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Numerical study of MHD pressure drop in rectangular ducts with insulating coatings

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ABSTRACT

The MHD (magnetohydrodynamic) effect is a key issue, and quite often a constraint, in the development of liquid metal breeder blankets. The insulating coating is an effective approach to reduce the MHD effect. However, the insulating performance of coatings may be weakened by cracks caused by mechanical stresses, corrosion and so on. A three-dimensional code named MTC-H 1.0 was adopted to simulate the MHD flow in rectangular ducts with perfect and imperfect coatings. The results showed that perfect coatings could maintain the pressure drop to the level with fully electrically insulated wall when *coating resistance* was greater than 0.01, and longer *crack distance* (L) would lead to higher MHD pressure drop in the duct with imperfect coatings.

1. Introduction

Liquid metal breeder blankets have been investigated widely because of many advantages including relatively simple design, adequate tritium breeding ratio, high heat removal and so on [1–4]. However, the motion of liquid metal under strong magnetic field causes serious MHD pressure drop, which is often a constraint issue in the design of liquid metal blankets. In conducting ducts, the induced currents close their circuits through the conduct walls, which lead to big current and MHD pressure drop. In contrast, insulating ducts make current circuits close in extremely thin boundary layers, named Hartmann layers, which causes relatively small MHD effects. Insulating coating is effective to reduce MHD effects [5–8], and it has been widely used in the design of fusion blankets [1,4,9,10]. However, a perfect coating without cracks cannot be guaranteed in manufacture and severe operation scenarios. A few cracks may lead to high MHD pressure drop and peculiar flow pattern, so effects on the MHD flow due to some cracks are very important.

Many works on MHD flow with insulating coating had been made in recent years. Theoretic analyses of MHD pressure drop were summarized in Refs. [9–12]. The influences of coating cracks on side walls in 2D were shown in Refs. [11,13], and Refs. [14–16] provided some experimental studies of effects of imperfect coatings on MHD flow.

In this paper, a 3D code MTC-H 1.0 [17], developed and validated by FDS Team [18], was adopted to simulate the MHD flows. The influences of perfect coating with different insulating performances on the MHD flow were investigated firstly. Then MHD effects under imperfect coating condition were analyzed emphatically.

2. Mathematical and numerical models

The dimensionless governing equations of MHD flow were expressed as follows.

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

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

$$\boldsymbol{J} = -\nabla \varphi + \boldsymbol{v} \times \boldsymbol{B} \tag{3}$$

$$\nabla \boldsymbol{J} = 0 \tag{4}$$

Here $t, \boldsymbol{v}, p, \boldsymbol{J}, \boldsymbol{B}, \varphi$ are dimensionless time, velocity, pressure, current density, applied magnetic field, and electrical potential, $\mathrm{Re} = \upsilon_0 L/\eta$ is the Reynolds number, $Ha = LB_0\sqrt{\sigma/\rho\eta}$ is the Hartmann number, and $N = Ha^2/\mathrm{Re}$ is the interaction number. η, ρ, σ are the kinetic viscosity, density and electrical conductivity of the fluid.

The code MTC-H 1.0 [17] solved the MHD flow through electric potential method which is suitable for low magnetic Reynolds numbers. The calculation was based on collocated non-uniform grid and control volume method. Current flux at cell face was calculated

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through solving electric potential poisson equation using a consistent scheme, and then the Lorentz force at cell center could be calculated base on current flux using a conservative interpolation. The Navier–Stokes equations, with the Lorentz force included as a source term, were solved by four-step projection method which had a second-order approximation [19,20].

This MTC-H 1.0 code has been validated with Hunt and Shercliff cases under the Ha number of 10^4 for 3D MHD duct flow, the detail design of this code and its benchmarks can refer to Ref. [17].

3. Influence of perfect coating on MHD flow

For fully developed flow in perfect coating duct with uniform thickness t_c, the pressure drop is given by the following analytical formulas [9]:

$$\frac{dp}{dx} = \frac{\sigma \upsilon B^2}{1 + (\rho_c t_c Ha/(\rho_c t_c + 2bHa\rho))} \quad (5)$$

and

$$\frac{\Delta P_c}{\Delta P_{\text{bare}}} = \frac{1+\kappa}{1 + (\kappa Hac/(1+c))}, \kappa = \frac{\rho_c t_c}{2bHa\rho} \quad (6)$$

Formula (6) [13] is expressed by pressure drop in duct with bared walls. In the formulas, σ and υ are the conductivity and mean velocity of fluid. a and b are half lengths between Hartmann walls and side walls respectively (walls perpendicular to applied magnetic field and parallel to it, respectively). ρ_c and ρ are the electric resistivities of the insulating coating and fluid. t_c is the thickness of the coating. $c(\sigma_w t_w/\sigma a)$ is the wall conductance ratio (σ_w and t_w are the electrical conductivity and thickness of the duct wall).

