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Magnetohydrodynamic flow in ducts with discontinuous electrical insulation

C. Mistrangelo*, L. Bühler

Karlsruhe Institute of Technology, Postfach 3640, 76021 Karlsruhe, Germany

HIGHLIGHTS

- Liquid metal MHD flows in ducts with flow channel inserts.
- Study of the influence of local interruption of electrical insulation.
- 3D numerical simulations.

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ABSTRACT

In liquid metal blankets the interaction of the moving breeder with the intense magnetic field that confines the fusion plasma results in significant modifications of the velocity distribution and increased pressure drop compared to hydrodynamic flows. Those changes are due to the occurrence of electromagnetic forces that slow down the core flow and which are balanced by large driving pressure heads. The resulting magnetohydrodynamic (MHD) pressure losses are proportional to the electric current density induced in the fluid and they can be reduced by electrically decoupling the wall from the liquid metal. For applications to dual coolant blankets it is foreseen to loosely insert electrically insulating liners into the ducts. In long channels the insulation could consist of a number of shorter inserts, which implies a possible local interruption of the insulation. Three dimensional numerical simulations have been performed to investigate MHD flows in electrically well-conducting channels with internal discontinuous insulating inserts. The local jump in the electric conductivity of the duct wall results in induced 3D electric currents and related electromagnetic forces yielding additional pressure losses and increased velocity in boundary layers parallel to the magnetic field.

1. Introduction

Dual coolant blanket concepts, where helium is used to cool the first wall and the Eurofer structure, while the liquid metal serves to remove the heat deposited in the breeding zone, are particularly attractive since they potentially allow for high power conversion efficiency [1]. Those designs are under investigation for many years in the US [2] and Europe [3].

In liquid metal blankets issues related to magnetohydrodynamic (MHD) interactions of the moving liquid breeder with the magnetic field required for plasma confinement have to be considered. They consist in the occurrence of increased pressure drops and modified flow distribution compared to hydrodynamic conditions. Electromagnetic Lorentz forces that tend to slow down the bulk flow result from interactions of induced electric currents with the magnetic field and they are balanced by large pressure heads. The resulting additional MHD pressure losses are proportional to the total electric currents induced in the fluid and they can be minimized by suitable insulation at channel walls. The use of insulating flow channel inserts (FCI) inside long channels to electrically and thermally decouple the flowing lead lithium from the load-bearing ferritic steel wall is a key technical feature in dual coolant blankets [4]. Liquid metal flows in ducts with FCIs have been studied in the past focusing on 2D fully developed conditions [5] and few studies have been dedicated to 3D MHD effects in ducts with insulating internal liners [6–8].

For blanket applications two types of electric currents should be considered that contribute to the total pressure drop in the system. In channels where the flow is nearly fully developed the MHD pressure drop is mainly related to cross-sectional currents that close through boundary layers or in electrically conducting walls. However, in a blanket most of the pressure losses associated

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* Corresponding author. Tel.: +49 721 608 2 3581.

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with electromagnetic forces are caused by 3D currents [9,10] due for instance to changes in duct cross-section or in wall electrical properties and to the presence of non-uniform magnetic fields. An example is represented by 3D MHD phenomena that occur in case of a gap between flow channel inserts, as investigated in the present study. Discontinuous insulation can be present in long ducts where a number of FCIs is required to cover the entire length of the channels. Numerical simulations are performed to study the influence on pressure drop and velocity distribution of the interruption of the insulating liner in a rectangular duct by using the European dual coolant lead lithium blanket concept as reference [3]. MHD issues related to the sudden change of wall electric conductivity are addressed.

2. Governing equations and scaling

The flow of a liquid metal with electric conductivity σ, density ρ and kinematic viscosity ν under the influence of a uniform magnetic field is described by the non-dimensional momentum equation

$$\frac{1}{N}\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla p+\frac{1}{Ha^2}\nabla^2\mathbf{v}+\mathbf{j}\times\mathrm{B}, \quad (1)$$

where $\mathbf{v}$, p, $\mathbf{j}$ and $\mathbf{B}$ stand for velocity, pressure, electric current density and magnetic field normalized by u_0, $\sigma u_0 B_0^2 L$, $\sigma u_0 B_0$ and B_0, respectively. Here B_0 is the magnitude of the magnetic field, u_0 the average velocity in the duct cross-section and $L = 0.1675$ m is half size of the channel along magnetic field lines. The current density is determined by the dimensionless Ohm's law as

$$\mathbf{j}=-\nabla\phi+\mathbf{v}\times\mathbf{B}, \quad (2)$$

where ϕ represents the electric potential, scaled by $u_0 B_0 L$. The non-dimensional groups in (1) are the interaction parameter and the Hartmann number

$$N=\frac{\sigma L B_0^2}{\rho u_0} \quad \text{and} \quad Ha = L B_0\sqrt{\frac{\sigma}{\rho\nu}}.$$

Conservation of mass and charge are satisfied according to

$$\nabla\cdot\mathbf{v}=0 \quad \text{and} \quad \nabla\cdot\mathbf{j}=0. \quad (3)$$

At the fluid-wall interface the no-slip condition $\mathbf{v} = 0$ is applied and continuity of wall-normal currents and electric potential is imposed

$$j_n = j_{n,w} \quad \text{and} \quad \phi=\phi_w. \quad (4)$$

If the walls are electrically insulating, currents close exclusively through boundary layers in the fluid domain and the current component perpendicular to the wall vanishes, $j_{n,w} = 0$. When the walls are perfectly electrically conducting a uniform potential distribution establishes on the wall and we can fix $\phi_w = 0$ without loss of generality.

