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Magnetohydrodynamic flows tuning in a conduit with multiple channels under a magnetic field applied perpendicular to the plane of flow*

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Abstract: In this study, three-dimensional liquid-metal magnetohydrodynamic flows in a conduit with multiple channels under a uniform magnetic field are numerically investigated. The geometry of the conduit is of a four-parallel-channels system including one inflow channel and three outflow channels. The liquid-metal flows into the inflow channel, then turns through 180° in the transition segment, finally flows into three different outflow channels. This kind of channel system can induce counter flow and co-flow, which is rarely investigated before though the conceptual designs of duct flow in the blanket have suggested this type of flow. A structured grid system is chosen after a series of mesh independence tests in the present study. The axial velocity in the side layer near the first partitioning wall, located between the inflow channel and the first outflow channel, is the highest with the lowest electric potential formed therein. The pressure almost linearly decreases in the main flow direction, except in the transition segment. Moreover, the pressure gradient in the first outflow channel is the largest among the three outflow channels. The interdependency of the current, fluid velocity, pressure, electric potential is examined in order to describe the electromagnetic characteristics of the liquid-metal flows.

Key words: Liquid-metal, magnetohydrodynamics, multiple channels

Introduction

This study explores the flow of an electrically conducting fluid under an external magnetic field. Magnetohydrodynamic (MHD) flow is a field of great interest in engineering applications, especially important in the design of liquid-metal (LM) cooling system of fusion reactor, where a plasma is confined by a strong magnetic field[1]. The fluid motion of LM in a strong magnetic field results in serious MHD effects, having enormous impact on velocity distribution, pressure drop and the required pumping power for the cooling system[2]. Therefore, the knowledge of LM MHD flow characteristics is one of the key issues in the optimal design for LM blanket.

A number of experimental studies have been conducted to investigate the LM MHD effects. Bühler et al.[3] performed experiments to investigate the LM flows through a sudden expansion of rectangular ducts at high Hartmann numbers. Stieglitz et al.[4] experimentally investigated the MHD flow in a direction perpendicular to the magnetic field.

A mathematical approach[5,6] has been taken to analyze the velocity profile in the developed region. Siddheshwar and Mahabaleswar[7] used mathematical method to study the MHD flow in a viscoelastic liquid. To make the analysis of MHD flow easier, numerous theoretical studies on MHD flow have been performed with an inertialess approximation. The asymptotic techniques[8] on MHD flows can be used, when the flow is fully developed or when the value of the interaction parameter is extremely large. Walker and Ludford[9] employed asymptotic techniques to analyze MHD flows in rectangular ducts with variable cross-sectional areas. However, the inertial effects cannot always be negligible in flows where liquid metal flows in complicated conduits, especially when the ratio of the interaction parameter to the Hartmann number is small[10]. For the complex geometries of

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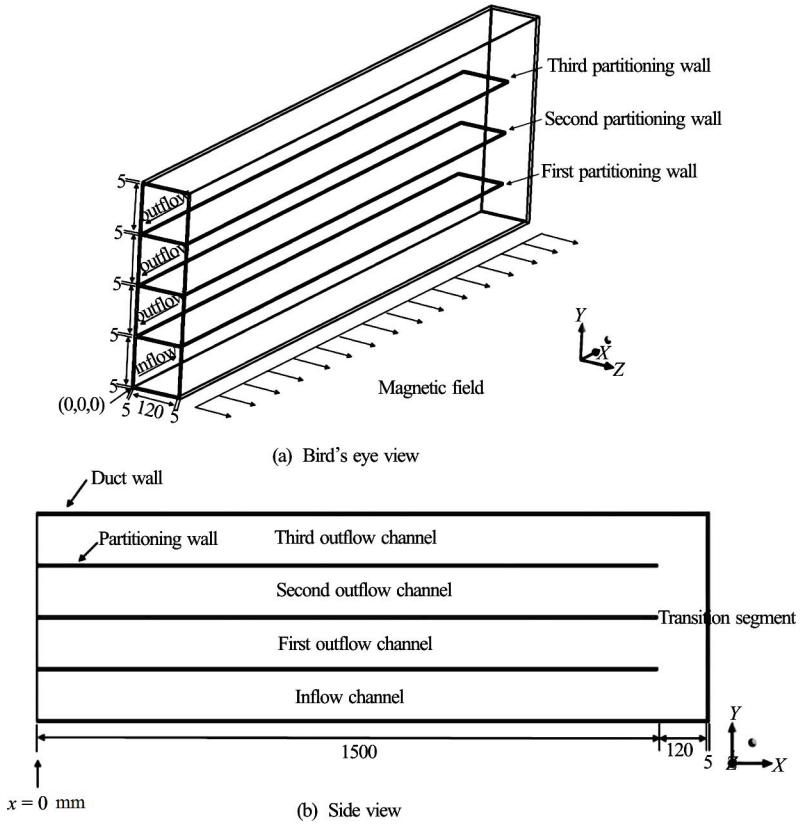

Fig.1 Duct geometry, coordinate system and the magnetic field applied (mm)

flow channels in blankets, detailed investigation of MHD flow characteristics is difficult with the use of theoretical analysis.

With the development of computer science, the numerical simulation becomes an effective method for analyzing MHD effects and optimizing blanket design. A lot of numerical codes have been developed for investigating liquid metal MHD flows. Vantieghem et al.[11] numerically investigated the velocity profile of laminar MHD flows in circular conducting pipes using a finite-volume code with high resolution unstructured meshes. Madarame and Tokoh[12] built a code that could analyze the MHD flows in a semi-cylindrical pipe under a uniform magnetic field.

In addition, three-dimensional numerical works with the use of CFX code have been employed for MHD flows in complex duct geometries. Reimann et al.[13] assessed pressure drop and velocity distribution in their study in which a strong three-dimensional electric current occurs, and explained the multi-channel effects in LM MHD duct flows. In the manifold with three sub-channels of co-current flow, the fully developed velocity profiles were numerically obtained with CFX software. However, there are no detailed explanations of the specific conditions for the MHD flow. Arshad et al.[14] performed a detailed numerical study of LM flow in a curved bend under two kinds of magnetic fields. The MHD pressure drop increases as the liquid metal flows increasingly transverse to the magnetic field. Morley et al.[15] performed a numerical simulation of MHD flows in a geometry consisting of a single rectangular duct and three rectangular sub-channels that are perpendicular to the applied magnetic field.

Although many studies on MHD flows in complicated geometries have been recently performed, the LM MHD flows in a conduit with multiple channels under a uniform magnetic field have rarely been investigated in detail before. This study numerically analyzes the three-dimensional MHD flows in a conduit with parallel inflow and outflow channels under a uniform magnetic field perpendicular to the plane of the flow. Here, the cooled liquid metal flows into the blanket through an inflow channel, reaches the region near the first wall, and comes back through the multiple outflow channels, resulting in co-flows and counter-flows. This type of flow system can be one of the good candidates for the flow design for the purpose of cooling the first wall and blankets. If the characteristics of MHD flows in the present study are to be investigated successfully, the results can be used to design the flows system with higher efficiency of heat extraction. Therefore, it is highly meaningful to examine the features of the proposed flows. In order to

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