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Forced convection heat transfer in a semi annulus under the influence of a variable magnetic field

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ABSTRACT

Since advective transport in a ferrofluid can be controlled by using an external magnetic field, magnetic nanofluid (ferrofluid) has various applications to heat transfer processes. Unlike free or forced convection, Ferrohydrodynamic convection is not yet well described. In the literature we see papers with constant magnetic fields; but the assumptions are not accurate, since the fields do not comply with the Maxwell's equations of electromagnetism. In this study, forced convection heat transfer in a semi annulus lid under the influence of a variable magnetic field is studied. The enclosure is filled with ferrofluid (Fe_3O_4–water). Control Volume based Finite Element Method (CVFEM) is used to solve the governing equations considering both Ferrohydrodynamic (FHD) and Magnetohydrodynamic (MHD) effects. It is assumed that the magnetization of the fluid is varying linearly with temperature and magnetic field intensity. The effects Reynolds number, nanoparticle volume fraction parameter, magnetic number arising from FHD, and Hartmann number arising from MHD are analyzed. Obtained results indicate that the effects of Kelvin forces are more pronounced for high Reynolds number. Heat transfer enhancement has direct relationship with the Reynolds number and the magnetic number; while it has inverse relationship with the Hartmann number.

1. Introduction

Ferrofluid is a magnetic colloidal suspension of single domain magnetic nanoparticles. It can be utilized for heat transfer applications, since the flow field established by ferrofluid can be suitably changed by applying external magnetic fields. Ferrofluid heat transfer treatment in the presence of variable magnetic field has been studied by Sheikholeslami and Rashidi [1]. Ganguly et al. [2] studied the effect of a line dipole on heat transfer enhancement. They found that an enhancement in the overall heat transfer depends on the net magnetizing current as well as the relative placement of the dipoles. Parsa et al. [3] investigated the magneto-hemodynamic laminar viscous flow of a conducting physiological fluid in a semi-porous channel under a transverse magnetic field. Sheikholeslami and Ellahi [4] studied three dimensional mesoscopic simulation of magnetic field effect on natural convection of nanofluid. They found that thermal boundary layer thickness increase with increase in the Lorentz force. The vortex dynamics behind various magnetic obstacles and characteristics of heat transfer were investigated by Zhang and Huang [5]. They found that the pressure drop penalty is not dependent on interaction parameter. Nanofluid flow and heat transfer characteristics between two horizontal parallel plates in a rotating system were investigated by Sheikholeslami et al. [6]. They found that the Nusselt number increases with an increase in nanoparticle volume fraction and the Reynolds number; but it decreases with an increase in the Eckert number, the magnetic and the rotation parameters.

Ghofrani et al. [7] presented an experimental investigation on forced convection heat transfer of an aqueous ferrofluid flow passing through a circular copper tube in the presence of an alternating magnetic field. They found that the effect of the magnetic field in low Reynolds numbers is higher, and a maximum of 27.6% enhancement in the convection heat transfer is observed. Sheikholeslami et al. [8] used lattice Boltzmann simulation (LBM) to simulate nanofluid flow and heat transfer results in a horizontal cylindrical enclosure with an inner triangular cylinder. Rashidi et al. [9] studied the effects of magnetic interaction number, slip

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Nomenclature

A	amplitude
B	magnetic induction $(=\mu_0 H)$
C_p	specific heat at constant pressure
Ec	Eckert number $(=(\rho_f u_r^2)/[(\rho C_P)_f \Delta T])$
En	heat transfer enhancement
H_x, H_y	components of the magnetic field intensity
H	the magnetic field strength
Ha	Hartmann number $\left(=\mu_0 H_0 L\sqrt{\sigma_f/\mu_f}\right)$
Mn_F	magnetic number arising from FHD $(=\mu_0 H_0^2 K'(T_h - T_c)/(\rho_f u_r^2))$
M	magnetization $(=K'\overline{H}(T'_c - T))$
Nu	Nusselt number
Pr	Prandtl number $(=\upsilon_f/\alpha_f)$
Re	Reynolds number $(=\rho_f L u_r/\mu_f)$
T	fluid temperature
T'_c	curie temperature
u, v	velocity components in the x-direction and y-direction
U, V	dimensionless velocity components in the X-direction and Y-direction
x, y	space coordinates
X, Y	dimensionless space coordinates
r	non-dimensional radial distance
k	thermal conductivity
L	gap between inner and outer boundary of the enclosure $L = r_{out} - r_{in} = r_{in}$

