the finite electric conductance of FCIs, are studied.

2. Formulation of the problem

2.1. Geometry and physics

Liquid metal MHD flows have been investigated in a long pipe with inner radius L, wall thickness t_w, and electric conductivity σ_w. A sandwich-like FCI with protecting steel layers of thickness t_{FCI}, and electric conductivity σ_{FCI} is inserted in the duct. The internal ceramic layer is assumed to be perfectly insulating so that the current can flow only tangentially or in axial direction along the thin inner protecting sheet. For simplicity of calculation it is assumed that no liquid metal gap exists between the pipe wall and the FCI. Fig. 1 shows the model geometry and the coordinate system. In the region $-l < x < l$ there is an opening in the low-conducting FCI. The geometrical configuration is similar to the one used in [8]. As a result of the interruption of the insulation, currents induced in the fluid can close their path by flowing inside the well-conducting wall of the pipe. Axial currents are driven by the potential difference that establishes between the flow in the insulating part of the pipe and the low potential zone in the highly conducting gap. A 3D current distribution sets up, as schematically depicted in Fig. 1. Transverse currents j_z interact with the magnetic field giving rise to electromagnetic Lorentz forces f_{Lx} that slow down the flow in the pipe core. Axial currents induced near the walls parallel to the magnetic field **B**, push the flow towards the sides for $x < 0$, in front of the insulation opening, and towards the center of the pipe for $x > 0$, behind the gap.

2.2. Equations and scaling

The MHD flow of the liquid metal in a blanket exposed to a strong magnetic field is modelled by equations for conservation of momentum, mass and charge, and electric currents are determined by Ohm's law, that in non-dimensional form can be written as

$$\frac{1}{N}\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -\nabla p + \frac{1}{Ha^2}\nabla^2\mathbf{v} + \mathbf{j}\times\mathbf{B}, \tag{1}$$

$$\nabla\cdot\mathbf{v} = 0, \quad \nabla\cdot\mathbf{j} = 0, \tag{2}$$

$$\mathbf{j} = -\nabla\phi + \mathbf{v}\times\mathbf{B}. \tag{3}$$

In (1)–(3) velocity **v**, pressure p, current density **j**, magnetic field **B**, and electric potential ϕ, are obtained by scaling the corresponding dimensional variables by u_0, $\sigma u_0 B^2 L$, $\sigma u_0 B$, B, and $u_0 BL$, respectively. The characteristic velocity u_0 is the mean value in the pipe without FCI and B is the magnitude of the applied magnetic field. The physical properties of the fluid, the density ρ, the kinematic viscosity ν, and the electric conductivity σ, are constant. The two non-dimensional numbers in (1), that describe the MHD flow, are the interaction parameter N and the Hartmann number Ha

$$N = \frac{\sigma L B^2}{\rho u_0} \quad \text{and} \quad Ha = LB\sqrt{\frac{\sigma}{\rho\nu}}. \tag{4}$$

The former one weights the importance of electromagnetic forces compared to inertia, the second gives a non-dimensional measure for the strength of the magnetic field and its square quantifies the ratio between electromagnetic and viscous forces.

The boundary conditions at the fluid-solid interface are the no-slip condition, $\mathbf{v} = 0$, and those stating continuity of the wall-normal component of current density and of electric potential

$$j_n = j_{n,w,\mathrm{FCI}} \quad \text{and} \quad \phi = \phi_{w,\mathrm{FCI}}. \tag{5}$$

The first condition in (5) can be expressed by the so-called thin wall condition [9] that assumes that the current entering the wall from the fluid turns in wall-tangential direction and produces there a distribution ϕ_w of potential according to

$$\mathbf{j}\cdot\mathbf{n} = \nabla\cdot((c+\delta)\nabla_t\phi_{w,\mathrm{FCI}}), \tag{6}$$

where

$$c = \frac{t_{w,\mathrm{FCI}}\sigma_{w,\mathrm{FCI}}}{L\sigma}$$

is the conductance parameter that gives the ratio of the conductance of the solid material to the one of the fluid and δ is the thickness of the viscous boundary layer. In (6) ∇_t stands for the wall-tangential component of the gradient operator.

2.3. Solution procedure

In liquid metal blankets for fusion reactors the characteristic flow parameters (4) reach very large values, $N > 10^4$, $Ha \gtrsim 10^4$. Under these flow conditions inertia may become negligible in most of the fluid domain and the core flow can be assumed as inviscid and governed by a balance between electromagnetic forces and pressure gradient (core flow approximation [10]). Viscous effects are confined to thin boundary layers that develop along walls. This type of MHD flows in which $N \to \infty$ and $Ha \gg 1$ can be efficiently described by asymptotic methods that consist in integrating the governing equations analytically along magnetic field lines to obtain a set of equations for pressure p and electric potential ϕ that can be solved numerically on a 2D computational domain represented by the wall of the considered geometry. The 3D solution of the problem is reconstructed by means of analytical relations between flow variables [11].

It should be mentioned that neglecting nonlinearities excludes a priory inertia effects and the occurrence of instabilities that might emerge in flows with high velocity near duct walls. However, previous comparison of results with full numerical solutions and experiments for MHD flows in sudden expansions of rectangular ducts have shown quite good agreement for large values of Ha and N [12]. Comparison of asymptotic results obtained by same assumptions with experiments for 3D circular pipe flow at the exit of a magnet has shown very good agreement as well [13]. These results confirm the validity of the asymptotic solution for flows with small velocities ($N \gg 1$), exposed to intense magnetic fields ($Ha \gg 1$). Therefore we are confident that the present analysis yields accurate results.

Due to the linearity of the asymptotic problem it is possible to apply symmetry conditions in the middle of the insulation gap at $x = 0$:

$$p = \mathrm{const} = 0 \quad \text{and} \quad \frac{\partial\phi}{\partial x} = 0. \tag{7}$$

The flow at the entrance of the pipe is assumed to be fully developed.