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Magnetohydrodynamic flows entering the region of a flow channel insert in a duct

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ABSTRACT

In this study, three-dimensional developing liquid-metal (LM) magnetohydrodynamic (MHD) flows entering the region of the flow channel insert (FCI) under a uniform magnetic field are numerically analyzed. The features of the LM MHD flows in a square duct near the leading edge of the FCI are examined in terms of flow velocity, pressure, current, electric potential, and Lorentz force. Because near the leading edge of the FCI the current moves obliquely in the inner flow region, the pressure gradient along the main flow direction near the slit of FCI's leading edge is smaller, yielding a region of velocity recirculation with lower electric potential therein. The interdependency of current, fluid velocity, pressure, electric potential gradient, and Lorentz force is examined in order to describe the electromagnetic features of the current flows.

1. Introduction

Infusion blankets, the liquid metal, Pb–17Li, serves as both a breeder material and coolant; however, there are problems associated with Pb–17Li in terms of a large pressure drop due to a strong magnetic field and degraded heat transfer due to suppressed turbulence [1]. Many experimental works [2,3] and mathematical approaches [4,5] have been performed to investigate the features of liquid-metal (LM) magnetohydrodynamic (MHD) flows in ducts. Recently, three-dimensional MHD flows in a straight duct have been numerically analyzed by different codes developed by respective authors [6–13].

Piazza and Buhler [14] performed a numerical analysis of buoyant MHD flows in differentially heated and internally heated ducts using commercial code CFX. Using the same code, Mistrangelo and Buhler [15] also investigated LM MHD flows in rectangular sudden expansions. These works showed that the numerical code gives accurate results up to the Hartmann number $M \leq 1000$.

Pressure drop can be reduced with electrical insulation of channel structures in MHD duct flows. However, with long-term use of a blanket cracks may develop in the insulating coating, which would enable electric currents to seep into the cracks and flow through the channel structures, resulting in a large pressure drop. Therefore, the use of a flow channel insert (FCI) is needed to reduce pressure drop.

Wong et al. [16] performed a numerical study of MHD flows with FCIs, including slots and holes, and demonstrated that MHD flows with FCIs with holes yielded more notable 'M-shaped' velocity distribution. Smolentsev et al. [17] numerically analyzed MHD flows and heat transfer in fully developed MHD duct flows with an FCI of SiC_f/SiC. They showed that pressure drops with FCIs of the electric conductivities of 5 $(\Omega\,m^{-1})$ and 500 $(\Omega\,m^{-1})$ are 1/(200–400) and 1/10 times of those without FCIs, respectively.

Smolentsev et al. [18] showed the formation of high-velocity near-wall jets close to FCI walls when the electrical conductivity of FCIs is higher in a fully developed flow. Mao and Pan [19] calculated the current using the induction equation for a magnetic field to analyze a fully developed flow with the FCI. Additionally, several works [20–22] numerically obtained fully developed MHD flows with FCIs in a straight duct. Sutevski et al. [23] numerically performed a three-dimensional study of an MHD duct flow with an FCI in which a spatially-changing magnetic field is applied. In this study, it is argued that there-dimensional effect of MHD flows should be taken care of. Morley et al. [24] numerically investigated a developing MHD flow entering an FCI in an MHD channel when the Hartmann number is 1000.

Though the work [23] performed a three-dimensional investigation of an MHD flow in fringing magnetic field and the study [24] showed the current and velocity streamlines near the leading edge of an FCI, detailed works on three-dimensional developing MHD flows in association with an FCI have not been performed much. In the current study, characteristics of three-dimensional developing MHD duct flows entering into an FCI under a uniform magnetic field are to be numerically investigated using CFX. Detailed information on the variables of velocity, pressure, current, and electric potential is to be elucidated. In the discussion section, the electromotive component of current induced by a local fluid velocity under a