Greek symbols

ζ	angle measured from the lower right plane
α	thermal diffusivity
ϕ	volume fraction
γ'	magnetic field strength at the source
ε_1	temperature number $(=T_1/\Delta T)$
ε_2	curie temperature number $(=T'_c/\Delta T)$
σ	electrical conductivity
μ	dynamic viscosity
μ_0	magnetic permeability of vacuum $(=4\pi \times 10^{-7}\ \mathrm{Tm/A})$
υ	kinematic viscosity
$\psi \& \Psi$	stream function and dimensionless stream function
Θ	dimensionless temperature
ρ	fluid density
ω, Ω	vorticity and dimensionless vorticity

Subscripts

c	cold
h	hot
ave	average
loc	local
nf	nanofluid
f	base fluid
s	solid particles

factor and relative temperature difference on velocity and temperature profiles as well as entropy generation in Magnetohydrodynamic (MHD) flow of a fluid over a rotating disk with variable properties. Ellahi et al. [10] studied the effect of the nanoparticle shape on natural convection boundary layer flow along an inverted cone. Garoosi et al. [11] used two-phase mixture model to simulate steady state mixed convection heat transfer of nanofluid in a two-sided lid driven cavity with several pairs of heaters and coolers (HACs). They found that by changing the direction of the moving walls the heat transfer rate changes significantly. Numerical analysis of the heat transfer enhancement and fluid flow characteristics of a rotating cylinder under the influence of magnetic dipole in the backward facing step geometry was conducted by Selimefendigil and Oztop [12]. They found that the effect of cylinder rotation on the local Nusselt number distribution is more pronounced at low Reynolds number. Nanofluid flow and heat transfer in presence of magnetic field were investigated by several authors [13–44].

The CVFEM uses the advantages of both finite volume and finite element methods for simulation of multi-physics problems in complex geometries (see [44]). MHD effect on natural convection heat transfer in an enclosure filled with nanofluid was studied by Sheikholeslami et al. [45]. Their results indicated that the Nusselt number is an increasing function of buoyancy ratio number; but it is a decreasing function of the Lewis number and the Hartmann number. Sheikholeslami et al. [46] studied the problem of natural convection between a circular enclosure and a sinusoidal cylinder. They concluded that the streamlines, the isotherms and the formation of the cells inside the enclosure strongly depend on the Rayleigh number, values of the amplitude and the number of undulations of the enclosure. Effects of magnetic field on nanofluid flow and heat transfer are studied by several authors [47–50].

The main objective of the present work is to study ferrofluid forced convection heat transfer in a semi annulus in the presence of an external magnetic field. CVFEM is applied to solve this problem. The numerical investigation is carried out for various values of the governing parameters such as the Reynolds number, the nanoparticle volume fraction, the magnetic number and the Hartmann number.

2. Geometry definition and boundary conditions

The physical model along with the needed geometrical parameters and the mesh of the enclosure used in the present CVFEM program are shown in Fig. 1. The outer wall is maintained at constant temperature T_h and the other walls are maintained at a constant temperature T_c. The shape of inner cylinder profile is assumed to mimic the following form:

$$r = r_{in} + A\cos(N(\zeta)), \tag{1}$$

in which r_{in} is the base circle radius, r_{out} is the radius of the outer cylinder, A and N are amplitude and number of undulations, respectively, and ζ is the rotation angle. In this study A and N are equal to 0.2 and 4, respectively. For the expression of the magnetic field strength, it can be considered that the magnetic source represents a magnetic wire placed vertically to the xy-plane at the point $(\overline{a}, \overline{b})$. The components of the magnetic field intensity $(\overline{H_x}, \overline{H_y})$ and the magnetic field strength $(\overline{H})$ can be considered as:

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

$$\overline{H_y} = -\frac{\gamma'}{2\pi}\frac{1}{(x-\overline{a})^2 + (y-\overline{b})^2}(x-\overline{a}), \tag{3}$$

$$\overline{H} = \sqrt{\overline{H}_x^2 + \overline{H}_y^2} = \frac{\gamma'}{2\pi}\frac{1}{\sqrt{(x-\overline{a})^2 + (y-\overline{b})^2}}, \tag{4}$$