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Numerical study of the ferrofluid flow and heat transfer through a rectangular duct in the presence of a non-uniform transverse magnetic field

H. Aminfar [a], M. Mohammadpourfard [b,*], S. Ahangar Zonouzi [a]

[a] Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Mechanical Engineering, Azarbaijan Shahid Madani University, Tabriz 53751-71379, Iran

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ABSTRACT

This paper investigates numerically the hydro-thermal characteristics of a ferrofluid (water and 4 vol% Fe_3O_4) in a vertical rectangular duct which is exposed to a non-uniform transverse magnetic field generated by an electric current going through a wire located parallelly under the duct. The two phase mixture model and the control volume technique have been used to study the flow.

The results show that applying the aforementioned magnetic field increases the Nusselt number and friction factor and also creates a pair of vortices that enhances heat transfer and prevents sedimentation of nano-particles. Furthermore, unlike the axial non-uniform magnetic field, the increase of the Nusselt number for the transverse magnetic field is considerable in all length along the duct and it is also concluded that with increasing the Reynolds number, the effect of the transverse non-uniform magnetic field on the Nusselt number is more than that of the axial non-uniform magnetic field.

1. Introduction

Magnetic fluids, also called ferrofluids, are synthesized using colloidal mixtures of non-magnetic carrier liquid, usually an organic solvent or water, containing single domain magnetized particles with diameters of order 5–15 nm.

A ferrofluid behaves as a fluid that is affected by an external magnetic field and externally applied magnetic fields can be used to control and direct the flow of ferrofluids, because of which it is applicable in various fields such as electronic packing, mechanical engineering, thermal engineering, aerospace and bioengineering [1–4].

Many investigations were carried out 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].

Strek and Jopek [15] simulated heat transfer through a ferrofluid under the influence of magnetic dipole. Wrobel et al. [16] studied thermo-magnetic convective flow of paramagnetic fluid in an annular enclosure with a round rod core and a cylindrical outer wall numerically and experimentally. Their results show that magnetizing force affects the heat transfer rate and a strong magnetic field can control the magnetic convection of paramagnetic fluid.

Tzirtzilakis et al. [17] investigated biomagnetic fluid flow in a 3D rectangular duct. Their investigations showed that the flow is appreciably influenced in the presence of magnetic field. Tzirtzilakis [18] also studied electrical conductive blood flow under the influence of localized magnetic field in a channel with stenosis. His results showed that the effects of magnetic field are considerable and it can shift the reattachment of the flow in the downstream direction. Ganguly et al. [19] simulated a two-dimensional pressure-driven flow of a magnetic fluid in a channel to investigate the influence of line source dipole magnetic field on the convective heat transfer. Recently Aminfar et al. [20,21] investigated the effects of positive and negative non-uniform axial magnetic fields and uniform transverse magnetic field on hydrodynamic and thermal behaviors of a ferrofluid mixed convection flow in a vertical tube. They showed that the negative gradient axial field and uniform transverse field act similarly and enhance both the Nusselt number and the friction factor while positive gradient axial field decreases them.

Many numerical investigations related to ferrofluids which are limited to study the hydrodynamics of flow have used single phase model for their numerical simulation while ferrofluids are colloidal mixtures. So in the present study, for a better investigation of the flow, the two phase mixture model is used for numerical simulation. Furthermore the flow is assumed to be viscous, laminar, incompressible and three dimensional.

* Corresponding author. Tel./fax: +98 412 4327566.
E-mail addresses: hh_aminfar@tabrizu.ac.ir (H. Aminfar), Mohammadpour@azaruniv.edu (M. Mohammadpourfard), sajjadahangar89@ms.tabrizu.ac.ir (S. Ahangar Zonouzi).