For the numerical simulations fully developed profiles for the velocity and the electric potential are applied at the inlet of the duct and at the outlet a reference pressure $p = 0$ is given and the axial derivatives of velocity and potential are set to zero.

3. Description of the problem

We consider MHD flows in a long rectangular duct of yz cross-section $2L \times 1.25L$ with two semi-infinite FCIs that cover the internal surface of the channel. A uniform magnetic field is imposed in y-direction. The inlet duct has a length of $20L$ and the outlet one of $50L$. For small interaction parameters, $N < 150$, simulations have been performed by increasing the length of the outlet channel up to $70L$. It is assumed that the liners are ideally electrically insulating and the insulation is discontinuous i.e. the inserts are separated by a gap, $l_g = 0.25L$, as shown in Fig. 1. The thin liquid metal gap that in real technical applications is present between the insert and the wall has been neglected in the present study since it is expected that its influence on the phenomena described is very small. Far enough upstream and downstream of the gap the flow is fully developed, while around the opening intense 3D MHD phenomena occur. The characteristics of the flow in the latter zone depend on the length l_g of the gap and on the electric conductivity of the channel wall. In a first conservative example the external duct is assumed to be perfectly conducting.

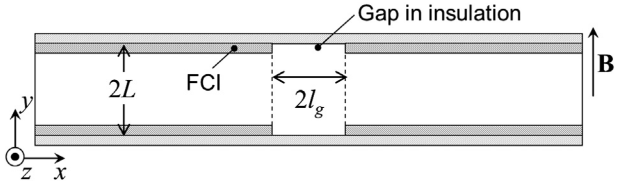

Fig. 1. Rectangular duct with two flow channel inserts separated by a gap of length $2l_g$.

4. Discussion of numerical results

Numerical calculations are carried out by using a solver developed in the finite volume code OpenFOAM. The current density conservative scheme proposed in [11] is employed, the Pressure Implicit with Splitting of Operators algorithm is used for pressure–velocity coupling, the central difference scheme for spatial discretization.

In the following, results are discussed for a constant Hartmann number $Ha = 1000$. The computational mesh consists of $170(y) \times 100(z)$ points in the duct cross-section and in the axial direction there are 300 nodes in the inlet duct and 800 in the outlet channel. Higher spatial resolution in viscous boundary layers and near the insulation gap has been achieved by non-equidistant spacing, so that each Hartmann layer ($\delta_{Ha} \sim Ha^{-1}$) at walls perpendicular to the magnetic field is resolved with 9 points and the side layer ($\delta_s \sim Ha^{-0.5}$) along walls parallel to the magnetic field with 20 nodes. In case of insulating ducts the velocity profile is of slug type and therefore even less points in the side layers would be sufficient. However, as described later in this section, due to the jump in the electric conductivity of the wall, the velocity at the gap increases in the side layers and jet-like velocity profiles appear (see Fig. 6). The fully developed velocity profile in the inlet and outlet duct at some distance from the gap has been compared with an analytical solution [12] and the relative error for the normalized pressure gradient $k = \partial_x p/\sigma u_0 B_0^2$ is $\Delta k < 1\,\%$. Results are presented in non-dimensional form according to the scaling introduced in Section 2 and coordinates are normalized by the typical size L of the duct.

In Fig. 2 the electric potential is shown on the surface of the duct (a) and on the symmetry plane $y = 0$ together with streamlines of electric currents (b). Upstream and downstream at some distance from the FCI interruption the flow is fully developed and hence $\partial_x\phi = 0$. In the core the electric potential is constant along magnetic field lines, $\partial_y\phi = 0$, and in transverse direction $\partial_z\phi \approx 1$. In the portion of the channel for $-l_g < x < l_g$, as a result of the jump in the wall electric conductivity, the transverse potential gradient reduces to zero $\partial_z\phi \to 0$ and an axial potential gradient $\partial_x\phi$ arises for $-l_{3D} < x < l_{3D}$ (see Fig. 3). The latter potential difference drives axial currents whose magnitude increases by approaching the side walls parallel to the magnetic field, as visible in Fig. 3. Here the axial component of the current density j_x is plotted on the plane $y = 0$ at two transverse positions $z = 0.57$ and $z = 0.3$, as indicated in the picture on the top right.