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Effect of electromagnetic coupling on MHD flow in the manifold of fusion liquid metal blanket

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ABSTRACT

In fusion liquid metal (LM) blanket, magnetohydrodynamics (MHD) effects will dominate the flow patterns and the heat transfer characteristics of the liquid metal flow. Manifold is a key component in LM blanket in charge of distributing or collecting the liquid metal coolant. In this region, the complex three dimensional MHD phenomena will be occurred, and the velocity, pressure and flow rate distributions may be dramatically influenced. One important aspect is the electromagnetic coupling effect resulting from an exchange of electric currents between two neighboring fluid domains that can lead to modifications of flow distribution and pressure drop compared to that in electrical separated channels. Understanding the electromagnetic coupling effect in manifold is necessary to optimize the liquid metal blanket design.

In this work, a numerical study was carried out to investigate the effect of electromagnetic coupling on MHD flow in a manifold region. The typical manifold geometry in LM blanket was considered, a rectangular supply duct entering a rectangular expansion area, finally feeding into 3 rectangular parallel channels. This paper investigated the effect of electromagnetic coupling on MHD flow in a manifold region. Different electromagnetic coupling modes with different combinations of electrical conductivity of walls were studied numerically. The flow distribution and pressure drop of these modes have been evaluated.

1. Introduction

The liquid metal breeder blanket concept has been studied extensively in the world due to their high heat removal, adequate tritium breeding ratio, relative simple design, potential attractiveness of economy and safety [1,2]. A number of liquid metal PbLi blanket concepts have been developed in the world. And some liquid metal PbLi test blanket module (TBM) concepts for ITER, such as the EU HCLL, US DCLL and China DFLL have been proposed [3–6].

In fusion liquid metal blanket, uniform coolant/breeder flow distribution is an important design goal which influences the heat and mass transfer [7]. This issue is critical to the design of manifold of liquid metal blanket concepts. The manifold distributes the liquid metal coolant from a single supply channel to a series of parallel blanket channels. Some numerical simulations and experiment activities [8,9] have been done to investigate MHD flow in the blanket manifold. Great imbalance of flow distribution and complex flow phenomena were found in these works. Meantime, one important electromagnetic coupling effect, also called "Madarame effect" initiated by Madarame et al. [10], was found in blanket manifold, which results from an exchange of electric currents between two neighboring fluid domains and leads to modifications of flow distribution and pressure drop. The electromagnetic coupling effect is striking in blanket manifold and has been discussed in some works [11–14]. In order to have a deep understanding about this effect, some key issues should be further investigated, such as the influence of electrical conductivity of structural material on the flow pressure drop and the balance of the flow rate.

This paper will investigate the effect of electromagnetic coupling on MHD flow in a manifold region of China DFLL-TBM [6]. Different coupling modes with different combinations of electrical conductivity of walls were studied numerically. The flow balance ability and increased pressure drop of these modes have been evaluated.

2. Description of numerical simulations and model

2.1. Physic model

The physical model of MHD flow of liquid metal under the influence of strong external magnetic field was governed by the following equations:

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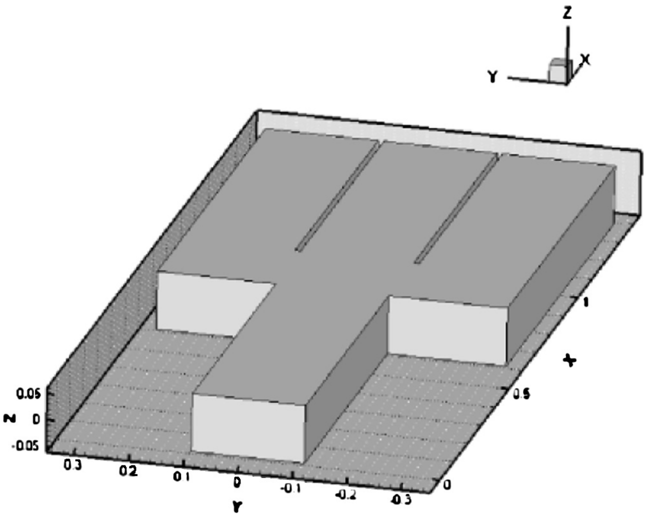

Fig. 1. Simplified geometry model of manifold.