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Nomenclature

ρ	density (kg/m^3)
c_p	specific heat (J/kg K)
μ	dynamic viscosity (kg/m s)
k	conductivity (W/m K)
α_m	thermal diffusivity ($=1.5994815\times10^{-7}$ m^2/s)
β	thermal expansion coefficient (K^{-1})
$\underline{g}$	gravitational acceleration ($=-9.81$ m/s^2)
$\overrightarrow{v}$	velocity (m/s)
V_0	inlet velocity (m/s)
$\overline{v}_{pf}$	slip velocity vector (m/s)
$\overline{v}_{pf}$	drift velocity vector (m/s)
T	temperature (K)
P	pressure (Pa)
α_p	particle volume fraction
d_p	magnetic particle diameter (m)
l	vertical tube length ($=0.2$ m)
a	half of a cross section side ($=0.01$ m)
h	cross section side ($=0.02$ m)
x	axis in the Cartesian coordinates
y	axis in the Cartesian coordinates
z	axis in the Cartesian coordinates
Pr	Prandtl number ($=6.2361$)
(a,b)	center of magnetic wire (m)
q_w	wall heat flux ($=158.4\ W/m^2$)
Mn	magnetic number $\left(\frac{\mu_0\chi H_r^2 h^2}{\rho_m\alpha_m^2}\right)$
Re	Reynolds number $\left(\frac{\rho_m V_0 a}{\mu_m}\right)$
Nu	Nusselt number $\left(\frac{q_w 2a}{k_m(\overline{T}_w-T_b)}\right)$
Gr	Grashof number $\left(\frac{g\beta_m q_w\rho_m^2(2a)^4}{k_m\mu_m^2}\right)$
c_f	friction factor $\left(\frac{\tau_w}{1/2\rho_m V_0^2}\right)$
M	magnetization (A/m)
$\underline{M}_s$	saturation magnetization (A/m)
$\overrightarrow{H}$	magnetic field vector (A/m)
H_r	characteristic magnetic field strength (A/m)
H_x	magnetic field intensity component in x direction (A/m)
H_y	magnetic field intensity component in y direction (A/m)
G	axial magnetic field gradient(A/m^2)
I	electric intensity (80 A)
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)
χ	magnetic susceptibility
k_B	Boltzmann constant (1.3806503×10^{-23} J/K)
j	flux of magnetic nanoparticles (m/s)
S_T	Soret coefficient (K^{-1})
D	diffusion coefficient of particles in the base fluid ($=2.7\times10^{-11}$ m^2/s)

Subscripts

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

The main purpose of the present work is to investigate numerically hydro-thermal features of water based ferrofluid flowing upward in a vertical rectangular duct under the influence of non-uniform transverse magnetic field resulting from a wire of current. The performance and efficiency of this transverse and non-uniform magnetic field will be compared with axial non-uniform magnetic field. Also the effects of the external magnetic field gradients on the hydrothermal behaviors of the ferrofluid flow are analyzed.

2. Theoretical formulation

2.1. Governing equations

Fig. 1 shows the schematic of the investigated problem which is a vertical duct of length l and square cross section of side $2a$. The magnetic field is generated by an electric current going through a thin and straight wire oriented parallel to the longitudinal axis (z) at the position (a,b) and the current in the wire flows in the direction of positive z-axis. The components of the magnetic field H_x,H_y in the x and y directions, due to the electric current flowing through the wire, are given by [22]

$$H_x(x,y)=\frac{I}{2\pi}\frac{(x-a)}{(x-a)^2+(y-b)^2} \tag{1}$$

$$H_y(x,y)=-\frac{I}{2\pi}\frac{(y-b)}{(x-a)^2+(y-b)^2}. \tag{2}$$

The magnitude of the magnetic field intensity is given by

$$H(x,y,z)=H(x,y)=\frac{I}{2\pi}\frac{1}{\sqrt{(x-a)^2+(y-b)^2}}. \tag{3}$$

Physical properties of the fluid are assumed to be constant except for the density in the body force, which varies linearly with the temperature based on the Boussinesq's model. The effects of magnetic field on the viscosity and the thermal conductivity of the ferrofluid have been assumed to be negligible. It should be mentioned that the non-uniform transverse magnetic field has negligible effect in MHD, and the Lorentz force due to the electrical conductivity is also considered negligible compared to the magnetization force. Moreover dissipation and pressure work are ignored in the present study. Considering these assumptions the dimensional conservation equations for steady state condition are as follows:

Continuity equation:

$$\nabla(\rho_m\overrightarrow{v}_m)=0. \tag{4}$$

Momentum equation:

$$\nabla(\rho_m\overrightarrow{v}_m\overrightarrow{v}_m)=-\nabla p+\nabla(\mu_m\nabla\overrightarrow{v}_m)+\nabla(\alpha_p\rho_p\overrightarrow{v}_{dr,p}\overrightarrow{v}_{dr,p})$$
$$-\rho_{m,0}(T-T_0)\beta_m\overrightarrow{g}+\mu_0(\overrightarrow{M}\nabla)\overrightarrow{\mathrm{H}}. \tag{5}$$

The term $(M\,\nabla)H$ is related to FHD due to the existence of the magnetic gradient and is called the Kelvin force. $\overrightarrow{\mu}_0\overrightarrow{M}\ \frac{\partial\overrightarrow{H}}{\partial\overrightarrow{x}}$ and $\overrightarrow{\mu}_0\overrightarrow{M}\ \frac{\partial\overrightarrow{H}}{\partial\overrightarrow{y}}$ are the components of Kelvin force in the x and y