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Numerical study of magnetic field effects on the mixed convection of a magnetic nanofluid in a curved tube

H. Aminfar [a], M. Mohammadpourfard [b,*], Y. Narmani Kahnamouei [a]

[a] Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Mechanical Engineering, Azarbaijan Shahid Madani University, P.O. Box: 53714-161, Tabriz, Iran

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ABSTRACT

In this paper, effects of applying a linear magnetic field on a ferrofluid (water and 4 vol% Fe_3O_4) flow in horizontal straight and curved tubes have been investigated. The hydro-thermal behavior of the flow is investigated numerically using the two phase mixture model and control volume technique. The linear magnetic fields with various gradients in the perpendicular direction of the main flow have been examined. Based on the obtained results the heat transfer coefficient can be enhanced using the curved tube instead of straight tube, adding magnetic nanoparticles to the base fluid and applying external magnetic field. It is concluded that the heat transfer is enhanced due to the secondary flow augmentation (because of centrifugal force and Kelvin force) and thermal conductivity improvement (because of high thermal conductivity of magnetic nanoparticles relative to base fluid).

1. Introduction

Ferrofluids (or magnetic nanofluids) are magnetic colloidal suspensions consisting of carrier liquids and magnetic nanoparticles with a size range of 5–15 nm in diameter coated with a surfactant layer. The advantage of the ferrofluids is that the fluid flow and heat transfer may be controlled by an external magnetic field which makes it applicable in various fields such as electronic packing, mechanical engineering, thermal engineering, aerospace and bioengineering [1–4]. Ferrofluids have promising potential for heat transfer applications, since advective transport in a ferrofluid can be readily controlled by using an external magnetic field. However, unlike conventional free or forced convection, ferrohydrodynamic convection is not yet well characterized.

Many studies have been performed numerically and experimentally in the field of thermomagnetic convection of the ferrofluids in different geometries in the presence of an external magnetic field [5–14]. Results of these investigations show that the thermal behaviors of the magnetic fluids inside an enclosure are dominated by both the intensity of the external magnetic field and the temperature gradient. Wrobel et al. [15] carried out an experimental and numerical analysis of a thermo-magnetic convective flow of paramagnetic fluid in an annular enclosure with a round rod core and a cylindrical outer wall. Their results show that magnetizing force affects the heat transfer rate and that a strong magnetic field can control the magnetic convection of paramagnetic fluid.

Sambamurthy et al. [16] presented a numerical analysis of a horizontal circular annulus with an inner heat source of square and circular shapes. They described the flow pattern with double or quadruple vortices. Lajvardi et al. [17] carried out an experimental work on the convective heat transfer of a ferrofluid flowing through a heated copper tube in the laminar regime in the presence of magnetic field and observed a significant enhancement in the heat transfer of ferrofluid by applying various orders of magnetic field. Kamiyama and Ishimoto [18] and Liu et al. [19] performed experiments to characterize boiling two-phase flow heat transfer and pool boiling respectively, using water-based magnetic fluids. Their results show that the boiling heat transfer characteristics of the magnetic fluid are strongly influenced by the external magnetic field.

Aihara et al. [20] simulated a two-dimensional flow of a magnetic fluid with 50% mass concentration of Mn–Zn ferrite particles in a horizontal circular tube using a single phase model and explained the controllability of convective heat transfer in the presence of a non-uniform magnetic field. Ganguly et al. [21] simulated a two-dimensional pressure-driven flow of a magnetic fluid in a channel to investigate the influence of magnetic field created by a line-source dipole on the convective heat transfer.

* Corresponding author. Tel./fax: +98 412 4327566.
E-mail addresses: hh_aminfar@tabrizu.ac.ir (H. Aminfar), Mohammadpour@azaruniv.edu (M. Mohammadpourfard), Narmani87@ms.tabrizu.ac.ir (Y.N. Kahnamouei).

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Nomenclature

ρ	density (kg/m^3)
k	conductivity (w/m K)
β	thermal expansion coefficient (1/K)
$\vec{v}$	velocity (m/s)
T	temperature (K)
P	pressure (Pa)
$\vec{v}_{pf}$	slip velocity vector (m/s)
$\vec{v}_{dr}$	drift velocity vector (m/s)
α_p	particle volume fraction
d_p	magnetic particle diameter (m)
l	tube length ($=R_c\pi$)
R_c	curvature radius of curved tube (m)
d_h	horizontal diameter direction (m)
d_v	vertical diameter direction (m)
D	tube diameter (m)
r	radial direction (m)
φ	circumferential direction
θ	axial direction in curved tube
x	axial direction in straight tube (m)
q_w	wall heat flux (W/m^2)
Re	Reynolds number $\left(\frac{\rho_m v_{mD}}{\mu_m}\right)$
Nu	Nusselt number $\left(\frac{q_w D}{k_m(T_w-T_b)}\right)$
Gr	Grashof number $\left(\frac{g\beta_m q_w \rho_m^2 D^4}{k_m \mu_m^2}\right)$
c_f	skin friction factor $\left(\frac{\tau_w}{\rho_m v^2}\right)$
τ_w	wall shear stress (kg/m s^2)
M	magnetization (A/m)
M_s	saturation magnetization (A/m)
$\vec{H}$	magnetic field vector (A/m)
G	magnetic field gradient (A/m^2)
g	gravitational acceleration (m/s^2)
m_p	particle magnetic moment (A m^2)
μ_0	magnetic permeability in vacuum ($=4\pi\times10^{-7}$ T m/A)
L	Langevin function
ξ	Langevin parameter
μ_B	Bohr magneton ($=9.27\times10^{-24}$ A m^2)
k_B	Boltzmann constant(1.3806503×10^{-23} J/K)

