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Flow characteristics of ferrofluid in a microchannel with patterned blocks

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ABSTRACT

The thermal flow characteristics of a ferrofluid under magnetic field effects in a microchannel were investigated with different patterned blocks of rectangular and triangular configurations, which were mounted on the top and bottom wall surfaces alternately. Also, the effects of external magnetic fields of different orientations on the thermal behaviors of the ferrofluid in the modeled microchannel were numerically investigated. The results showed that the external magnetic field critically affected the heat transfer performances of the ferrofluid because the generated pressure gradients of the ferrofluid flow changed with strength and orientation of the external magnetic field. Using these phenomena, we could control the heat transfer processes of the ferrofluid flow in the modeled microchannel.

1. Introduction

Heat transfer is obstructed by many complex factors. Consequently, low heat transfer coefficients have become a considerable concern in many fields of thermal systems. Recently, nanofluid or ferrofluid has been concerned as a feasible medium to radiate the increment of heat in miniaturized systems [1].

Magnetic nanofluid, also called ferrofluid, was developed from ferrohydrodynamics (FHD), and the main type is the colloidal ferrofluid, which is a magnetic colloidal mixture consisting of a carrier liquid and magnetic nanoparticles of size ranging from 5 to 15 nm in diameter coated with a surfactant layer. A ferrofluid with magnetic and fluid properties has many advantages: the fluid flow and heat transfer may be controlled by an external magnetic field, making it applicable in various fields such as electronic packaging, mechanical engineering, thermal engineering, aerospace and bioengineering, etc. [2–6].

In general, fluids such as liquids and gases have a lower thermal conductivity than metallic substances. But many researchers confirmed that mechanical characteristics like thermal conductivity can be enhanced by adding metallic nanoparticles to fluids. Choi and Eastman [7] enhanced the thermal conductivity of conventional fluids, like water, by adding metallic nanoparticles to them. Wang et al. [8] observed the enhancement in thermal conductivity of ferrofluid applied with Al_2O_3 and CuO particles dispersed in water, and discussed the enhancement mechanism. Liu et al. [9,10] investigated the remarkable enhancement in the thermal conductivity of different base fluids used in carbon nanotubes. They confirmed about 22% improvement in thermal conductivity of ethylene glycol containing CuO nanoparticles and showed that for low volume fractions, the thermal conductivity of ferrofluid is approximately linear with the volume fraction. Li et al. [11] measured the viscosity and thermal conductivity of a ferrofluid under external magnetic fields and investigated the effects of the volume concentration of nanoparticles and the type of surfactant.

The mechanical characteristics of ferrofluid such as viscosity and conductivity can be influenced by an external magnetic field, which can be used to control the rheological characteristics of ferrofluid efficiently. Forced convection heat transfer of ferrofluid under a uniform magnetic field was investigated by Lajvardy et al. [12]; they confirmed enhanced thermal performances. Ganguly et al. [13] analyzed a two-dimensional pressure-driven flow of a ferrofluid in a channel to investigate the influence of line source dipole magnetic field on convective heat transfer. Aminfar et al. [14,15] numerically investigated the effects of positive and negative non-uniform axial magnetic fields and a uniform transverse magnetic field on the thermal-flow characteristics of a ferrofluid mixed convection flow in a vertical tube. They showed that the negative gradient axial magnetic field and the uniform transverse magnetic field acted similarly and enhanced both the

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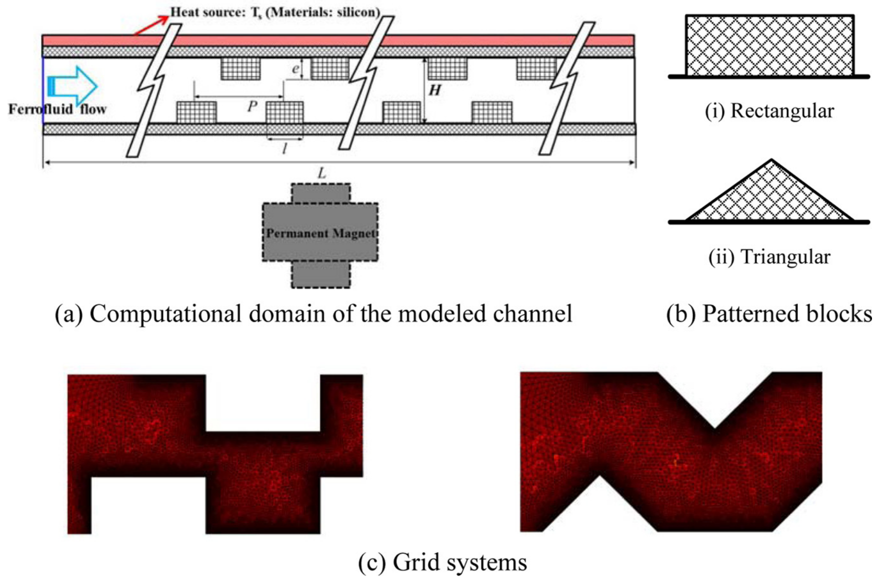

