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Effect of wall thickness and helium cooling channels on duct magnetohydrodynamic flows

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HIGHLIGHTS

- MHD flows in ducts of different wall thickness compared with wall uniform.
- Study of velocity, pressure distribution in ducts MHD flows with single pass of helium cooling channels.
- Comparison of three types of dual helium cooling channels and acquisition of an option for minimum pressure drop.
- A single short duct MHD flow in blanket without FCI has been simulated for pressure gradient analysis.

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ABSTRACT

The concept of dual coolant liquid metal (LM) blanket has been proposed in different countries to demonstrate the technical feasibility of DEMO reactor. In the system, helium gas and PbLi eutectic, separated by structure grid, are used to cool main structure materials and to be self-cooled, respectively. The non-uniform wall thickness of structure materials gives rise to wall non-homogeneous conductance ratio. It will lead to electric current distribution changes, resulting in significant changes in the velocity distribution and pressure drop of magnetohydrodynamic (MHD) flows. In order to investigate the effect of helium channels on MHD flows, different methods of numerical simulations cases are carried out including the cases of different wall thicknesses, single pass of helium cooling channels, and three types of dual helium cooling channels. The results showed that helium tubes are able to affect the velocity distribution in the boundary layer by forming wave sharp which transfers from Hartmann boundary layer to the core area. In addition, the potential profile and pressure drop in the cases have been compared to these in the case of walls without cooling channel, and the pressure gradient of a simplified single short duct MHD flow in blanket shows small waver along the central axis in the helium channel position.

1. Introduction

The concept of dual coolants liquid metal blanket has been proposed and studied in many countries with different design schemes [1–4]. In the system, the coolant channel flows into helium gas and it is separated by the structure grid to cool the first wall and main structure in TBM, and PbLi eutectic as self-cooled breeder material is used for heat removal and tritium extraction [5]. Liquid metal flows in the blanket under strong magnetic fields will generate induced current, which will produce Lorentz force in magnetohydradynamic (MHD) flow and further affect the pressure and velocity distribution especially in the boundary layer. In the breeder zones with conductive walls, the electrical conductance ratios determine the electric potential and current density. It results in the velocity distribution and pressure drop of MHD flows change [6–9].

In the past, numerical calculation of MHD flows in geometries is mainly carried out by uniform wall thickness [10–12]. It was performed to investigate the characteristics of liquid metal MHD flows in channels by reducing effective conductivity of the walls [13] or applying low conducting flow channel inserts (FCIs) [14,15]. However, helium channels inside the cooling plates (CP) and inhomogeneity of the walls correlate to wall electrical ratio conductance which could lead to the velocity distribution unsteadiness and pressure drop change in the blanket breeder unites. Helium channels in the side walls and the effect of multi-channel on velocity profile have been studied in HCLL blanket [16]. However, Hartmann walls impact on the MHD flows is not described in sufficient detail and there is no investigation about pressure drop.

In this paper liquid metal MHD flows are investigated for different design options of a duct based on code named KMC-MHDOF

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(a MHD solver from Keda(USTC) Multi-physics Coupling program based on OpenFOAM) [17,18], which was based on conservative and conservation scheme [19]. Similar initial geometry structure is set up for contrastive analysis. First numerical step is taken account of different wall thickness in ducts by increasing the same conductivity in side or Hartmann walls. Next, increasing single pass of helium cooling channels in the uniform walls by four different styles, the effects on MHD flows have been separate analyzed for non-channel duct. According to the existing model of helium channel in liquid blanket, then, three styles of cooling channels, which are composed of four basic single pass, have been investigated and shown the options for minimum pressure drop. Finally, the pressure gradient of a simplified single short duct in blanket has been shown along the central axis.

2. Mathematical formulation and solution method

For a low magnetic Reynolds number liquid metal MHD flow, with steady state, incompressible, and constant physical properties (density, electrical conductivity and viscosity), the system governing equation of mass, momentum, conservation of charge, and Ohm's law is described as follow:

$$\frac{1}{N}(\mathbf{u}\bullet\nabla)\mathbf{u} = -\nabla p + \frac{1}{Ha^2}\nabla^2 u + \boldsymbol{j}\times\boldsymbol{B} \tag{1}$$

$$\nabla\bullet u = 0 \quad \nabla\bullet\mathbf{j} = 0 \tag{2}$$

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

where the vector variables **u**, **B** and **j** mean dimensionless velocity, applied magnetic field and current density. They are scaled by the reference values u_0, B_0, and $\sigma u_0 B_0$, respectively. The scalar variables p and ϕ stand for the pressure and electric potential, scaled by means of $\sigma u_0 B_0^2 L$ and $u_0 B_0 L$. The scaling dimension L is half width length of the rectangular fluid region along magnetic field.

