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Magnetothermal force on heated or cooled pipe flow

Masayuki Kaneda*, Kazuhiko Suga

Osaka Prefecture University, 1-1 Gakuencho, Naka-ku, Sakai 599-8234, Japan

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ABSTRACT

The effects of the magnetothermal force on the flows of heat and fluid through a pipe are investigated numerically when the pipe wall is either heated or cooled at constant heat flux. The flow is laminar and a paramagnetic fluid is presumed as the working fluid. Because the magnetic susceptibility of a paramagnetic fluid depends on the inverse of its temperature, the magnetothermal force is induced by coupling of the temperature field and magnetic induction. First, the effects are discussed using the case of a magnetic field induced by a single-turn concentrically placed electric coil. It is found that the effects of the magnetothermal force differ according to whether the pipe is cooled or heated. When cooled, the heat and fluid flows are affected behind the coil; the flow is repelled from the wall to the center and the thermal boundary layer thickens. By decomposing the force into the radial and axial directions in the heated and cooled cases, it is clarified that the axial force changes from positive to negative depending on the coil location in the heated case. Therefore, it can be concluded that the effects are not simply oppositional in the heated and cooled cases. In relation to the heat transfer, only when the coil is placed at the threshold of the heating/cooling zone do the effects on the local heat transfer become the opposite of each other. At other coil locations, the suppression of heat transfer is dominant ahead of the coil in the heated case, as indicated in previous work by our group. However, in the cooled case, this effect occurs behind the coil. For a more practical case, a solenoid coil is employed in the simulation. It is then found that the effect on the heat transfer becomes remarkable at the solenoid edges, especially for the heat-transfer suppression in both the heated and cooled cases.

1. Introduction

Magnetic susceptibility is a physical property. Materials with positive magnetic susceptibility are attracted to magnets, whereas those with negative susceptibility are repelled. Ferromagnetic materials (e.g., iron, cobalt, nickel) have large positive magnetic susceptibility ($>10^9$ cm^3/g), whereas paramagnetic materials have small positive susceptibility (e.g., oxygen: $\sim 10^{-4}$ cm^3/g). Although the magnetic force on paramagnetic materials is extremely small, its effect was detected in the 19th century (Faraday, 1847) and has since been applied to, for example, oxygen gas sensors.

In the late 20th century, extremely strong magnetic fields became available with the emergence of superconducting magnets. Magnetic fields of several tesla or more have allowed various new findings such as the levitation of water droplets under gravity (magneto-Archimedes effect) (Ikezoe et al., 1998), jets of nitrogen gas in air (Wakayama jet) (Wakayama, 1991), and nonmagnetic particle alignment (Sun et al., 2011). Each of these phenomena is induced by a magnetic force on a material that is not electrically conductive, as given by

$$f = \Delta\chi \nabla B^2 / 2\mu_0. \tag{1}$$

This suggests that overall force is due to differences in magnetic susceptibility among the various materials involved in each phenomenon.

Another characteristic of the magnetic susceptibility of a paramagnetic material is that it depends on the inverse of absolute temperature:

$$\chi = C/T, \tag{2}$$

where C is a constant. This is known as Curie's law. Therefore, even for a single component, a magnetic force is induced that depends on the local temperature. This is known as the magnetothermal force. In terms of problems involving the flow of heat and fluid, this force can be used to control convection, and many such studies have been reported to date. Braithwaite et al. (1991) found that Rayleigh–Bénard convection is enhanced/suppressed under a strong magnetic field by placing above/below a superconducting magnet. Uetake et al. (1999) demonstrated the spontaneously induced flow of air in a tube due to the combination of a heater and a superconducting magnet. Kaneda et al. (2002) reported the convection of air under thermally

* Corresponding author.
E-mail address: mkaneda@me.osakafu-u.ac.jp (M. Kaneda).

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Nomenclature

B	dimensionless magnetic induction
C	constant
D	dimensionless diameter
FR	dimensionless force in radial direction
FZ	dimensionless force in axial direction
g	acceleration due to gravity, m/s^2
k	thermal conductivity of fluid, W/m^2
P	dimensionless pressure
Pr	Prandtl number
q	heat flux, W/m^2
Q	dimensionless heat flux
R	radial coordinate
Ra^*	modified Rayleigh number
T	dimensionless temperature
T_{bulk}	local mixed mean temperature
T_{wall}	local wall temperature
U	dimensionless velocity
Z	axial coordinate
α	thermal diffusivity, m^2/s
β	expansion coefficient due to temperature, 1/K
γ	magnetization number
ϕ	circumferential coordinate
μ	viscosity, Pa s
μ_m	magnetic permeability, H/m
χ	mass magnetic susceptibility, Wb m/kg

stratified conditions in a cubic enclosure. Kenjereš et al. (2012, 2014) investigated oscillatory convection in a magnetic field for a paramagnetic fluid in a cubic enclosure heated from bottom and cooled from above.

