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Flow and heat transfer past row of magnetic obstacles for various separation ratios[☆]

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ABSTRACT

This paper presents the effect of the spacing between the magnetic obstacles on the overall transport processes at interaction parameter $N = 11$ and Reynolds number $Re = 600$. The numerical simulations are performed for separation ratio (spacing to magnet width ratio), g^*, of 1.0, 1.25, 1.5 1.75, 2.0, 2.25, 2.5 and 3.0 in a staggered grid system. No significant interaction between the wakes is observed for $g^* \geq 2.25$. However, at smaller separation ratio (such as, $g^* = 1.0$), the wakes interact in a complicated manner resulting in different thermo-hydrodynamic regimes. Moreover, the convection effect is much stronger than absent magnetic obstacles situation for all separation ratios, and the maximum value of overall heat transfer increment is about 52.3% at $g^* = 1.0$. The optimum separation ratio for heat transfer enhancement is $g^* = 2.0$ with only a modest increase in friction loss.

1. Introduction

The study of electrically conducting fluid flow in duct under a transverse magnetic field (uniform or non-uniform magnetic field) has received attention because of its application to important technologies such as metallurgical processing, the cooling blankets enveloping magnetic confinement fusion reactors, electromagnetic brake and the interaction of aerodynamics [1–5]. The motion of electrically conducting fluid in an external magnetic field induces electric currents, which in turn interact with the magnetic field resulting in a Lorentz force which leads to the deformation of velocity distribution. A large number of theoretical and experimental studies on the mechanism and characteristics of an electrically conducting fluid flow under a uniform/non-uniform magnetic field have been carried out. The results show that the so-called M-shaped velocity profile appears in duct flows with homogeneous/non-homogeneous or fringing magnetic fields [6–10]. The M-shaped profile is characterized by two side jets around a central stagnant region.

As to a local non-uniform magnetic field, the electrically conducting fluid flow is decelerated in the local region, and the phenomenon is similar to the flow around a solid obstacle. So, one can say that the local magnetic field produces a magnetic obstacle in local fluid region. For this new magnetohydrodynamic (MHD) problem, Cuevas et al. [11,12] found a vortex dipole in the two-dimensional creeping flow, and discovered the periodic vortex shedding in the wake of magnetic obstacle at Reynolds numbers 100 and 200. Votyakov et al. [13] performed a series of three-dimensional numerical simulations and physical experiments and indicated that the electrically conducting fluid past a magnetic obstacle can form a vortex-pair and complex six-vortex patterns at appropriate interaction parameter (N), Reynolds number (Re) and constrainment factor (κ) for the first time. Andreev et al. [14] proved that the interaction parameter N governed the flow in especially designed experiment. Votyakov et al. [15] reported the effect of constrainment factor on steady vortex structures. Votyakov and Kassinos [16] firstly detected the vortex shedding past a magnetic obstacle in the three-dimensional simulation. Furthermore, Votyakov and Kassinos [17] detailedly investigated the core of the magnetic obstacle at larger interaction parameter by three and two-dimensional numerical simulations. Kenjereš et al. [18] investigated numerically the turbulent bursts behind a magnetic obstacle in transitional flow regimes, and showed that the turbulence was sustained locally in the proximity of the magnetic wake edge and the flow will fully relaminarize farther downstream. Zhang and Huang [19–21] investigated the effect of stable vortex structures and periodic vortex shedding on heat transfer at various parameters (N, Re, κ and blockage ratio β). However, as an equally valid obstacle arrangement, the unsteady flow past multiple magnetic obstacles attract little attention. Kenjereš [22] analyzed local heat transfer features of fluid region past different magnetic dipole configurations (one magnetic dipole, two magnetic dipoles placed side-by-side, and three magnetic dipoles placed triangularly) with a fixed inflow condition of $Re = 10^3$ in a channel. A review of the literatures finds just 12 papers concerning the flow recirculation induced by magnetic obstacle and the heat transfer characteristic past magnetic obstacle. In contrast to hundreds papers on the flow around multiple bluff bodies (such as