Momentum equations:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u} = -\nabla p + \frac{1}{Re}\nabla^2\vec{u} + N(\vec{J}\times\vec{B}) \tag{1}$$

Continuity equation:

$$\nabla\cdot\vec{u} = 0 \tag{2}$$

Ohm's law:

$$\vec{J} = -\nabla\varphi + \vec{u}\times\vec{B} \tag{3}$$

And the current density was conservative, such that

$$\nabla\cdot\vec{J} = 0 \tag{4}$$

In above equations, $\vec{u}, p$ are the non-dimensional velocity vector and pressure scaled with u_0 and ρu_0^2, respectively, where u_0 is characteristic velocity and ρ is the density of fluid. Let L be characteristic length, η be fluid kinematic viscosity and σ be fluid conductivity, then $Re = u_0L/\eta$ is the Reynolds number, $Ha = LB_0\sqrt{\sigma/\rho\eta}$ is the Hartmann number and $N = Ha^2/Re$ is the interaction parameter. $\vec{J}$ represents the current density, and $\vec{B}$ is the applied magnetic field scaled with $\sigma u_0 B_0$ and B_0 respectively.

Code MTC 2.0 is used for the numerical calculation, which is developed to study MHD flows at high Hartmann number based on the unstructured grid. It is a parallel code, and the induced current and the Lorentz force are calculated with a current density conservative scheme [15]. MTC code has been benchmarked and validated using Shercliff's case, Hunt's case, experimental results of KIT and IEA circular conducting pipes case, etc. [16].

2.2. Geometry model and electromagnetic coupling modes

The geometry model of manifold simulated is simplified from the inlet manifold of China DFLL-TBM [6]. To focus on the influence of electromagnetic coupling to the flow distribution, the structure of the inlet manifold was simplified, as showed in Fig. 1. The manifold has a single rectangular supply channel with cross section of size 0.207 m × 0.11 m, entering a rectangular expansion of size 0.641 m × 0.11 m × 0.18 m, finally feeding into 3 rectangular parallel channels stacked in the flow direction. Each parallel channels is of the same size, with cross section 0.207 × 0.11 m^2. The thickness of outer wall is 5 mm, while the plate between the 3 parallel channels is 10 mm thick.

To simplify the analysis of electromagnetic coupling effect of this manifold, the outer walls of the supply channel and the expansion area are assumed to be electric insulated, while the electromagnetic coupling effect happened inside the 3 rectangular parallel channels. Since the route of currents could influence the flow field and pressure drop remarkably, to get the uniform flow distribution and an acceptable pressure drop, the optimization of current route is important. The route of currents could be decided partly by the electrical conductivity of walls of channels. Different combinations of conductivity of walls could form different electromagnetic coupling modes which lead to different current route and flow distribution. The magnetic field was in the y-axis direction, so the walls in the x–y plane are the side walls, while the walls in the x–z plane are the Hartmann walls. By assuming the side walls and Hartmann walls to be electric conducting or electric insulating separately, we could get 4 combinations of electromagnetic coupling modes, whose flow distribution and pressure drop were assessed.

Table 1
The physical properties for 3D simulations.

Name	Values
Inlet velocity (m/s)	0.009
Magnetic field (T)	(0, 1, 0)
Density of PbLi (kg/m^3)	9318
Conductivity of PbLi (1/Ωm)	0.764×10^6
Conductivity of wall (1/Ωm)	1.245×10^6
Dynamic viscosity of PbLi (Pa s)	0.0015
Temperature of PbLi (°C)	400

- *Mode 1*: Both side walls and Hartmann walls are electric insulating. In this case, there is no electromagnetic coupling between the channels.
- *Mode 2*: Both side walls and Hartmann walls are electric conducting with conductivity 1.245×10^6 (1/Ωm). In this case, the 3 parallel channels in the feeding area are fully electromagnetic coupled.
- *Mode 3*: The side walls in the x–y plane are electric conducting while the Hartmann walls in the x–z plane are electric insulating. The 3 parallel channels are electromagnetic coupled through side walls.
- *Mode 4*: The Hartmann walls in the x–z plane are electric conducting while the side walls in the x–y plane are electric insulating. The 3 parallel channels are electromagnetic coupled through Hartmann walls.

In Table 1 the physical properties are given for the simulation, where the liquid metal is chosen to be PbLi. In the 3 feeding parallel pipes, $Re = 2677$, $Ha = 3242$, which is moderate compared with the DFLL blanket.

3. Results and discussion

3.1. Velocity and current distributions of the four modes

Figs. 2–5 show the velocity distributions in the fully developed part of the 3 parallel channels of modes 1–4. Fig. 6 shows the current distributions of the 3 parallel channels of modes 1–4. The Hartmann walls of channels in modes 1 and 3 are all insulating, and the velocity in these two scenarios has no jets as shown in Figs. 2 and 4, and current distribution forms recirculating loop in liquid metal, as shown in Fig. 6. These phenomena are similar to those of Shercliff's case [17], where no velocity jets happen and the pressure drop maintains at a low value. In modes 2 and 4, the Hartmann walls are electric conducting, and the velocity in Figs. 3 and 5 forms jets and current distribution circulates through Hartmann walls. These cases resemble those of Hunt's case [18], where the jet flow exists and pressure drop is much larger than that of Shercliff's case.