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Heat transfer enhancement by external magnetic field for paramagnetic laminar pipe flow

Masayuki Kaneda *, Akira Tsuji, Hiroki Ooka, Kazuhiko Suga

Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuencho, Naka-ku, Sakai, Osaka 599-8531, Japan

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ABSTRACT

Effect of an external magnetic field is numerically investigated on heat transfer of a horizontal constant laminar pipe flow of a paramagnetic fluid. A single current-carrying coil is presumed for the magnet and the pipe is heated at a constant heat flux. It is found that the effect on the heat and fluid flow strongly depends on the coil location, resulting in local heat transfer enhancement/suppression. Only when the coil is placed at threshold of the heating zone, the enhancement is achieved. This is due to the magnetothermal force which attracts cold fluid toward the coil, and the force induces boundary layer thinning behind the coil. In the case, the heat transfer enhancement at the threshold remains approximately 10% at Reynolds number of 10 in no-gravitational field, although the enhancement decreases with the increase of the Reynolds number under constant magnetic induction. Computations in the presence of the gravity reveals that the magnetothermal force becomes effective especially at upper region. It is found that the effectiveness is in a same order as cases without gravity in slow flow field. The contribution of the magnetic field merges to the no-gravity case in higher flow field.

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1. Introduction

Magnetic field has been applied to various processes, such as magnetic separation [1], continuous steel casting [2], Czochralski process for the crystal growth [3], etc. Most of these targets are ferromagnetic and/or electrically-conductive fluid such as molten steel or silicon. Ferromagnetic materials are attracted to magnets with the remarkable force due to the magnetization. In case of electrically-conductive fluid, induced Lorentz force suppresses or enhances the flow, which have been intensively studied for the convection control of liquid metal [4–6].

Strong magnetic field in the order of several tesla or more has been available since the emergence of superconducting magnets. Under such strong magnetic field, magnetizing or magnetic force becomes remarkable not only in the ferromagnetic materials but also in the paramagnetic and diamagnetic materials. Various new phenomena have been reported such as levitation of water droplet [7], magneto-Archimedes levitation [8], nitrogen jet (Wakayama jet) [9], magneto-thermal wind [10], effect on the natural convection [11], etc. Recent progress of the related studies are imposed on the combination with natural convection in a horizontal annulus [12], laminar-to-turbulence regime with natural convection inside a cubic enclosure [13], and transient flow characteristics in Rayleigh–Benard convection [14]. Since water is diamagnetic, water drop can be repelled from strong magnetic field. Magneto-Archimedes levitation and Wakayama jet utilize the difference of the magnetic force on each material ($CuSO_4$ aqueous solution and air, nitrogen and air), since every material has its magnetic susceptibility as physical property.

Whilst, the magnetic susceptibility of paramagnetic fluids also have the temperature dependency. It has an inverse dependency on the absolute temperature, which is called Curie's law. This suggests that the magnitude of magnetic force depends on local temperature. Rest of aforementioned phenomena are derived from this characteristic, thus they belong to so-called 'magneto-thermal convection'. Various investigations have been reported so far to clarify the fundamental characteristics in pure magneto-thermal convection or in mixed convection. Kaneda et al. [15] found that the natural convection of air in a cubic enclosure is suppressed when the magnet is placed above the enclosure. In contrast, it is enhanced by placing the magnet below the enclosure.

In case of the magneto-thermal wind phenomenon, a spontaneous flow in a pipe is generated by supplying both heat source and magnetic field without pumps or blowers [10]. The case under the presence of main flow was also studied [16]. However, these are limited in two-dimensional and flow without gravity or vertical system. The heat transfer characteristic has not been discussed in such system.

* Corresponding author. Tel.: +81 72 254 8480; fax: +81 72 254 9904.
E-mail address: mkaneda@me.osakafu-u.ac.jp (M. Kaneda).

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Nomenclature

b	magnetic field
B	$=\mathbf{b}/b_0$
d	diameter
D	$=d/r_0$
g	gravity acceleration
k	thermal conductivity
P	p/p_0
p	pressure
q	heat flux from pipe wall
R	$=r/r_0$
r	radial coordinate
Ra^*	modified Rayleigh number
Re	Reynolds number
s	circumferential length of coil
T	dimensionless temperature
t	time
t_0	characteristic time = r_0/u_0
u	velocity = (u, v, w)
u_0	characteristic velocity
U	$=\mathbf{u}/u_0$
Z	$=z/r_0$
z	axial coordinate

Greek letters

α	thermal diffusivity
β	expansion coefficient due to temperature
γ	dimensionless magnetic strength to the gravity, $=\chi b_0^2/\mu_m g r_0$
ϕ	circumferential coordinate (rad)
μ	viscosity
μ_m	magnetic permeability
ν	kinematic viscosity of fluid = μ/ρ
ρ	fluid density
τ	dimensionless time = t/t_0
χ	mass magnetic susceptibility

Subscript

0	reference value
c	coil location
p	pipe

In this study, the effect of the external magnetic field on heat transfer is numerically investigated for a heated laminar pipe flow. Followed by the schematics and governing equations, the case without gravity is firstly discussed especially for the effect of the magnet location and its strength. The effect of additional force of the gravity is then studied.