subscripts

f	pertaining to base fluid
p	pertaining to magnetic particles
b	pertaining to bulk condition
m	pertaining to mixture
0	pertaining to inlet conditions

Xuan et al. [22] have developed the mesoscopic model to simulate the magnetic fluid flowing through a microchannel in the presence of a magnetic field gradient using the lattice-Boltzmann method. Also Li and Xuan [23] carried out an experiment to investigate the heat transfer characteristics of magnetic fluid flow around a fine wire under the influence of uniform and non-uniform external magnetic fields. However, a full understanding of the effects of the magnetic field on the hydrothermal characteristics of the ferrofluid flow needs more research.

This paper is a continuation of our previous work [24], in which we studied the effects of buoyancy force and magnetic force on the hydrothermal behavior of kerosene based ferrofluid flow in a vertical tube using the two phase mixture model. In the present paper we are investigating the effects of buoyancy force, magnetic force and centrifugal force on the mixed convection heat transfer of a water based ferrofluid flow in horizontal straight and curved tubes using the two phase mixture model. The effects of the external magnetic field gradients on the hydrothermal behaviors of the ferrofluid flow are analyzed. In the next section the basic theoretical formulation including the governing equations, boundary conditions, and the numerical method is presented. Results are discussed in Section 3. Finally, the concluding remarks are presented in Section 4.

2. Theoretical formulation

2.1. Governing equations

Fig. 1 shows a schematic of the investigated problem. The physical properties of the fluid are assumed constant except for the density in the body force, which varies linearly with the temperature based on Boussinesq's model. In the present work, dissipation and pressure work are ignored. Considering these assumptions the dimensional conservation equations for steady state condition are as follows:

Continuity equation : $\nabla.(\rho_m \vec{v}_m)=0. \quad (1)$

Momentum equation :

$$\nabla.(\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla.(\mu_m \nabla \vec{v}_m) + \nabla.(\alpha_P \rho_P \vec{v}_{dr,p} \vec{v}_{dr,p}) - \rho_{m,0}(T-T_0)\beta_m \vec{g} + \mu_0(\vec{M}.\nabla)\vec{H} \quad (2)$$

The term $\rho_{m,0}(T-T_0)\beta_m \vec{g}$ is the buoyancy force and the term $\mu_0(\vec{M}.\nabla)\vec{H}$ is due to FHD which is the so-called Kelvin force density, derived from the stress of an electromagnetic field where M is the magnetization and is defined as [25]

$$M = M_s L(\xi) = \frac{6\alpha_p m_p}{\pi d_p^3}\left(\coth(\xi) - \frac{1}{\xi}\right). \quad (3)$$

The unit cell of the crystal structure of magnetite has a volume of about 730 Å^3 and contains 8 molecules of Fe_3O_4 and each of them having a magnetic moment of $4\mu_B$ [24]. Therefore the particle magnetic moment for the magnetite particles is obtained as

$$m_p = \frac{4\mu_B \pi d_p^3}{6\times 91.25\times 10^{-30}} \quad (4)$$

also ξ is the Langevin parameter and is defined as [25]

$$\xi = \frac{\mu_0 m_p H}{k_B T} \quad (5)$$

Energy equation:

The energy equation for the incompressible mixture is as follows:

$$\nabla.[(\alpha_P \rho_P c_{p,p} \vec{v}_p + (1-\alpha_P)\rho_f c_{p,f} \vec{v}_f)T] = \nabla.(k_m \nabla T) \quad (6)$$

Volume fraction:

The volume fraction equation is the continuity equation for the particles phase. Clearly the volume fraction equation and the other equations of the flow are coupled.

$$\nabla.(\alpha_P \rho_P \vec{v}_m) = -\nabla.(\alpha_P \rho_P \vec{v}_{dr,p}) \quad (7)$$

here

$$\vec{v}_m = \frac{\alpha_P \rho_P \vec{v}_p + (1-\alpha_P)\rho_f \vec{v}_f}{\rho_m} \quad (8)$$