Convection control is also possible in case of forced convection. Our group has implemented the magnetothermal force in a lattice Boltzmann code for heat and fluid flows, and has investigated the effect of this force on flow through a heated open-cell porous medium (Kaneda et al., 2015a). It was found that the magnetothermal force enhances the local heat transfer inside the porous medium.

As a simpler case, we consider heat and fluid flows through a tube. Heat transfer in a straight tube occurs in various heat exchangers, the performance of which depends on the ability to control the heat transfer. Kaneda et al. (2015b) considered heat-exchange tubes that are heated externally. In particular, they reported the effect of the magnetothermal force on the flow of heated paramagnetic fluid in a pipe at a constant flow rate (i.e., fixed Reynolds number). They discussed the roles of magnet location, Reynolds number, and magnetic induction. It was found that the magnetothermal force induces vortex flow in the vicinity of the magnet and that heat transfer is suppressed in front of the magnet and enhanced behind it. For pressure-driven flow inside the tube (Kaneda et al., 2017), the flow pattern changes and the heat-transfer enhancement is weakened compared with above case. It was suggested that the magnetothermal force increases the pressure loss by acting like a rib on the internal surface of the pipe, which eventually reduces the flow flux. Kaneda et al. (2017) also implied that the effect of the magnetothermal force decreases with Reynolds number. Additionally, millimetre-scale flow or less is preferable for the application of low-cost magnets such as permanent magnets.

The aforementioned studies were focused on heat-exchange tubes that were heated by the surrounding medium. Clearly, another possible situation is where the tube and the medium flowing inside it are cooled (e.g., automotive radiators). In such a case, when the magnetothermal force is applied to the cooled fluid, its effect is not symmetric to that in

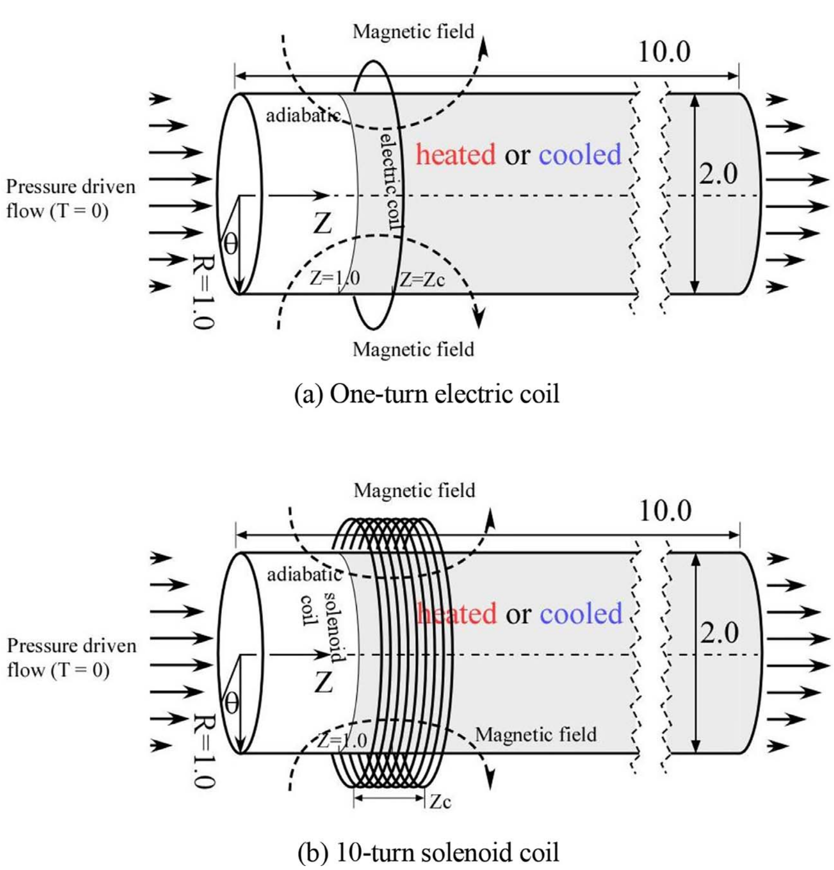

Fig. 1. Schematic of computational model.