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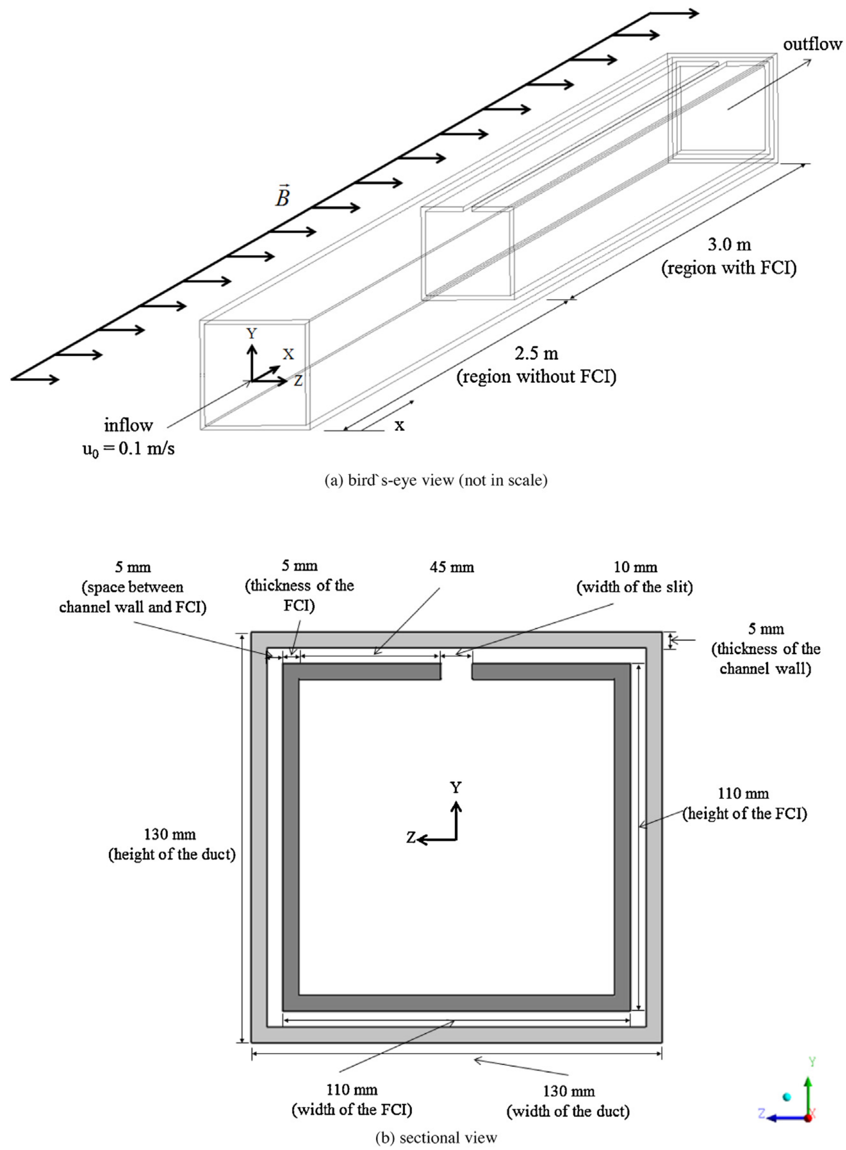

Fig. 1. Geometry and applied magnetic field.

magnetic field, and the electric-field component of current created by a local gradient of electric potential are considered for the analysis of electromagnetic features of the flow. It is known to be advantageous for the FCI slit to be located near the Hartmann wall rather than near the side layer in a rectangular duct. However, this study investigates the electromagnetic effect of a liquid metal flow with the FCI slit located near the side layer.

2. Problem formulation and solution method

2.1. Duct geometry and material properties

The duct geometry considered in this study is presented in Fig. 1, where an FCI is installed inside the channel wall in the downstream segment. The cross-sectional dimensions are also denoted. The slit of the FCI is furnished in order to equalize the pressures of the fluids in the FCI and in the narrow region. The current analysis is basically performed with a uniform magnetic field strength $B_0 = 0.9632$ T, yielding the Hartmann number 1000 based on the length scale of 0.05 m, which is the half-length of a side of the cross-section of inner-flow region inside the FCI. The properties of the channel wall, FCI, and liquid metal are provided in Table 1.

2.2. Governing equations, boundary conditions, and the numerical method

The system of governing equations for a steady-state, incompressible, constant-property laminar LM MHD flow includes the conservation of mass, equation of motion, conservation of charge, and Ohm's law, with a negligible magnetic Reynolds number. The system of equations governing an LM MHD flow can be written as follows:

$$\text{Conservation of mass} \quad \nabla \cdot \vec{u} = 0 \tag{1}$$

Table 1
Properties of the materials.

Region	Fluid	Duct	FCI
Density	9500 kg/m^3	·	·
Dynamic viscosity	1.786×10^{-3} kg/m s	·	·
Electrical conductivity	7.7×10^5 S/m	10^7 S/m	500 S/m