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Nomenclature

A	side-wall surface
$\boldsymbol{B}$	magnetic field intensity
$\boldsymbol{B}_0$	application magnetic intensity
$\boldsymbol{b}$	induced magnetic field intensity
f	friction factor
g^*	separation ratio
Ha	Hartmann number
HI	heat transfer increment
$\boldsymbol{J}$	current density
L	characteristic dimension
M_x, M_y, h	characteristic magnet dimensions
N	interaction parameter
Nu	local Nusselt number
$\langle Nu \rangle$	surface-averaged Nusselt number
$\langle \overline{Nu} \rangle$	time and surface-averaged Nusselt number
p	pressure
Pr	Prandtl number
Pe	Peclet number
Re	Reynolds number
Re_m	magnetic Reynolds number
t	time
T	temperature field
T_0	free stream temperature
T_f	bulk fluid temperature
T_w	hot wall temperature
u_0	the area-averaged inflow velocity
$\boldsymbol{u}$	velocity vector (u, v, w)
x, y, z	Cartesian coordinate

Greek symbols

κ	magnetic constrainment factor
μ_m	magnetic permeability (H/m)
ν	kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^3)
σ	electrical conductivity ($1/\Omega \cdot m$)
τ_ρ	period of time integration
η	heat transfer performance factor

Subscripts

w	wall
m	magnetic
s	absent magnetic obstacles

circular cylinders and square prisms) can be found in literature [23–27]. Moreover, the magnetic obstacle plays an essential role in a variety of industrial applications (such as electromagnetic mixing of glass melt and efficient enhancements of the wall-heat transfer for heat exchangers) [22,28].

The aim of the present work is to study the heat transfer and flow characteristics of an electrically conducting fluid past a row of magnetic obstacles placed in a side-by-side arrangement. In particular, the effect of separation ratio on the structure of the flow and heat transfer will be investigated. For simplicity, the interaction parameter, N and Reynolds number, Re are assumed to be constant, which will be investigated in our near future paper.

2. Problem definition

The geometry of the problem under consideration is shown in Fig. 1. A long duct has a uniform rectangular cross-section with width L_y and an out-of-plane height L_z, carrying an electrically conducting fluid. Four same magnetic obstacles with length M_x and width M_y are exposed to a constant and uniform velocity u_0. The distance (S) between two consecutive obstacles is the same and can be defined relative to the magnetic obstacle width as separation ratio, $g^* = S/M_y$. The effect of magnetic obstacle spacing on the flow pattern and heat transfer from the hot wall is analyzed for g^* of 1.0, 1.25, 1.5 1.75, 2.0, 2.25, 2.5 and 3.0. The interaction parameter and Reynolds number are fixed ($N = 11$ and $Re = 600$) for the investigation. The eutectic alloy GaInSn with Prandtl number $Pr = 0.020$ is selected as working fluid.

2.1. Governing equations and parameters

When the electrically conducting fluid flow under a transverse magnetic field, it is critical to know the electric current. Generally, the electric potential method (φ-formulation), the magnetic induction method ($\boldsymbol{B}$-formulation) and the induced electric current method ($\boldsymbol{J}$-formulation) may be used to evaluate the electric current [29]. The $\boldsymbol{B}$-formulation and $\boldsymbol{J}$-formulation do not use Ohm's law to calculate electric currents, and thus is free from the specific errors associated with Ohm's law. Moreover, the $\boldsymbol{B}$-formulation has been widely employed in our previous published papers [19–21,30]. In this case non-dimensional MHD equations of continuity, momentum, and energy can be expressed in Cartesian coordinates as

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

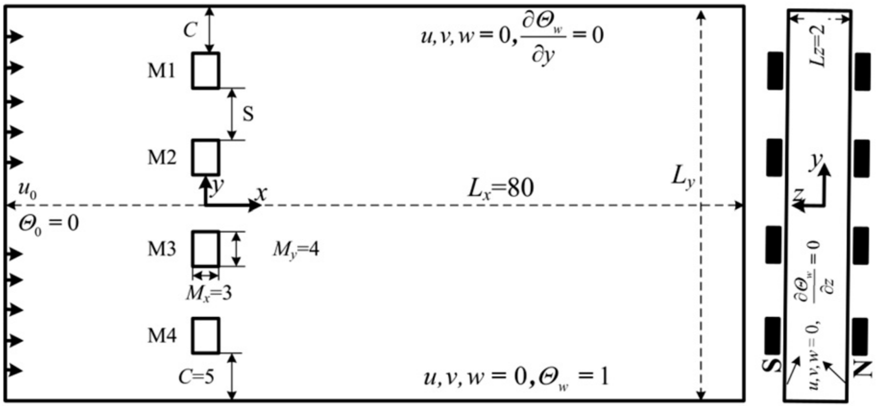

Fig. 1. Schematic representation of the system under investigation along with boundary conditions. Dark shading shows external magnet with the same size and opposing polarization axes separated by a distance $H = 3$. The four magnetic obstacles have been marked as M1 to M4, starting from the top of the computational domain.