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Electro-magnetic flow coupling for liquid metal blanket applications

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HIGHLIGHTS

- Numerical simulations to study the effects of electrical coupling of adjacent fluid domains caused by leakage currents across common walls are performed.
- Various orientations of magnetic field and driving pressure gradients are considered.
- Intense multi-channel effects are present when ducts are connected at the side walls and the flow is driven in the same direction.
- Calculations of 3D MHD flows in parallel bends are performed too. An example is shown for the case in which the flow is driven only in the lateral ducts.

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ABSTRACT

In the framework of the development of liquid metal blankets to be tested in ITER and for applications in a DEMOnstration reactor, magnetohydrodynamic (MHD) interactions between the electrically conducting lead lithium alloy and intense magnetic fields have been investigated numerically. In all proposed liquid metal blanket designs the presence of leakage currents that flow from one fluid domain into the adjacent one crossing electrically conducting walls has to be taken into account since it influences significantly the flow partitioning in parallel ducts. The way in which electrically coupled flows affect each other depends on orientation of common walls with respect to the magnetic field, on flow direction in adjacent channels and on the path of leakage currents. The present paper aims at providing an overview of main phenomena that occur in multiple channels where flows are coupled by an exchange of electric currents. The understanding of those basic flows is required for the study of complex 3D coupling conditions.

1. Introduction

In liquid metal blankets the interaction of the electrically conducting fluid with the magnetic field that confines the plasma induces electric currents and electromagnetic forces that influence velocity and pressure distribution and cause increased pressure drops compared to hydrodynamic conditions. These additional pressure losses are proportional to the electric current density induced in the fluid. The electrical conductance of the circuit formed by liquid metal and electrically conducting walls determines the magnitude of the induced currents and therefore in turn the pressure losses in the system. Therefore an analysis of the current path and its resistivity gives a good understanding of expected pressure drops. Closing of electric current paths is also affected by multi-channel effects caused by an exchange of current through electrically conducting walls that separate different fluid domains [1]. The presence of those leakage currents can lead to increased pressure drops compared to the one in separated channels and to non-uniform flow distribution in parallel ducts. In a liquid metal blanket, engineering parameters such as structural stress, local high temperature, corrosion rate and pumping power are related to flow rates in channels and therefore control of flow partitioning among parallel ducts is of primary importance for the thermodynamic efficiency of the system. Flow distribution in multi-channel configurations is strictly related to the electrical resistance of the current path. Flow uniformity can be enforced or enhanced by electrically coupling of parallel ducts [2]. Hua and Picologlou [3] studied MHD flows in a manifold that feeds electrically coupled ducts and showed that non-uniform flow partition can be reduced by a proper choice of wall conductance. The orientation of the magnetic field and the direction of flow in adjacent ducts have also a significant impact on flow rates and pressure losses [4,5]. The occurrence of these coupling phenomena is of relevance in particular for blanket concepts where no electric insulation in the ducts is foreseen, such as the helium cooled lead lithium (HCLL) blanket design.

The goal of this paper is to gain insight in the main effects of electrical coupling of MHD flows depending on orientation of

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the magnetic field and direction of driving pressure gradients. Moreover fully developed flows are required as inlet boundary conditions for simulations of 3D MHD flows in electrically coupled bends as studied experimentally in [6,7]. Some preliminary 3D results in this complex configuration are shown as well.

2. Description of the problem

For the present study two geometries are considered. The first one consists of a number of square channels connected through common electrically conducting walls, as shown in Fig. 1. A magnetic field is applied, which forms an angle α with the z-axis. Dimensions of the channels and material properties are taken according to the ones of the experimental test section used by Stieglitz and Molokov [7] for the analysis of MHD flows in parallel electrically coupled bends.

The second geometry consists of three electrically coupled rectangular bends (Fig. 2). A magnetic field is applied in y-direction. Dimensions of the cross-section are as shown in Fig. 1 [7]. In liquid metal blankets this geometry represents a situation in which the liquid breeder flows first radially and then it turns in toroidal direction along the main component of the magnetic field. This configuration was for instance proposed for cooling of the first wall in self-cooled blanket designs [8]. A comparison of numerical results with experimental data allows to further validate the code in case of complex 3D flow conditions.

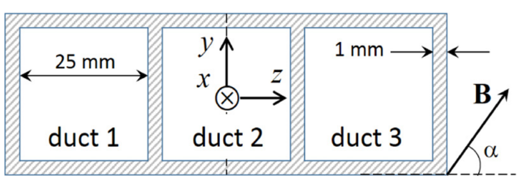

Fig. 1. Reference geometry and coordinate system for the study of electric flow coupling in parallel ducts. The middle channel is referred to as duct 2, the lateral ones as 1 and 3.