2. Modeled system and governing equations

Schematic model for the computation is shown in Fig. 1. The three-dimensional cylindrical coordinate (R–ϕ–Z) is employed. A straight pipe is set horizontally, of which non-dimensional radius and length are respectively 1.0 and 10.0. The paramagnetic fluid is presumed as a working fluid. Inlet fluid dimensionless temperature is 0, which flows in uniformly at the constant flux. The flow is fully developed before the heated region of $Z \geqslant 4.0$. The free-outflow condition is employed for heat and fluid flow. The stationary magnetic field distribution is presumed by a coaxial single electric coil for a simplicity. The coil can be fixed at the arbitrary axial location, Z_c. In this study, local enhancement in front of/behind the coil may be different and to be discussed. Thus the single turn coaxial coil is employed to avoid the complexity of solenoid coil such as number of turn, coil pitch and solenoid length.

The governing equations consist of the continuity, momentum, and energy equations for the heat and fluid flow in the pipe, and Biot–Savart law for the magnetic field in the computational region.

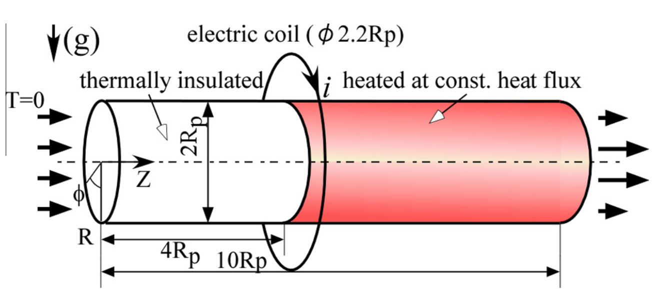

Fig. 1. Schematic model for computation.

The buoyant force due to temperature difference, and magnetic force due to temperature and magnetic fields are simultaneously considered in the momentum equation as force terms by using Boussinesq approximation. The detailed derivation can be referred to Maki et al. [17]. The working fluid is presumed as incompressible Newtonian and paramagnetic ($\chi = 1/T$). The non-dimensional governing equations in three-dimensional cylindrical coordinate system can be obtained by the method of Hellums and Churchill [18] and are as follows;

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

$$D\mathbf{U}/D\tau = -\vec{\nabla}P + (1/\mathrm{Re})\nabla^2\mathbf{U} - (Ra^*/\mathrm{Pr}\mathrm{Re}^2)T[\gamma\vec{\nabla}B^2/2 - (\cos\phi, \sin\phi, 0)^T] \tag{2}$$

$$DT/D\tau = \nabla^2 T \tag{3}$$

$$\mathbf{B} = -\frac{1}{4\pi}\oint\frac{\mathbf{R}\times d\mathbf{S}}{R^3} \tag{4}$$

where,

$$\mathrm{Pr} = \frac{\nu}{\alpha}, \quad \mathrm{Re} = \frac{u_0 r_p}{\nu}, \quad Ra^* = \frac{g\beta q r_p^4}{k\alpha\nu}, \quad \gamma = \frac{\chi b_0^2}{\mu_m g r_0}.$$

Modified Rayleigh number Ra^* corresponds to the magnitude of heat flux from the pipe wall and γ represents the magnetization number, the strength of the magnetic field induced from the coil.

The boundary conditions are as follows. For the velocity boundary, a non-slip condition is applied to the cylindrical wall. At the inlet of the pipe, constant and uniform flow flux is presumed ($\mathbf{U}|_{Z=0} = (0, 0, 1)$). The free-outflow condition is considered (zero velocity gradient in axial direction, $\partial W/\partial Z = 0$). As for the temperature boundary condition, pipe wall except the heated region is thermally insulated, and the constant heat flux is presumed at the heated region ($Z \geqslant 4$). The inlet fluid temperature is 0, and the outlet of the pipe is presumed as free-outflow ($\partial T/\partial Z|_{Z=\mathrm{kmax}} = \partial T/\partial Z|_{Z=\mathrm{kmax}-1}$). The initial conditions are that a uniform velocity profile of (0, 0, 1) for all region, temperature is set at 0, and no magnetic field nor heat flux are applied.

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