The dimensionless parameters in Eq. (1) are the Hartmann number and interaction parameter:

$$Ha = B_0 L\sqrt{\frac{\sigma}{\mu}}, \quad N = \frac{Ha^2}{Re} = \frac{\sigma L B_0^2}{\rho u_0}$$

The square of the Hartmann number represents the ratio of electromagnetic to viscous forces while the interaction parameter represents the ratio of electromagnetic to inertia forces. The physical properties ρ, σ, and μ represent the liquid metal density, electrical conductivity and dynamic viscosity, respectively.

In the numerical simulation, a non-slip velocity boundary condition has been applied on fluid walls which is interfaced with electrical conductivity walls or low electrical conductivity flow channel inserts (FCI). At the interface, the values of currents and electric potential between solid and fluid are contiguous:

$$j_n = j_{n,w} \quad \text{and} \quad \phi = \phi_w$$

where the subscript of w means the variables of solid wall boundary. An important parameter $c = \sigma_w t_w / \sigma L$ represents the ratio of electrical conductance between wall with thickness and liquid metal characteristic length L. The parameter c is closely related to the liquid metal MHD pressure gradient. is the electrical conductivity of duct wall.

Simulations were carried out by using open source package OpenFOAM and applying electrical current density conservative scheme as proposed in [19]. The numerical codes are able to predict accurately three dimensional, incompressible and viscous MHD flows under strong magnetic field [17,18]. The numerical solution of equations has a second-order accurate solution in space and time. Therefore, time derivatives are discretized by a semi-Implicit Crank–Nicolson scheme. Central differencing scheme has been used in spatial terms. The standard no-slip boundary condition is used at the channel walls. Electrically insulated walls are defined as $\nabla_n \phi = 0$, and perfectly conducting walls were defined at a fixed number Ø = 0. The solver precision in all cases has been set to 10^{-8}. In order to reduce the computing time of code and ensure the feature point can be captured, the grids near the walls are using a non-uniform meshes. 3–5 grids are set in Hartmann layers and 6–10 grids are set in side layers to guarantee a high accuracy.

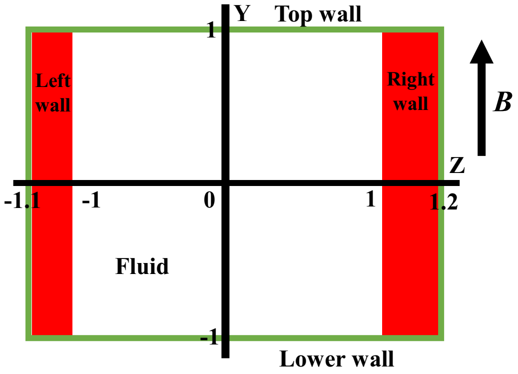

Fig. 1. MHD flows in a rectangular duct with transverse magnetic field applied.

3. Program validation

To analyze the effect of wall thickness and helium cooling channels on duct magnetohydrodynamic flows, a numerical simulation of an MHD flow in a duct with unsymmetrical thickness side wall is carried out to validate the present numerical method against an analytical solution [20]. The flow geometry and geometrical parameters are illustrated in Fig. 1, where the LM flows in the x-direction, and a transverse magnetic field is imposed in the y-direction with Hartmann number 1000 and Reynolds number 1000. The dimension of fluid domain is $5 \times 2 \times 2$. The Hartmann walls are perfectly conductive and the side walls are of same finite conductivity. A uniform inlet fluid velocity of $u = 1$ m/s is prescribed. The current study grid uses non-uniform grid technology and the cells number is 600,000.

Velocity profile in the present simulation and the analytical results of Tao [20] are shown in Fig. 2. It shows a good agreement in the velocity distribution in both the mid x–y and mid x–z planes along cross section at $x = 4$, implying that the current numerical simulation is reasonably correct. The velocity jet near the left side wall is much stronger than that near the right side wall. It may have great effects on flow instability and the temperature distribution in real fusion conditions.

4. Numerical results and discussion

In a duct with uniform wall thickness, the theoretical result of dimensionless pressure gradient and $-\mathrm{d}p/\mathrm{d}x = k_p k \sigma_f U_0 B^2$ and $k_p = c/\left(1 + a/3b + c\right)$ [9] is proportional to conductance ratio c, where a and b are the lengths of the sides of the rectangular pipe. There are usually two ways to decrease the pressure gradient: one is decreasing the solid wall electric conductivity and the other is decreasing the wall thickness according to the definition of c. The effect of two methods is complementary. However, in fusion liquid metal blanket, it is usually adopting insulation coating [13] or low electrical conductivity of flow channel insert (FCI) [14,15] to decrease pressure gradient without affecting the blanket external geometric design.

Due to the existence of helium cooling channels and limit of manufacturing process in the TBM design, we took three steps to