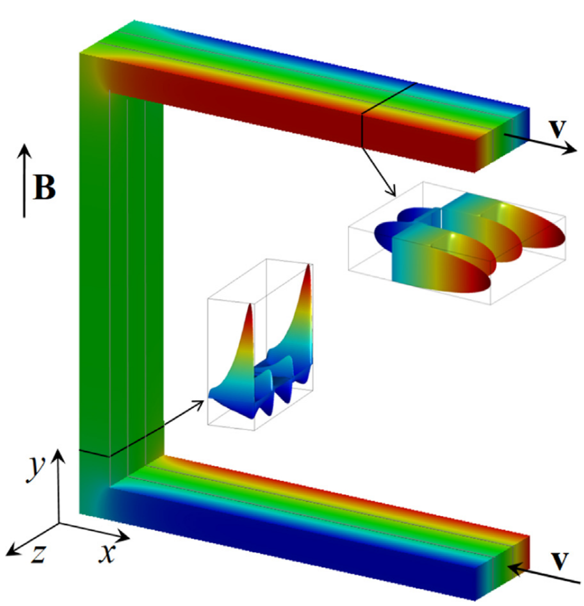

Fig. 2. Three bends with square cross-section electrically coupled through common walls. Contours of electric potential on the fluid-wall interface and velocity profiles. Flow at $Ha = 1200$ and $N = 2370$.

3. Mathematical formulation

The system of non-dimensional equations describing the MHD flow of an incompressible, electrically conducting fluid includes conservation equations for momentum, mass and charge

$$\frac{1}{N}\frac{D\mathbf{v}}{Dt} = -\nabla p + \frac{1}{Ha^2}\nabla^2\mathbf{v} + \mathbf{j}\times\mathbf{B}, \quad (1)$$

$$\nabla\cdot\mathbf{v} = 0, \qquad \nabla\cdot\mathbf{j} = 0. \quad (2)$$

The variables $\mathbf{v}, p, \mathbf{j}$ and $\mathbf{B}$ indicate velocity, pressure, current density and magnetic field normalized by u_0, $\sigma u_0 B^2 L$, $\sigma u_0 B$ and B, respectively. All dimensions are scaled by half of the size of the duct, $L = 0.0125m$, and the characteristic velocity u_0 is chosen as the average value in the cross-section of the multi-channel geometry. Fluid properties such as density ρ, electric conductivity σ, and kinematic viscosity ν, are assumed to be constant. The electric current density $\mathbf{j}$ is defined by the dimensionless Ohm's law as

$$\mathbf{j} = -\nabla\phi + \mathbf{v}\times\mathbf{B}, \quad (3)$$

where ϕ is the electric potential scaled by $u_0 BL$. The magnitude of the induced current density is determined by the resistance of the current path. In electrically conducting ducts the wall conductance is the main parameter that controls the magnitude of currents. The ratio between conductance of the wall to the one of the fluid is expressed by the conductance parameter $c = \sigma_w t_w/(\sigma L)$. Here σ_w is the electric conductivity of the wall and t_w its thickness. The equations are written according to the so-called inductionless approximation that assumes that the magnetic field induced by currents in the fluid is negligible compared to the externally imposed one. This approximation is valid for small magnetic Reynolds numbers, $Re_m = \mu\sigma L u_0 \ll 1$, where μ is the magnetic permeability. The dimensionless parameters in (1) are the interaction parameter and the Hartmann number:

$$N = \frac{\sigma L B^2}{\rho u_0}, \qquad Ha = LB\sqrt{\frac{\sigma}{\rho\nu}},$$

which quantify the relative importance of electromagnetic forces to inertia and to viscous forces, respectively. The Hartmann number provides a non-dimensional measure for the strength of the imposed magnetic field. At the fluid-wall interface the no-slip condition, $\mathbf{v} = 0$, is imposed and when the duct walls have finite electric conductivity wall-normal currents and electric potential are continuous

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

The analytical solution used to validate the code employs the so-called *thin wall boundary condition* [9] that is valid when duct walls are thin ($t_w \ll L$). According to this approximation the wall electric potential is given by

$$\mathbf{j}\cdot\mathbf{n} = -\frac{\partial\phi}{\partial n} = \nabla\cdot(c\nabla_t\phi_w), \quad (5)$$

where ∇_t denotes the components of the gradient tangential to the wall and $\mathbf{n}$ is the inward unit normal to the wall. Since the wall is thin, it is assumed that the current entering the wall turns immediately to flow only in tangential direction and therefore the potential does not vary along the wall thickness to the leading order of approximation.

4. Numerical results

Eqs. (1)–(3) are solved, together with a Poisson equation for the electric potential, obtained from Ohm's law (3) when electric current conservation (2) is satisfied, by using a solver

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