From the formulas above, we can see that the product $\rho_c t_c$ characterizes the insulating performance of coating. And it is an important parameter which is known as *coating resistance*. The numerical and analytical pressure drops are shown as a function of the coating resistance in Fig. 1. The flow parameters used in the simulations in this paper are listed in Table 1.

The results showed that MHD pressure drop decreased as coating resistance increased, and it approached that with electrically insulated wall when the coating resistance is higher than 0.01 Ω m^2.A very close result had been given in Ref. [5]. Also in Fig. 2, the velocity of fully developed flow presents a transition from M-type jet flow to n-type slug flow as coating resistance increases. This flow pattern should be taken into account when the coating resistance is considered.

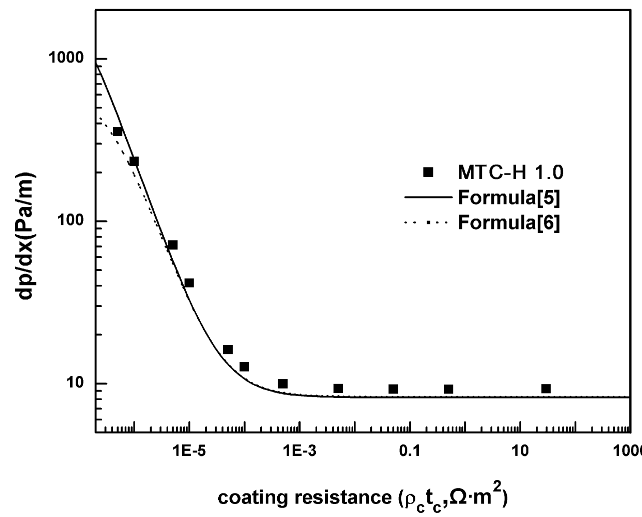

Fig. 1. Pressure drop comparison in ducts with different coating resistances.

4. MHD flow in imperfect coating ducts

MHD flow and pressure drop have great relations with the crack positions, the effect of cracks on MHD flow were studied, including cracks on Hartmann walls, Hartmann and side walls and side walls.

4.1. Cracks on Hartmann walls

When cracks occur on the Hartmann walls, currents flow through the wall where cracks occur, which increases total current and pressure drop. In Fig. 3, crack on one corner of Hartmann wall, and cracks on the two corners were discussed. The pressure drop of case Fig. 3a increases as crack width increases. In contrast, the pressure drop of Fig. 3b is much higher than that of Fig. 3a with

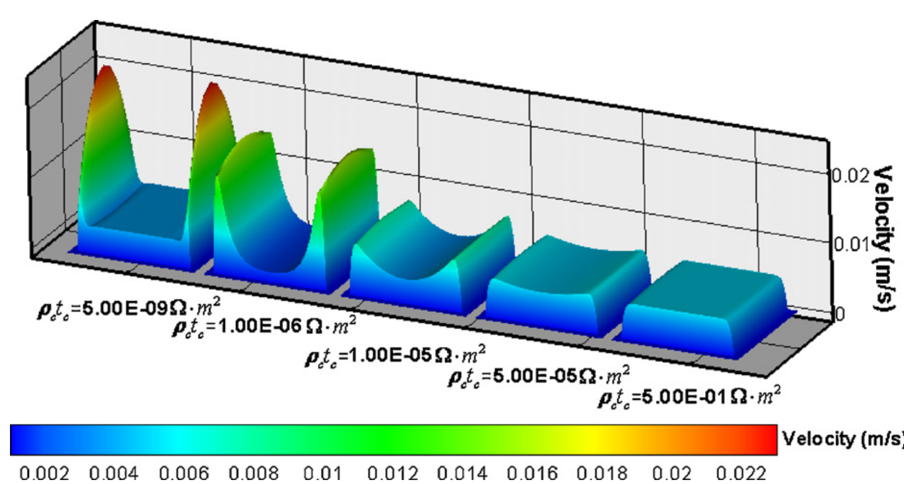

Fig. 2. Velocity profiles in ducts with different coating resistances.

Table 1
Flow parameters used in the simulation.

a (m)	b (m)	σ $(\Omega\,m)^{-1}$	σ_w $(\Omega\,m)^{-1}$	υ (m s^{-1})	t_w (m)	t_c (m)	Re	Ha
0.025	0.025	7.9×10^5	1.49×10^6	0.005	0.003	0.0005	10	480