Fig. 1. Schematic of the analysis model and grid systems.

Nusselt number and the friction factor whereas the positive gradient axial magnetic field decreased them.

The main objective of this study is to numerically investigate the flow characteristics of a ferrofluid in a rectangular micro-channel considering the influence of patterned blocks such as rectangular and triangular blocks on the channel wall the effect of an external magnetic field, as shown in Fig. 1. Also, in order to confirm the thermal characteristics of the ferrofluid flow in the modeled channel for various operating conditions, we conducted a transient numerical analysis using a commercial code, COMSOL Multiphysics.

2. Methodology

The complex flow phenomena in the modeled microchannel were investigated by numerical methods. The analysis domain is schematically presented in Fig. 1. To describe the convection behavior of the ferrofluid in the designed model considering an external magnetic field, two-dimensional continuity, momentum and energy equations were used to simulate the thermal flow characteristics of the ferrofluid under unsteady-state conditions. The equation systems used in the above simulation are given as follows [16]:

Continuity:

$$\nabla \times V = 0 \tag{1}$$

Momentum:

$$\rho\left(\frac{\partial V}{\partial t} + V \times \nabla V\right) = -\nabla P + \mu \nabla^2 V + \mu_0 (M \nabla) H \tag{2}$$

Energy:

$$\rho c_p\left(\frac{\partial T}{\partial t} + V \times \nabla T\right) = -k\nabla^2 T - \mu_0 T \frac{\partial M}{\partial T}((V\nabla)H) \tag{3}$$

where ρ is the density of the working fluid, c_p is the specific heat at constant pressure, V is the fluid velocity, P is the static pressure, μ is the dynamic viscosity, μ_0 is the magnetic permeability of vacuum, and T is the temperature, k is the thermal conductivity, and M is the magnetization of the working fluid and H is the magnetic field strength.

Because the magnetic part of this problem is static, Maxwell-Ampere's law for the magnetic field H (A/m) and the current density J (A/m^2) are given as follows:

$$\nabla \times H = J \tag{4}$$

Furthermore, Gauss's law for the magnetic flux density B (V/m^2) states that

$$\nabla \times B = 0 \tag{5}$$

The constitutive equations describing the relation between B and H in the different parts of the analysis domain are given as follows:

$$B = \begin{cases} \mu_0 \mu_{r,magnet} H + B_{rem} & \rightarrow \text{permanent magnet} \\ \mu_0 (H + MH) & \rightarrow \text{working fluid flow } \} \\ \mu_0 H & \rightarrow \text{air and solid parts} \end{cases} \tag{6}$$

where $\mu_{r,magnet}$ is the relative magnetic permeability of the permanent magnet, and B_{rem} is the remanent magnetic flux (A/m). In this study, the remanent magnetic flux (B_{rem}) of 5 T is applied to the external permanent magnet to generate the magnetic field effect.

The solution domain and grid systems shown in Fig. 1 are designed for the micro-scale rectangular duct that was applied to the patterned block on the wall. The details of the dimensions of the domain are summarized in Table 1 and the physical properties of the working fluids used in this study are shown in Table 2. Also, to consider the effects of an external magnetic field on the thermal flow characteristics of the ferrofluid in the microchannel, an external magnetic field, which was generated by a permanent magnet located in lower part of the modeled channel, was applied to the analysis model.

The non-Newtonian aspect of ferrofluid flow is significant, as it is for laminar flow with low Reynolds number, in microfluidics, so

Table 1
Details of the modeled microchannel with patterned blocks.

Channel height, H	200 μm
Obstacle height, e	50 μm
Pitch length, P	200 μm
Channel length, L	2 mm
Pitch ratio, P/e	4