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Imbalance of the liquid-metal flow and heat extraction in a manifold with sub-channels having locally different eletric conductivity

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ABSTRACT

In this study, the characteristics of liquid metal (LM) magnetohydrodynamic (MHD) flow and convective heat transfer in a manifold with three sub-channels having locally different electric conductivity are investigated with the use of commercial code CFX, allowing an imbalance in flow rate among the sub-channels, which can be used for intensive cooling of the region with higher heat load in the blanket. In a manifold with co-flow multiple sub-channels, the electrical current can cross the fluid regions and channel walls, thus influencing the flow distribution in each sub-channel. In the present study, cases with various arrangements of the electric conductivity in different parts of the channel walls are investigated, yielding different distributions of the current and fluid flow in different cases. Here, the mechanism governing the imbalance in mass flow rate among the sub-channels is discussed. The interdependency of the fluid velocity, current and electric potential of LM MHD flows in the three sub-channels are analyzed in detail. The results show that, in the sub-channel surrounded by the walls with lower electric conductivity, higher axial velocity and superior heat extraction can be obtained, with an effective cooling associated with higher velocity, where the higher velocity is closely related to the distribution of the electromotive component of the current in the flow field.

1. Introduction

There has been an increasing interest in the study of liquid metal (LM) magneto-hydrodynamic (MHD) flows in the fusion blankets, where liquid metal serves both as breeder material and as coolant. In the fusion blankets, the pressure drop of liquid metal flows is large due to a strong magnetic field therein [1]. Thus, the design of a system for liquid metal flows aims to minimize the pressure drop, and pursues a proper velocity distribution for good heat transfer.

Many experimental studies on MHD flows in ducts have been conducted by various researchers. Kirillov et al. [2] performed experimental works to investigate magneto-hydrodynamic and heat transfer characteristics of liquid metal flows relevant to fusion blankets. Branover et al. [3] presented an experimental study of MHD flows in a duct with sudden expansion. Mathematical approaches [4–7] have been applied to analyze the velocity profile of MHD flows. Moon et al. [4] mathematically investigated the flow pattern of liquid metal in a manifold. Hunt [7] used a mathematical method to analyze the liquid metal flows in a rectangular duct under a uniform magnetic field, and obtained the exact solutions for MHD flows.

Since much time and efforts are needed for experimental works on LM MHD flows, and three-dimensional LM MHD flows may not be easily analyzed by mathematical method, the numerical solution method based on computational fluid dynamics is considered to be a fairly efficient way for the analysis of LM MHD flows.

A number of researchers developed a variety of numerical codes to investigate LM MHD flows [8–17]. Din et al. [8] obtained an explicit solution for MHD flows in a duct under a strong magnetic field based on Homotopy Perturbation Method. Swain et al. [9] carried out a three-dimensional simulation of LM MHD flows using FLUENT code, and illustrated the capability of the numerical code to predict MHD flows in a single channel with multiple 90° bends. Zhou et al. [10] developed a code named MTC-H 1.0 to evaluate MHD effect in rectangular ducts.

Commercial CFX code has been widely used for the three-dimensional numerical works of LM MHD flows. Mistrangelo and Buhler [18] numerically studied LM MHD flows in sudden expansion of rectangular ducts, and showed that the accuracy of the commercial CFX code is high up to Hartmann number 1000. In the work of Kim et al. [19], the numerical CFX results was validated against previous experimental results of MHD flows, showing that

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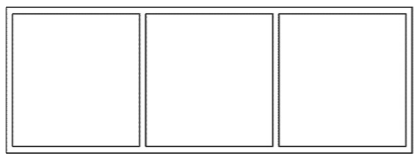
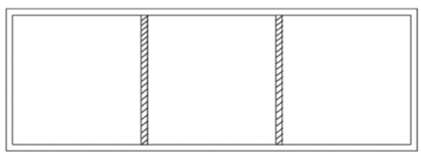
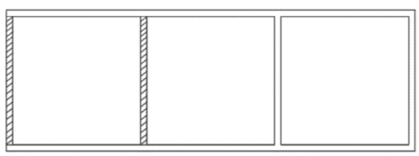
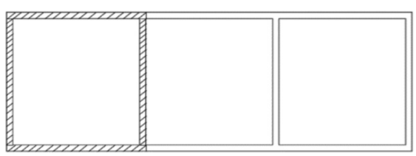
Table 1
Properties in Case 1.

		Density (kg/m^3)	Kinematic viscosity (m^2/s)	Electric conductivity (S/m)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
Channel wall	Part I	7850	–	7.69×10^6 [23]	40	1200
	Part II		–	8.0×10^5 [23]		
Liquid metal		505	8.2×10^{-7}	3.03×10^6	46	4260

Table 2
Arrangements of the electric conductivity for channel walls in different sub-cases (in the cross-sectional view) in Case 2.

Case 2-1	
Case 2-2	
Case 2-3	
Case 2-4	

In Table 2, represents Part I of the channel walls with electric conductivity 1.33×10^7 S/m, and represents Part II of the channel walls with electric conductivity 8.0×10^5 S/m [23].

CFX presents a good performance in predicting the pressure drop of MHD flows.

A manifold with multiple sub-channels can be considered in the design of MHD flows in a fusion blanket. Moon et al. [4] presented a mathematical work for liquid metal flows in manifolds under a uniform transverse magnetic field. Morley et al. [20] numerically investigated an MHD flow in a manifold of electrically insulating ducts in a plane parallel to the magnetic field, using HIMAG code. Reimann et al. [21] carried out a three-dimensional CFX simulation of an MHD flow in a conduit system including three electrically conducting sub-channels. In the work of Reimann et al. [21], only the fully developed velocity profile was presented and the specific electromagnetic features were not explained. Chen et al. [22] investigated the effect of electromagnetic coupling on MHD flows in a manifold. Different coupling modes with different combinations of electrical conductivity of walls were studied numerically using MTC code.

In view of the above, several studies [4,20–22] have been performed for LM MHD flows in a manifold with multiple channels, but works on MHD flow and heat transfer in manifolds with locally different electrical conductivity have rarely been conducted. This study numerically investigates the characteristics of a steady-state, three-dimensional MHD flow and heat transfer in a manifold with three sub-channels having locally different electrical conductivity of various steels [23], which may yield the imbalance in flow rate among the sub-channels, enabling us to effectively cool the region with higher thermal load (for example, a region near the first wall) in the blanket.

Cases with various arrangements of the electric conductivity in different parts of the channel walls are investigated. And, detailed discussions about the mechanism governing the imbalance of mass flow rate in the sub-channels are presented. The interdependency of velocity, pressure drop, current density and electrical potential in the flow system is elucidated in this study.

2. Problem formulation and solution method

2.1. Geometry and properties in different cases

In this study, three-dimensional LM MHD flows in a manifold with three sub-channels are considered. The geometry of the manifold is shown in Fig. 1. Here, a uniform magnetic field with the intensity of 0.2338 T is applied in the z-direction. The Hartmann number is 1000 based on the length scale of 0.05 m, the length of a half side of the square cross-section of a sub-channel.

With the properties of the channel walls and liquid metal given in Table 1 the imbalance in the flow rate and heat extraction is investigated (Case 1). And, with diverse arrangements of the electric conductivity in different parts of the manifold shown in Table 2 the flow situations with the properties given in Table 3 are analyzed (Case 2).

2.2. Governing equations

Steady-state, incompressible, constant-property, laminar, LM MHD flows under a uniform magnetic field are considered. The sys-